ALEXANDER LANG
Linde AG.

Air fractionation plant explosion

Investigations of the causes indicate wooden structures may be rendered dangerous by liquid oxygen. Plant modifications are suggested; also, interim safety measures are proposed.

HERE IS A DETAILED REPORT on the causes of an explosion in an air fractionation plant and the lessons learned from the accident.

Description of the plant

The plant, which is situated on the site of the Hoesch AG. Abt. Westfalenhütte in Dortmund, belongs to and is operated by the Knapsack Griesheim AG. in Duesseldorf. It was built and installed by Gesellschaft für Linde's Eismaschinen AG. in 1953. The oxygen plant TR 131 was a Linde-Fränkl plant and was a so-called "low-pressure process" plant. This expression indicates that the air to be fractionated is only compressed to the pressure of the pre-fractionation column plus the pressure drop brought about by the heat exchange between the air and the fractionation products. This air was supplied by a compressor plant located in the adjoining Kaiserstuhl mine, a plant which is equipped exclusively with turbo-compressors.

There was an additional high-pressure system which supplied the necessary refrigeration for the extraction, in liquid condition, of part of the pure oxygen produced. The air used for this purpose was tapped off a branch air stream originating from the middle of the nitrogen-air regenerators and, after heating in heat exchangers, was compressed to 200 atm. in a horizontal, oil-lubricated, high-pressure air compressor of conventional design. The compressed air after thorough oil-separation was then pre-cooled to −40°C in a twin-stage ammonia refrigeration plant and subsequently cooled down counter current to the extracted low-pressure air almost to its liquefaction temperature. It was then expanded into the pre-fractionation column.

The original design provided for the production from 11,904 std. cu.ft./min. of low-pressure air at 5.6 atm. ab. of 1860–2108 std. cu. ft./min. of industrial oxygen of a purity of 99–92%, 124 std. cu. ft./min. of pure oxygen in gaseous form of a purity of 99.5%, and 124 std. cu. ft./min. of pure oxygen in liquid form, also at a purity of 99.5%.

The coldbox shell of the fractionation plant covered a surface area of 20 x 25 ft. and had an over-all height of 43 ft.-7 in. The height of the coldbox shell enclosing the main pieces of apparatus and the regenerators was 21 ft.-7 in. Mounted above this lower section of the plant was the coldbox shell surrounding the main fractionation column (upper column) which added a further 21 ft.-7 in. to the over-all height. The dimensions of the oval perimeter of this upper half of the coldbox shell were 7 ft.-2.4 in. x 9 ft.-9.5 in.

The main pieces of apparatus located within the coldbox shell consisted of the nitrogen and oxygen regenerators (heat exchangers for cooling the low-pressure air to be

Wrecked nitrogen regenerators and upper section of the coldbox shell. (Opposite page.)

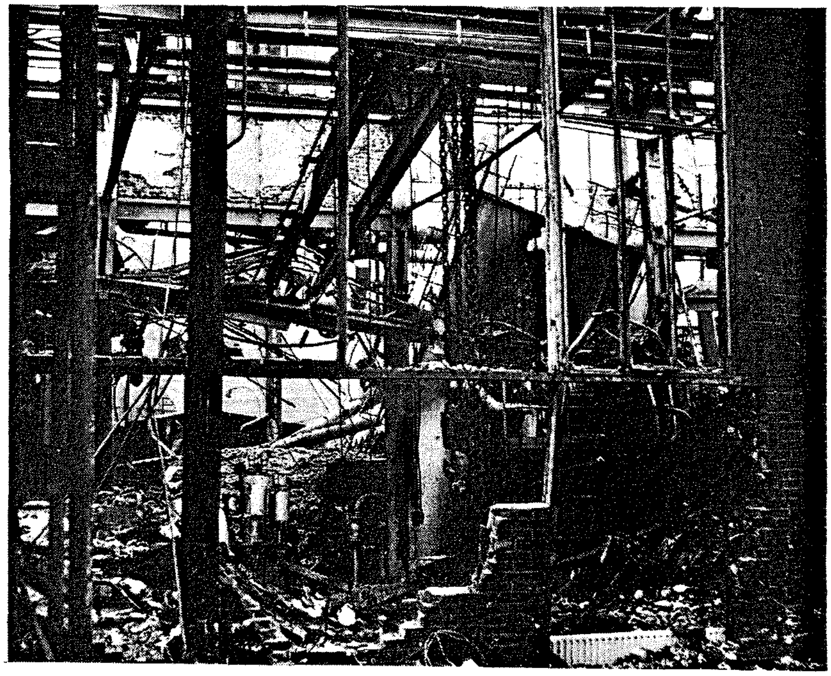

Figure 1. View of the plant after the explosion as seen from the engine-room end.

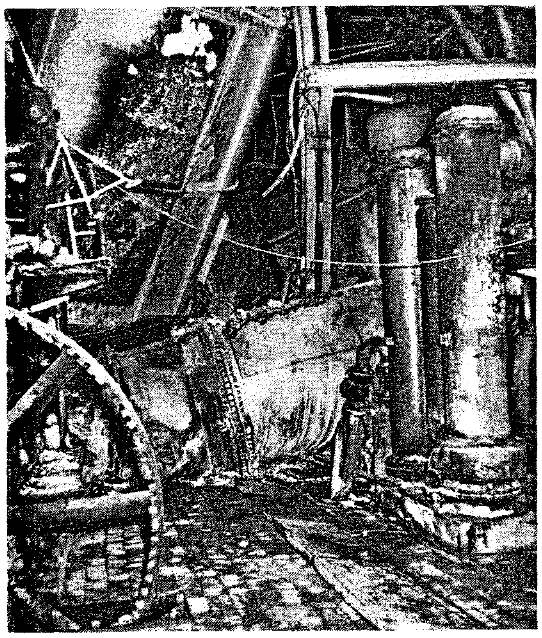

Figure 2. Pressure column with main condenser.

fractionated and for heating the products of fractionation), and the actual rectifying column, consisting of pressure column, main condenser, and upper column.

In addition to these main pieces of apparatus the following items were also housed in the coldbox shell: a small supplementary column for the production of the pure oxygen; the filter adsorbers for purifying the liquid of the pressure column before it passes into the upper column; the adsorbers used for removal of the carbon dioxide from a branch air stream which is tapped off from the middle of the nitrogen regenerators; and various heat exchangers for cooling the compressed air, for liquefying a portion of the low-pressure air, and for subcooling the reflux liquid passing into the main rectifying column (upper column).

All these pieces of apparatus were insulated with slag wool which filled the entire interior of the sheet-steel coldbox shell. The base-plate of the coldbox shell was lined with wood, forming a wooden floor, made of impregnated pinewood planks of an over-all thickness of 4 in. and clad on all sides with galvanized iron sheet. The sheet-metal was neatly lapped and nailed at the edges.

The weight of the entire plant including insulation material was approximately 200 tons.

The plant was erected on a brick foundation, surfaced with concrete, and was located in a shop having a height of 59 ft. and a roof-span of 33.5 ft., the shell being of steelwork with brickwork. The roof was covered with prefabricated concrete slabs. Above the plant was a travelling crane of 12-ton lifting capacity. Next to the shop housing the plant was the engine-room of 40-ft. roof-span and approximately 23-ft. height, housing the compressors for compressing the industrial oxygen produced and the compressed air. The ammonia plant, including compressor, pre-coolers, condenser, and switchboard was located next to the air fractionation plant within the shop which housed the main apparatus units. On the other side of the air fractionation plant inside this shop was a spray cooler for cooling and purification of the low-pressure air. Adjacent to this vessel was located the apparatus for a second oxygen plant belonging to the Knapsack-Griesheim A.G.; this apparatus was housed in an extension of the shop housing the main plant.

Operating conditions

During the first few years after its erection, the plant was operated under varying loads. For more than 12 months, however, the plant has been running at full capacity and in the course of a production run of 92% industrial oxygen the rated output was exceeded. Operation was continued at this rate, with the exception of Sundays, from 6 o'clock in the morning until 6 o'clock in the evening and, during long periods of operation, the plant proved fully capable of carrying the loads imposed upon it. No production difficulties such as, for example, a premature rise in regenerator resistance, were recorded. In order to accelerate the weekly start-ups after Sunday shut-downs, it was normal practice, as in various other plants, to pass liquid oxygen from a storage container into the main condenser.

The apparatus had been overhauled before the explosion; five days before the actual accident it was given its normal start-up. Starting-up of the plant is normally carried out initially with low-pressure air, the required amount of refrigeration being generated in an expansion turbine where the low-pressure air is expanded performing mechanical work in the process. Later, the high-pressure cycle is also put into operation in order to accelerate the cooling of the system and to facilitate the formation of liquid.

The start-up for the production run commencing on December 30, 1960, went according to normal plan; however, there was definite evidence of leakage at some point in the lower section of the nitrogen regenerators. Cold gas was found to be escaping at this point and the liquefaction output was inadequate. On January 2, 1961, a leaking flange at the base of the nitrogen regenerator No. 4 had to be tightened up. In order to carry out this operation, one of the covers of the coldbox shell had to be opened up and sufficient insulating material (slag wool) temporarily removed to facilitate access to the flange. It was assumed that the reason for the malfunction was connected with the high-pressure compressor and this latter was therefore over-hauled on the same day. The overhaul brought to light the fact that the piston rings of the third stage were defective and

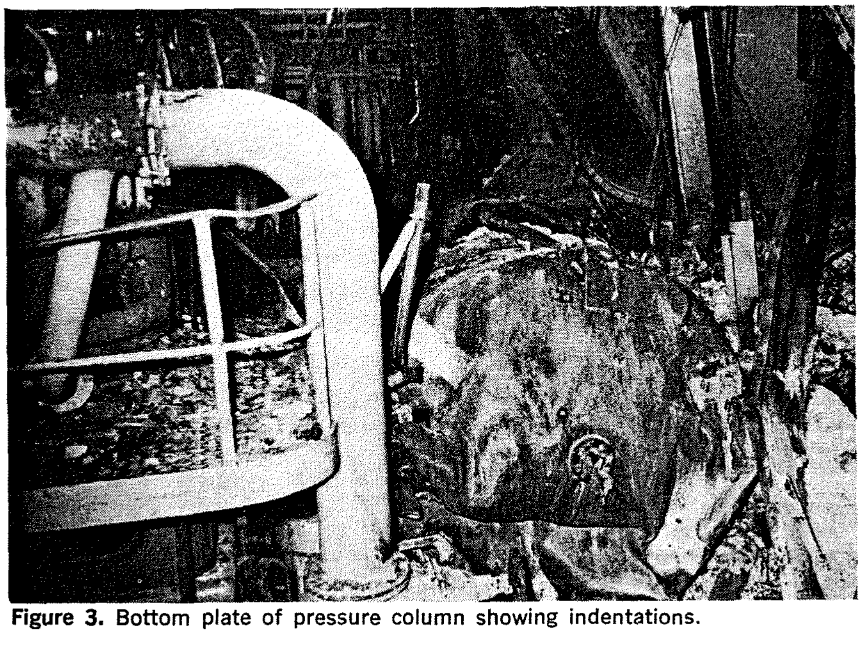

Figure 3. Bottom plate of pressure column showing indentations.

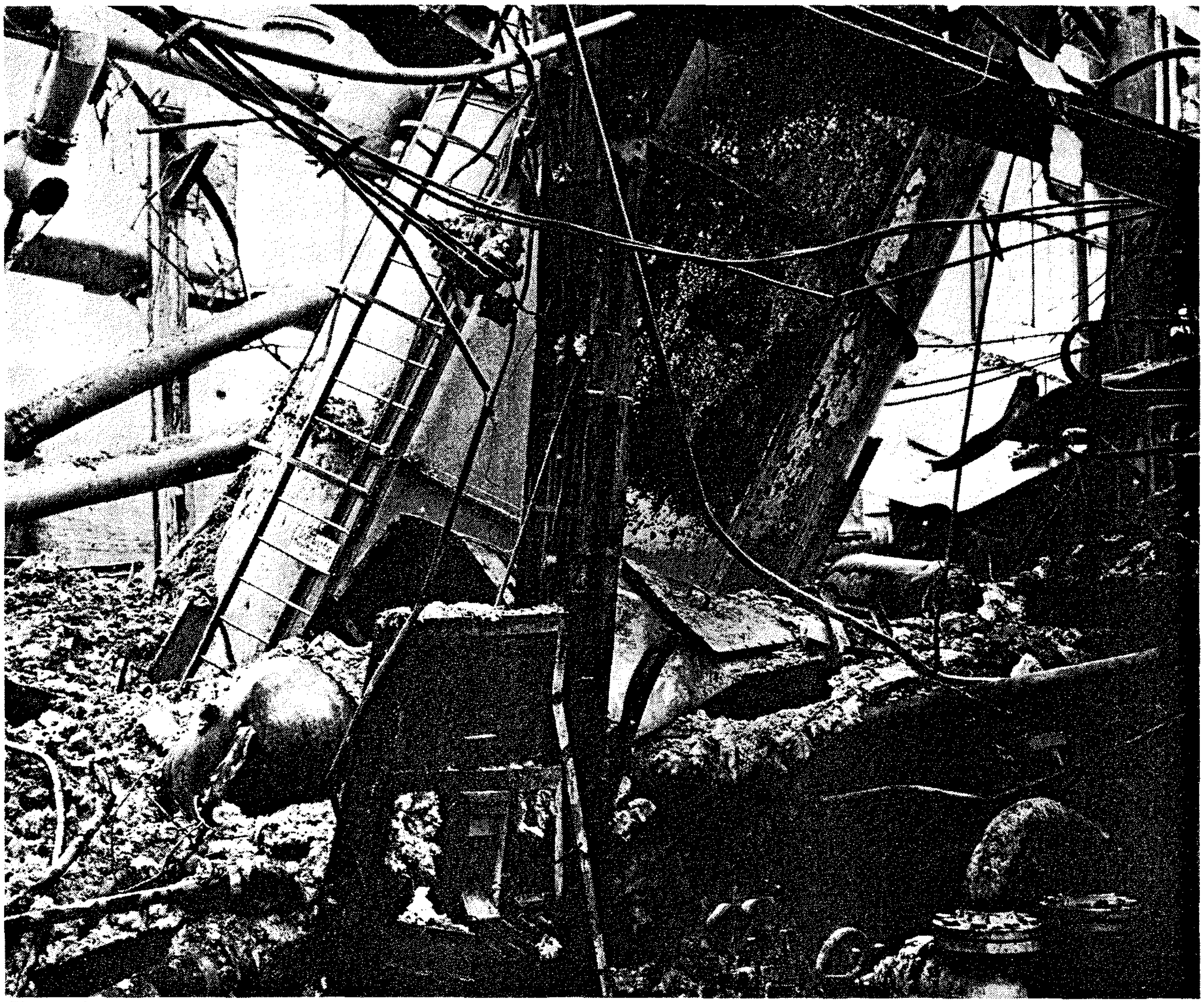

Figure 4. Position of upper section of the coldbox shell after the explosion.

these were replaced. The apparatus unit in the meantime had resumed the production of oxygen; and liquid oxygen was fed backwards from other units into the condenser of the fractionation plant TR 131 while these repairs were taking place. In this way some 14,000 liters of liquid oxygen were fed into the plant within a period of approximately 30 hr. Although the plant subsequently reached a capacity of approximately 1860 std. cu. ft./min. of oxygen, there was nevertheless an appreciable leakage in the area of the oxygen regenerators as became apparent one to two days before the catastrophe through the escape of cold gas from the coldbox shell.

Damage from the explosion

Owing to the fact that certain repair work and other maintenance work which was started during the shutdown period was still in progress, a considerable number of personnel were present in the plant at the time of the explosion.

Shortly before the explosion, it was noticed that the gasket of the coldbox shell at the foundation, in the area of the nitrogen regenerators, had caught fire. This gasket consisted of a 1.57-in. wide sealing strip with vulcanized canvas binding which was clamped between the base frame of the foundation and the angle-iron framework of one of the metal panels of the shell. An attempt was made to put out the fire with portable fire extinguishers. The manager of the works was summoned, and he immediately hastened to the scene of the fire together with his assistants. It was at this moment that the explosion occured, causing 15 deaths and considerable damage to the plant and the associated buildings.

The brick panels in the steelwork shell of the shop housing the main plant were almost entirely blasted out by the explosion; the same was true of the engine-room. The roof of both shops was blown off completely and the uprights of the steel structure and the steel beams were appreciably distorted outwards. The upper section of the coldbox shell was tilted in the direction of the machine shop. Altogether, the destruction caused was so widespread that it was at first thought that the entire shop—and not one individual piece of apparatus—was the seat of the explosion, Figure 1.

Investigations on the possible causes of the catastrophe were considerably hindered by the extent of the destruction caused; the first stage of the salvage work was extremely difficult and dangerous for the personnel concerned. It soon became evident, however, that there was no question of there having been a total shop explosion as distinct from an explosion of the industrial apparatus itself. The position of the individual vessels after the explosion led to the assumption that the source of the catastrophe was actually inside the coldbox shell. All the regenerators had clearly received an impact from beneath and this had obviously been responsible for some of them being ejected from their normal position in the plant. The lower sections of all pressure shells had burst as shown in the introductory photograph. The pressure column, together with the main condenser which was bolted to it, was torn away from the upper part of the column and was found at a point outside the main shop, *i.e.*, in the engine-room section of the plant at the point where the main control panel had previously been located. This section of the plant, which had a total weight of approximately 15 tons, had obviously been hurled through the air as a result of an impact received from below. It dislocated the crane gantry and another of the main supports of the steelwork structure as it somersaulted through the air, Figure 2. The bottom end of the column shows clear traces of indentation, obviously caused by external impact, Figure 3. The upper column was found within the upper section of the coldbox shell. This latter had obviously fallen down after the lower part of the shell, the pressure column, and the main condenser had been blown away; and it finished up leaning against the steelwork structure of the building, Figure 4.

Figure 5. View of the cover (top) of the main condenser.

Possible causes of explosion

When an air-fractionation plant explodes it is reasonable to assume at first that a reaction may have taken place within the apparatus between liquid oxygen or liquid air and some organic substances. The initial inquiry, therefore, proceeded along these lines in evaluating all the indications which might possibly furnish an explanation of the tragedy.

Supervision of the normal running of the plant had previously shown that acetylene had never actually been detected, not even in trace quantities. The air intake for the fractionation air at the Kaiserstuhl mine is located in a yard in one of the workings where obviously the air carries a certain amount of dust but, at the same time, there is no indication that acetylene or hydrocarbons are present in the surrounding air in any unusual concentration. In the course of the daily acetylene determinations which were carried out by the works, the amount of acetylene present in the main condenser was invariably less than 0.025 ppm.

The following points were established in connection with the possibility of an acetylene or hydrocarbon explosion with liquid oxygen within the apparatus. The main condenser, the shell of which was at first impacted through the force of the explosion and then subsequently split apart, was otherwise completely intact, Figure 5. It is thus obvious that no explosion could have taken place at this point. The acetylene adsorbers were also quite undamaged externally. The lower section of the pressure column had obviously been indented from below by some external force, as already mentioned. The lower sections of the regenerators, all of which were burst open, furnished no evidence pointing to a possible explosion within these vessels. Thus, there appeared to be little possibility that the explosion had actually taken place within the apparatus itself.

In order to make doubly sure, a sample of liquid oxygen manufactured by Plant TR 190, which was in operation at the same time, was taken from a stationary tank and tested for the presence of acetylene and hydrocarbons. This plant processes compressed air which originates from the same suction point as the air fractionated by TR 131; thus, any impurities in the air would contaminate the liquid produced by the two plants in approximately the same degree.

The results of the investigation showed that the purity of oxygen was 99.6% and contained the following impurities in ppm:

	Conc.	Detection threshold
CH_4	40	5
C_2H_6	0.1	0.01
C_2H_4	< 0.01	0.01
C_3H_8	0.01	0.005
C_3H_6	< 0.005	0.005
C_6H_{10}	< 0.005	0.005
CO	< 5	5
C_2H_2	< 0.005	0.005

The extremely low content of acetylene and other hydrocarbons would seem to preclude the possibility of the explosion having taken place within the apparatus. The result of the investigation thus added weight to the conviction already resulting from the external examination of the vessels, *i.e.*, that whereas the explosion actually did take place within the sheet-metal shell it must, on the other hand, have taken place at some point outside the actual vessels and pipelines.

Oil-soaked slag wool suspect

The high-pressure system by which oil traces originating in the lubrication system of the high-pressure air compressor might possibly have been carried into the unit was not entirely above suspicion as a possible cause of the explosion. The installation of a centrifugal oil separator with a coil element at a point before the ammonia pre-cooler insured optimal oil separation, *i.e.*, the most efficient form of oil separation available at the present time. The oil consumption of the compressor was normal. The type of oil used, HKP 300, has flash point and viscosity properties which fully satisfy the standards laid down in the normal regulations for air fractionation plants. There was, therefore, no valid reason for assuming excessive oil contamination of the high-pressure air. Nevertheless, this possibility was pursued as a line of inquiry and care-

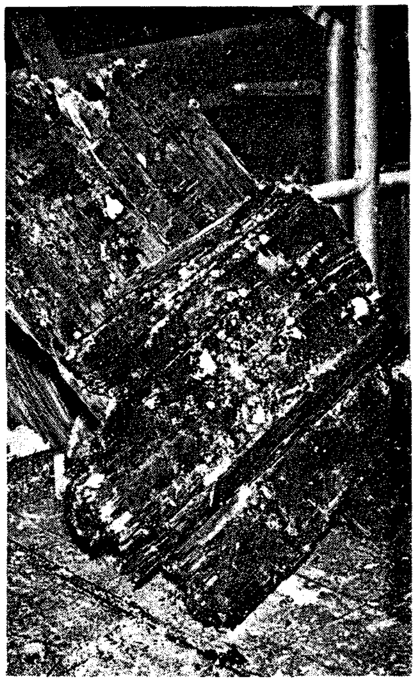

Figure 6. Remaining section of the partly-charred wooden floor.

ful investigations were carried out with the object of determining whether by any chance flange leakage in the high-pressure air line within the cold-box shell might have caused oil to be sprayed into the slag wool by escaping high-pressure air. Any such oil-soaked slag wool could conceivably form an explosive mixture in combination with liquid oxygen. However, all the high-pressure flanged joints or couplings were found to be intact after the explosion; the counter-current heat exchangers and lines alone had been blasted from their positions by the force of the explosion. Moreover, the center of the explosion was obviously not in the area of the high-pressure air line and the high-pressure pre-cooler. Nowhere was there any evidence of oil-soaked slag wool in the plant. It was thus possible to drop the idea that finely-dispersed oil particles transferred from the high-pressure air into the slag wool might be responsible for the explosion.

A further possible cause of explosion might have been the use of slag wool which was impregnated with oil or plastic substances and which might have contained an excess of inflammable substances.

A point of special importance was the possibility that an inflammable insulation material might have been inadvertently used during repair work to supplement the insulation material installed in the first instance. The management and all concerned were aware of the dangers arising in connection with the use of a type of slag wool containing an appreciable amount of inflammable substances, and conversations showed beyond all doubt that there was no possibility of the wrong kind of material having been supplied. It was also possible to exclude the thought of oil-soaked slag wool having been used for filling holes in the insulation after repair work had been carried out; it was quite clear that all personnel concerned were adequately instructed on this danger. It is true that some residue of slag wool, part of which was fused into a vitreous kind of substance by the heat, was found among the ruins; but this fusion of individual layers of slag wool was unanimously attributed by the examining experts to the fact that the flame-fronts of the explosion had penetrated the slag-wool packing at these points. There was no evidence whatever of oil-containing or oil-fouled slag wool being found during the search.

Smouldering fire develops

On the other hand, wood in the form either of chips or larger pieces of various sizes, which were either totally or partly charred, were found in the ruins. Figure 6 shows the largest of the remaining sections of the wooden floor—partly charred—which has yet come to light.

Figure 7 shows the splintered wood. Several pieces of wood were found which were considerably charred on the outside surface but certain surfaces of which were not blackened and which must therefore have been split open after the explosion. From this evidence, the examining experts gained the impression that a charring process must have preceded the actual explosion itself. Statements were made by eyewitnesses showing that in the course of repair work carried out before the start-up of the plant, certain work had been undertaken within the coldbox shell. In the course of this work a copper pipe had been welded at a point close to the surface of the floor. This at first gave rise to the assumption that the wooden floor (which was covered with galvanized iron and thus was unrecognizable to the personnel concerned as a wooden floor) had been caused to smoulder by the dropping of incandescent globules of metal or even by contact with the welding torch itself.

Thus, from these points it would have been possible for a smouldering fire to develop and to spread unnoticed along the wooden floor, since as soon as the repair work was finished, the slag wool was packed into place again and the coldbox shell sealed. The flange or coupling leaks which were later discovered might be explained by the fact that the strength of the wooden floor had been reduced by the partial charring of the wood—for instance, under the supporting framework of one of the containers. In consequence, the container itself may have sunk, thus causing leakage of the coupled piping due to the resultant stresses. Liquid oxygen may then have escaped at these points. Owing to the fact that the metal surfacing of the wooden floor is not absolutely leak-proof and may well have been damaged at certain points, it is possible for liquid oxygen—when present in large quantities—to penetrate into the wood underneath. It is, of course, obvious that the partly-charred wood flooring, which thus becomes soaked with liquid oxygen, is highly explosive.

The ignition may have been caused by the smouldering fire, for instance as the result of several flame fronts happening to coincide and causing a considerable increase in temperature. The smouldering fire may also conceivably have caused the fire at the gasket of the coldbox shell which was observed immediately prior to the explosion. At this late stage, however, it will not be possible to establish with absolute certainty the actual ignition mechanism which triggered off the explosion.

Where was center of explosion?

It became increasingly clear that the explosion must have originated in the wooden floor or some part of it and, in consequence, the clearance of the remaining debris was awaited with considerable interest since it was thought that this would reveal the probable center of the explosion. The position of the various parts of the equipment after the explosion led to the assumption that the center of the explosion was immediately above the foundation in the area between the pressure column and the oxygen regenerators.

When the rubble-clearance work had been completed, however, it was discovered that the surface concreting of the foundation was relatively undamaged and that it was not possible to pin-point any actual place as the center of the explosion, Figure 8. It became quite clear that the explosion must have actually taken place over the whole surface area of the foundations.

The base-plate was forced into the footings at a slight angle by the explosion. Figure 9 shows the amount of subsidence of the base-plate after the explosion, as compared with its original position (measurements were taken after completion of the clearance work). This irregular sinking of the base-plate leads to the assumption that the center of the explosion was on the floor between the pressure column and the oxygen regenerators. This opinion is reinforced by the position of the individual vessels after the explosion as shown in Figure 10.

Report of experts

The experts of the Public Prosecutor's Office, who were charged with the investigation of the causes of explosion, and, at the same time, the representatives of the operating company of the plant and the members of Linde AG. present at the enquiry, have unanimously arrived at the verdict that the above is the probable way in which the accident occurred. This provisional verdict, which was unanimously agreed by all those taking part in the enquiry as being the most likely explanation of the catastrophe, was disclosed to the press on January 10, 1961.

Materials testing

As soon as it had become apparent that the explosion probably originated in the wooden floor, numerous explosion tests with wood or other organic substances ("Iporca" and bitumen) in liquid oxygen were immediately undertaken by Linde and the Federal Institute for the Testing of Industrial Materials at Berlin-Dahlem. The experiments produced surprising results. In the first place it was shown that both porous materials, such as charcoal and hardwoods and softwoods are capable of rapid absorption of liquid oxygen. Just as charcoal soaked in liquid oxygen can be detonated in various ways, so can specimens of this latter material soaked in this way be detonated. If the ignition is carried out with sufficient energy (with a detonator) or if the wood is enclosed in sheet-metal casing, the reaction is a violent explosion or detonation.

Links to the chain process

If the above is taken as a basis for reasoning, the chain process leading to the explosion can be presented in a somewhat different manner.

The liquid oxygen, seeping through to the floor, penetrated through the joints, or cold cracks, in the sheet metal to the wood and soaked into it over a period of several days. Some of the liquid oxygen overflowed the 2-in. groove between the wooden floor and the coldbox shell and was thus observed outside the coldbox shell. On the morning of January 4, approximately a quarter of an hour before the explosion, fire accompanied by black smoke was noted at the coldbox shell. Rubber is the only substance that causes really black smoke on combustion. Consequently, it must have been the rubber gasket strip fitted at the very bottom of the coldbox shell, between an angle iron and the foundation, which had caught fire. Whether the gasket had been ignited by a spark or was particularly susceptible to the action of oxidation cannot be stated with any certainty.

The chain of reasoning advanced here does not allow the assumption of ignition of the rubber gasket by burning wood; had this been the case the explosion would have started at the coldbox shell.

An attempt was made to bring the fire under control by means of fire extinguishers; at the same time, heavy-gauge steel wire was used in an endeavor to remove the burning parts. It may well be that burning fragments found their way into the groove between the metal-clad wooden floor and the coldbox shell; at this point, oxygen—and possibly even liquid oxygen—was certainly present. The fire obtained a hold on the metal shell, then on the oxygen-soaked wood and thus spread with increasing rapidity, culminating in detonation throughout the solid mass of the wooden floor.

This explanation of the origin of the explosion takes into account only the two witnessed and reported processes of leakage of liquid oxygen and the fire described. At present, it does not appear essential to discuss in detail whether preference should be given to explanation of the experts or to the explanation just cited since the conclusions to be drawn in respect to safe operation of fractionating equipment are, for the most part, the same in both cases—namely, the elimination

Figure 7. Splintered remains of the wooden floor.

of woodwork which may well be rendered dangerous by liquid oxygen.

Conclusions—existing plants

From the above arguments and experiments it may safely be concluded that substances of organic origin are always sources of potential explosion danger if they are soaked with liquid oxygen. It is not, of course, a practical proposition to eliminate such parts of the equipment in already-existing plants immediately; on the other hand, modifications to eliminate these sources of danger should be undertaken as soon as possible.

In the fixing of priorities for plant modification the actual degree of possible danger should be taken as a criterion. If any danger of explosion is considered to exist, the fact must be taken into account that the probability of an explosion taking place within the shell, but outside the actual apparatus, is extremely remote as compared, for instance, with the danger of an explosion within the apparatus caused by the processing of contaminated air.

Danger to the plant can only arise where inflammable materials are so completely soaked with liquid oxygen that an explosive mixture results. It is for this reason that those inflammable items located at the *base* of the various apparatus units, where accumulations of liquid oxygen may be assumed in the event of any considerable degree of leakage, head the list of such dangerous materials.

Inflammable materials located at a higher physical level in the plant are less likely to become sources of danger; these include, for instance, wooden supports between structural framework and vessels which, nevertheless, are so located that any leaks developing in apparatus units mounted above them will cause liquid oxygen or liquid air to flow down onto the woodwork. The lowest danger classification would be for those inflammable parts of the plant which are so fitted that liquid oxygen from potential points of leakage cannot penetrate to them and for which the only possible danger is that of contact with oxygen-enriched air in gaseous form.

Any wooden floors or foundations present in existing plants should be replaced by non-inflammable materials as soon as possible. Suitable substitutes for wooden pads for plant frame bases are, for instance, asbestos cement sheets. Asbestos cement is perfectly adequate for this job from the point of view of compressive strength and resistance to frost. The quantity of organic constituents in the pure, safe material is so low that this structural material even remains non-explosive when soaked with liquid oxygen. It should, however, be pointed out that asbestos cement manufactured outside Germany does not exhibit similar properties and the latter should always be examined before being used.

Fairly tall wood foundations are best replaced by a sheet-metal box-section pad, the walls of which should be as thin as possible consistent with strength and should be drilled or air-spaced at appropriate intervals so that heat conduction will be kept at a minimum. An additional method of interrupting the heat flow is to mount these box-section foundations themselves on asbestos cement sheeting. This assumes, of course, that the entire insulation material has previously been removed from the apparatus. It will not be necessary to dismantle the vessels. These can generally be propped on some kind of jack inserted between the plant frame bases. The old wooden floor should be cut away by means of specially-adapted saws and removed in sections. It should be pointed out that work of this kind may take up to several weeks, depending on the size of the plant, and in any case, requires very careful planning.

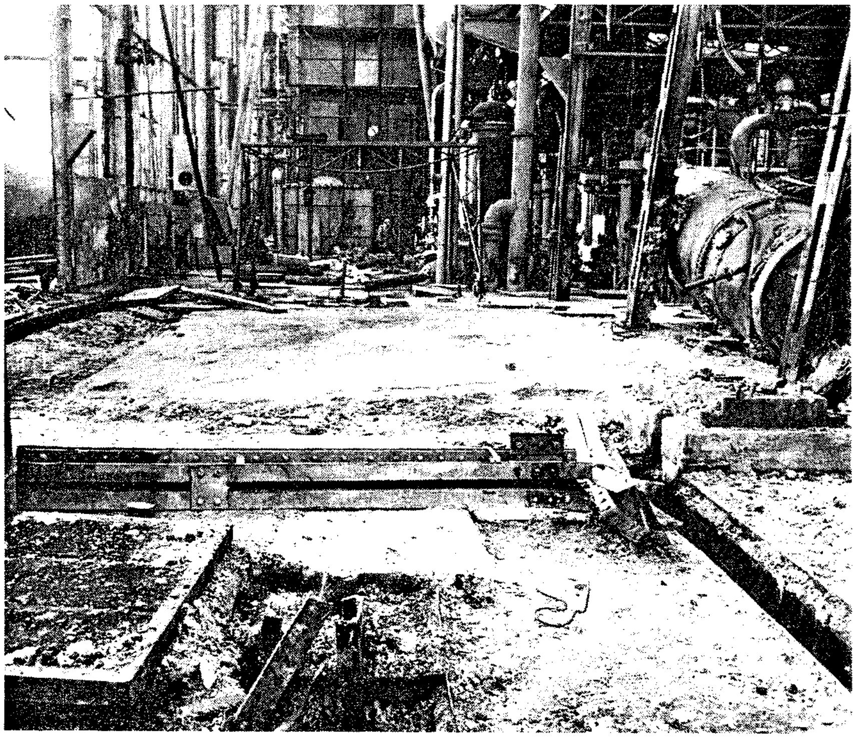

Figure 8. Apparatus base-plate after rubble clearance.

Special precautionary measures

If existing wooden floors cannot be immediately replaced, special precautionary plant supervision must be carried out in the intervening period. Should any leaks occur, an immediate investigation should be made to establish whether liquid air or liquid oxygen is escaping.

If the escape is serious enough for the liquid to penetrate as far as the wooden floor without evaporating, the plant must be shut down and the leak stopped. Care must be taken to insure that there is always a responsible person present or easily accessible with the necessary authority and the ability to stop operation of the plant. Plant operators should not be invested with supervision responsibility unless they can show that they have the necessary training to enable them to stop the operation of the plant in the event of an emergency. It is also advisable that the most important instructions dealing with the stopping of operation of the plant in an emergency should be conspicuously displayed in an easily-accessible public place in the works, together with the current accident prevention regulations for oxygen plants.

It is during the starting-up process, after a complete warm-up of the plant, that the probability of leaky flanges or ruptured piping is greatest due to a slight unevenness in the cooling process. Therefore, special supervision must be exerted during the starting-up process in order to insure timely detection of any irregularities in the working of the plant which might lead to the assumption of a possible escape of liquid oxygen.

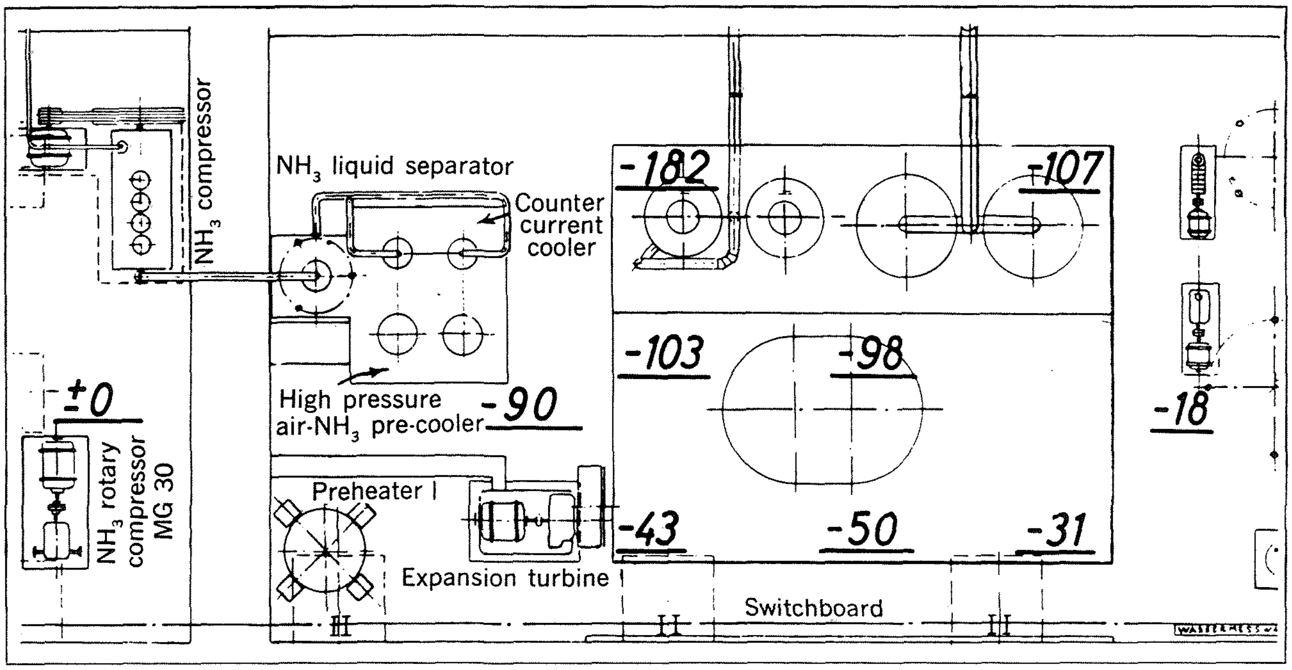

Figure 9. Base-plate settling resulting from the impact of the detonation.

It is also expected that the appropriate competent professional associations will lay down special security regulations for plants which still house inflammable substances, *e.g.*, wooden floors, wooden fittings, etc. This question has been brought up in conversations between the representatives of the various companies operating oxygen plants, the works inspectors, and the appropriate professional associations. In this connection, the regulations reproduced in the box below have been suggested.

The regulations require that measures be taken to insure the timely detection of the escape of liquid oxygen. For this purpose, certain items of equipment are specified which are to be used for gas analysis and temperature measurements. Equipment of this

Proposed safety measures

In air fractionation plants in which inflammable materials such as wooden floors or wooden fittings are still in use, the following safety measures should be observed:

1. Fractionation plants should be fitted with measuring equipment (instruments, etc.) placed directly above the wooden floor or on the wooden foundation pads in such a way as to enable timely detection of the escape of liquid oxygen, by means of either gas analysis or temperature measurements.

2. The following points should be taken into account when repair work is carried out on fractionation plants:

(a) In any work involving the use of naked flames all inflammable items of plant equipment must be protected completely against fire. For example, against the effect of incandescent globules of metal during welding work, it is emphasized that covering the parts in question with slag wool alone is not considered adequate protection.

(b) Work involving the use of naked flames should be carried out only under the actual supervision of the responsible works manager or a representative duly appointed by him.

(c) Any wooden items of equipment—for example, shuttering, scaffolding, etc.—must be removed from the coldbox shell in their entirety after the repair work has been completed.

(d) The insulation materials used should be subjected to quality tests; if they should prove to contain more than 0.5% by weight of inflammable constituents (for instance, oil or synthetic resin) they should be replaced by insulation materials, which do not exceed the permissible content of inflammable constituents.

3. The following points should be watched when starting up the fractionation plants:

(a) Numbers of personnel working in air fractionation plants must be confined to those that are absolutely necessary for the operation and supervision work on these plants.

(b) In the event of liquid oxygen being fed into the fractionation plant, this work should not be commenced until the liquefaction temperature has been actually reached.

(c) In the event of any irregularities being detected which lead to the assumption that liquid oxygen is escaping from the apparatus, the plant should immediately be stopped. From this point on, any liquid ovygen supply to the apparatus must positively be discontinued. In the event of any liquid oxygen loss due to leakage being detected, the liquid oxygen must be immediately drained from the fractionation plant.

4. For heat insulation material, for the lagging of oxygen-pipes, the regulations contained in 2 (d) have to be observed.

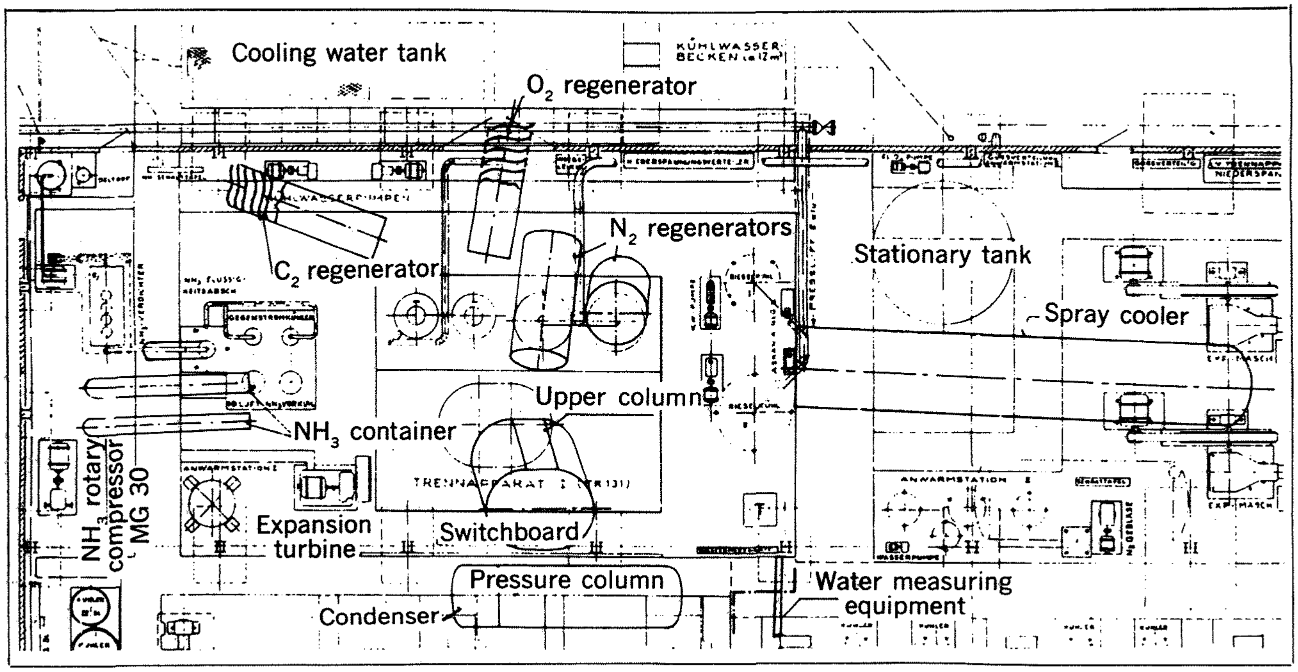

Figure 10. Position of the containers after the explosion.

kind has been installed in several plants in the meantime. It is not as yet possible to report on their actual effect in practice. Linde AG has therefore instituted experiments to demonstrate the value of these methods. A report will be issued when these experiments have been concluded.

The regulations also require special safety measures to be taken during repair periods or when the plants are being started up. The required testing of the insulation materials renders necessary a further agreement on the method of sampling and the method in which the content of combustible matter is to be determined. Discussions on these questions have, in fact, already taken place in the meantime; the results, however, have not yet been promulgated.

Summary

Investigations made as to the causes of the catastrophe have shown that there were various circumstances simultaneously prevailing which permit the incident to be described as a coincidence which, as far as could reasonably be foreseen, was an extremely unlikely occurrence. In the course of five decades, an accident of this nature has never once been experienced in the operation of oxygen plants despite the fact that in previous years the plants were exposed to considerably greater dangers than those encountered today with the technical advantages of modern scientific knowledge. It is as a result of the following extremely unfortunate concatenation of circumstances that the explosion presumably took place:

1. The plant had a wooden floor.
2. Leakage of the apparatus resulted in a considerable amount of liquid oxygen escaping; this flowed down onto the wooden floor, presumably completely soaking certain parts of the latter.
3. Certain welding operations took place within the coldbox shell prior to the starting-up of the plant and these may possibly have been responsible for smouldering fires at some parts of the wooden floor. This smouldering at first remained unnoticed owing to the fact that the insulation was immediately replaced after the repair work had been completed. It may well be, therefore, that the smouldering parts were responsible for the final detonation of the explosion.
4. Shortly before the explosion, a fire was detected at one of the gaskets of the coldbox shell.

The explosion experiments undertaken after the accident led to the surprising conclusion that even wood can be sufficiently saturated with liquid oxygen and made to react explosively if in a sufficiently enclosed space and given adequate ignition. This new discovery led to the conclusion that it was necessary, in all newly-erected premises, to insist on the complete exclusion of wood and all other inflammable materials from the floor of the plant and from any location within the sheet-metal shell of the plant. It is recommended that in existing plants, materials containing organic constituents should be replaced as soon as possible by non-inflammable materials.

In the interim period, supplementary security precautions are suggested, which can be relied upon to eliminate all possibility of such an unfortunate series of circumstances as led to the accident in Dortmund.

If the interim measures suggested in respect to the plants concerned are carried out with the necessary care, it may be confidently anticipated that there will be no further possibility of existing wooden supports exploding before the necessary reconstruction work can be undertaken. #

Questions and Answers

H. H. Hofmaier—American Cyanamid Co., Fortier Plant, La.: In your discussion you intimated that the problem with wood was greatest when the wood was incased. At our plant we have wooden bearing blocks under our column supports. Would you consider this to be a hazard?

Lang: I would not consider this as hazardous as long as it cannot get into contact with a large quantity of liquid oxygen. If they are between the supports and the foundation itself, perhaps they may be of some hazard and it would be best to replace them by some non-combustible material.

J. E. Hart—Dow Chemical Co., Midland, Mich.: Would this be your feeling if the wooden supports were not in the lower portion of the cold box? Perhaps you would not be too concerned by a gaseous oxygen leak in the wood.

Lang: That is right. That is generally in line with what the German insurance inspectors asked after this accident. They require replacement of wood in case it could come into contact with liquid oxygen.

F. Jones—Canadian Industries Ltd., Kingston, Ontario, Canada: I would like to ask a question about the mechanism of combustion. First, in your investigations did you determine the amount of liquid oxygen that could be absorbed by wood having its natural moisture content versus wood which had become substantially dehydrated resulting from a relatively dry environment? Second, are you suggesting that the smoldering which preceded the explosion depended upon an oxygen supply between the galvanized steel sheathing or was it a substantial leak of air or oxygen through the sheathing which enabled this rather large piece of wood to smolder? In other words, if the wood had adsorbed liquid oxygen as a consequence of a prior spill it is conceivable that local overheating due to dropping welding debris might have initiated combustion which perhaps would be able to continue. On the other hand, it is rather difficult to see how smoldering and combustion could continue unless there had been some prior saturation of the wood with liquid oxygen.

Lang: As to Question No. 1, I think we can assume that the wooden floor that had been in this plant for years was absolutely dry. Different types of combustible materials have been tested and the results will be published shortly. As to Question No. 2, this has been discussed often and the general procedure which you have described corresponds to what we had in mind. It means that the fire itself should have been ignited by some drops of welding. High temperature is not necessary. The experts say about 300-400°C would be sufficient, but there is always the question of where sufficient oxygen comes from to keep this smoldering fire going. But, it had been stated by witnesses that leakages have been in this plant from the start-up, and it is not impossible that the fire got sufficient oxygen in this way.

I. L. Gorup—L'Air Liquide, Montreal, Canada: How much time elapsed between the welding and the explosion?

Lang: The welding inside the cold box had been done during the repair work. That means before the 30th of December. The explosion was on the 4th of January.

Gorup: Was the plant in operation when the explosion occurred?

Lang: The plant was in operation, but I would not say that it was in full operation. I mentioned that it was producing about 100 short tons instead of 150 and this low output was due to the leakages.

G. W. Downie—Consolidated Mining & Smelting Co., Trail, British Columbia, Canada: Did your tests indicate how long it would take for wood to achieve a 100% (and above) take-up by weight of liquid oxygen?

Lang: It has been stated that between thirty minutes and two hours is necessary for the wood to become fully loaded with liquid oxygen.

Mason: I think there may be some confusion as to just how these timbers were wrapped with metal. Was each individual timber wrapped separately and then laid as a floor?

Lang: No. It was done in such a way that the cold box floor was separated in big sections. I would say four sections of about 8 ft. x 8 ft. were fabricated as a separate floor of 4-in. thickness. The wooden planks were then nailed together cross-wise and the whole thing clad by galvanized steel sheet.

Mason: Could the absorption of liquid oxygen into the wood have been accelerated greatly by the contraction of the air in the wood cavaties due to sudden chilling by the spilled liquid oxygen? It seems likely that such a contraction could rapidly reduce the temperature and the pressure and consequently cause a pressure difference that might force the liquid oxygen rapidly into the pores and cracks of the wood.

Lang: I think we have to assume that cracks had developed in this cladding which from the beginning was not absolutely tight.

Mason: The liquid oxygen that leaked in through these cracks in the cladding could actually have been sucked into the wood by a contraction of the air in the pores.

A. Lang has received a grade as "Diplom-Ingenieur" from the Technische Hochschule at Berlin in 1928. After several years of work in the cement industry, he joined the I.G. Farben Ind. where he worked as maintenance engineer and plant superintendent in their synthetic ammonia plant at Merseburg. Since 1950 he is working with the German Linde Co. where he is responsible for safety questions and plant servicing.

Lang: Of course it could go in this way, but I do not think that the contraction could explain the whole thing. This is very difficult to answer and we can only make assumptions.

E. L. Gibson—Atlantic Refining Co., Philadelphia, Pa.: Did you test plywood, particularly as it is affected by the laminating binder?

Lang: Plywood has not been tested. All different types of wood, pine, and spruce have been tested, but I do not know about plywood. This was not important for us because we did not use it.

D. Stockbridge, Jr., Southern Nitrogen Co., Inc., Savannah, Ga.: Is the equipment supported on the wooden floor? Do the supports come down on the wood?

Lang: Yes. The supports stood on the wooden floor.

Stockbridge: What are you replacing the wood with?

Lang: For these older plants we generally replace them with a compressed asbestos cement.

R. L. Stevens—Canadian Industries Ltd., Kingston, Ontario, Canada: In 1959, we removed all of the insulation from our air box for the main purpose of removing wooden blocks under the equipment from the base. We did this after the experience of another air box explosion which was ascribed to combustibles in the base of the air box. We replaced ours with aerated concrete blocks incased in a sealed galvanized metal cladding. The idea of the cladding was to eliminate moisture in the aerated concrete that might destroy it as a structural member, however we wanted the compressive strength of the concrete. We still have some wood in our air box but mostly boarding and planks at the upper elevation, which support tubing and light piping.

Lang: The information about aerated concrete is very valuable. I would like to ask one question. I understand that this is a porous insulation material. Are the pores separate like with foam glass?

Stevens: I could not say. I understand that the pores are supposed to be separated.

Lang: Thus, it would not be possible to be saturated with water. This is an important question for this floor concrete. We already considered the use of such a material. #