EXPLOSION IN AFTERCOOLER OF A COMPRESSOR USING SYNTHETIC LUBRICANT

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On February 23, 1963, at about 6 p.m. an explosion occurred in the fourth-stage aftercooler of the main air compressor of a tonnage air separation plant. This explosion was of particular significance because, as far as is known, it was the first such incident in a compressor using Cellulube for cylinder lubrication.

Compressor design

The main air compressor for this plant is a Cooper-Bessemer JM-6, a balanced-opposed reciprocating machine. The compressor design is such that the high and low pressure air streams to the air plant separate before the compressor and maintain separate paths through the compressor cylinders. The low pressure air (Service I) is compressed in two stages, then passes on to a water wash column and on to the regenerators. Service I cylinder lubricant is Ucon. The high pressure air (Service II) is compressed in four stages to 1500 lb./sq.in. gauge. Service II cylinder lubricant is Cellulube 220.

The fourth-stage aftercooler is located directly above the compressor with its axis at right angles to the axis of the compressor. The aftercooler is made up of eight Brown Fintube U-tube assemblies arranged four across and two high. From the fourth-stage discharge bottle the air flow divides, going to the two bottom right U-tubes when facing the fourth-stage cylinder. The flow is then upward through the right hand bank of tubes and downward through the left-hand bank with suitable manifolding at the top.

Sequence of events

The plant had been operating at about 80% of capacity. The sequence of events leading to the explosion first made itself known to the plant operator with the blowing of the third-stage discharge safety valve. The operator after noting that the third-stage pressure was high, assumed that a fourth-stage discharge valve had failed. He then left the control room to activate the system to take product oxygen from the liquid storage tanks before shutting down the plant, and replacing the broken valves. The explosion occurred, however, before he reached the outside door. The compressor was shut down by a vibration switch before the operator could reach the nearest emergency stop button. Not more than two minutes had elapsed from the time the safety valve first blew until the explosion occurred.

Fourth-stage valves and aftercooler

Disassembly of the fourth-stage valves and of the fourth-stage aftercooler revealed the following:

(1) The valve plate in the discharge valve nearest the crank end of the cylinder was broken, having lost a piece on the circumference about 2-in. long. The other discharge valve, and the two inlet valves were undamaged. (The piston is double-acting with one suction and one discharge valve at each end.)

(2) The tubing at the end of the first pass of the aftercooler had expanded to about 1.36 times its original diameter and then had split longitudinally for about 5 in. The greatest expansion was in the heat affected zone adjacent to the weld joining the tube to the return bend. The failure went through the weld and into the return bend about 1-1/4 in. A similar failure had occurred at the weld joining the same return bend to the end of the second pass tube except that the joint had also failed circumferentially in the tube metal adjacent to the weld. The water jacket had not failed, although the top works of a safety valve, connected to the end flange of the water jacket, was blown out of the valve body and through the roof.

This failure of the tubes and return bend occurred in only one of the two parallel passes.

(3) At the end of the second pass, where the tube is welded to a special fitting that exits from the water jacket, the tubes of both passes had failed in a manner typical of detonations. The tubes had each been split into four sections that had then peeled back in the same manner that one peels the skin from a banana. The water jacket had also burst in the general area of the tube failures.

(4) The upper halves of the bends (external from the water jacket), connecting the ends of the second passes to the beginning of the third passes, had also been shattered and most of the metal been scattered about as pieces of shrapnel.

(5) There were no further ruptures. Calipering of the third- and fourth-pass tubes showed that there had been no permanent set in the tubes except in the heat affected zones of the welds joining the tubes to the end fittings and to the return bends. Here there was a diameter increase of 1/64 in. to 1/32 in. A white

coating found on the water side of the tubes was spalling and falling off from the third and fourth passes. The degree of disruption of this coating diminished with distance from the last rupture until it was a solid uniform coating on all tubes after the fourth pass.

(6) The third-pass tubes directly above the ruptures in the exit end of the second-pass tubes received dents about 1-1/2 in. in diameter. Although the water shells were not broken here, it appeared that these dents were caused by impact from the explosions that occurred less than a foot below.

Cylinder and discharge piping

Inspection of the fourth-stage cylinder and discharge piping showed:

(1) The suction valves were clean and in good condition.

(2) The discharge valves were dry but covered with a "carbon" deposit about 1/16-in. thick. This deposit was hard and could be pried off in flakes with a fingernail. The discharge valve with the broken plate was drier and cleaner than the other.

(3) The discharge bottle contained a heavy "carbon" deposit about 1/8-in. thick. The piping to and from the discharge bottle was relatively clean.

(4) The first and second passes in the aftercooler were covered, on the air side, with a varnish-like coating but were dry with no evidence of an oil film. The third and following passes also had a varnish-like coating but also were covered with an oil film. This film was discernible to sight and touch and in places could be pushed into ridges by rubbing with a finger.

Intermixing of lubricants

One of the first thoughts was the possibility of intermixing Ucon or one of the straight hydrocarbon lubricants with the Cellulube used in all of the Service II cylinders, either within the compressor, or accidentally by an operator. Lubricant samples were taken from both lubricators. Also one of the seventh- and eighth-pass U-bends was solvent washed with methylene chloride. The lubricant samples and the solvent washing were then sent to the APCI Research Laboratory in Allentown, Penna. for analysis.

The analysis showed there was no intermixing of lubricants.

1. The oil from the Ucon lubricator showed no evidence of Cellulube or straight hydrocarbon oils.
2. The oil from the Cellulube lubricator showed no evidence of Ucon or straight hydrocarbon oils.
3. The lubricant in the solvent washing of the U-bends was Cellulube.

The compressor, when new, had been put into operation using Cellulube in the Service II cylinders. There was, therefore, no possibility of hydrocarbon oil or carbon residue being left behind as a result of inefficient cleaning at the time of change to Cellulube cylinder lubrication.

Ingredients for combustion

An oil-lubricated air compressor normally contains two of the three ingredients required for combustion—a fuel in the form of the cylinder lubricant that is carried with the air, and the oxygen in the air that is being compressed. The third ingredient, ignition energy, may occur when a valve fails by friction or by sparking caused by the misalignment or dislocation of the broken parts, by incandescent particles of the carbon deposits formed by breakdown of the lubricants, or by high temperatures caused by recompression. Another possible initiator is the exothermic reaction of oxygen with carbon to form the so-called "carbon-oxygen couple." This last effect has been described in the U. S. Bureau of Mines report R.I. 4465, "The Carbon-Oxygen Complex as a possible Initiator of Explosions and Formation of Carbon Monoxide in Compressed Air Systems," by Bausch, Berger, and Schrenk, published June, 1949, and by R. Loison in a paper, "The Mechanism of Explosions in Compressed Air Pipe Ranges," presented to the Seventh International Conference of Directors of Safety in Mines Research, July, 1952.

These papers have been discussed briefly at previous meetings. Of particular interest to this discussion was the experimental work of Loison to produce detonations in simulated air lines that contained oil, either in trays resting in the bottom of the pipe, or spread over the entire internal surface of the pipe. Initiation was by means of a combustion chamber containing a flammable mixture, at one end of the pipe and separated from it by a klingerite membrane.

Pressure and combustion wave

The results of these tests showed that if the initial cause of inflammation is sufficiently violent, a pressure and combustion wave may occur and be propagated in a pipe line covered only with a thin deposit of oil and in which preliminarily there was no flammable gaseous mixture. Speed of propagation of this wave was about 4,000 ft./sec. With no combustible material in the test section no reactions occurred. Within the limits of this test work the greater the deposit of oil within the test section, the greater was the possibility of a reaction. In the 10-in. diameter test section an oil deposit of 1 oz./yd. (30 g./m.) corresponds to a stoichiometric mixture of oil and air.

During normal operation, the passage of air through the system is incapable of raising an oil film on the piping into suspension to form a flammable mixture. However, a pressure wave may increase the temperature in the wave sufficiently high to vaporize the oil. Loison states that a wave propagated at 1500 ft./sec. will produce temperatures of about 150° F, but these temperatures will rise to 870° F in a wave propagated at 3300 ft./sec. This latter temperature should be sufficient not only to vaporize the oil film rapidly but also to ignite the resulting oil-air mixture. This mechanism differs from a gas-phase detonation in that the temperature increase must vaporize the fuel in addition to igniting the resultant oil vapors. In summarizing this explanation Loison states:

> (i) As the vaporization of the oil is followed immediately by its inflammation, the temperature of the oil deposit increases very rapidly above the temperature resulting from the passage of the shock wave, therefore, the vaporization must be extremely rapid.
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> (ii) It is not necessary to imagine the flame front as being close to the pressure wave front (in the detonation of gaseous mixtures the two fronts merge). The successive rise in the pressure as a result of the inflammation of new portions of combustible matter are in effect capable of maintaining a shock wave even if this

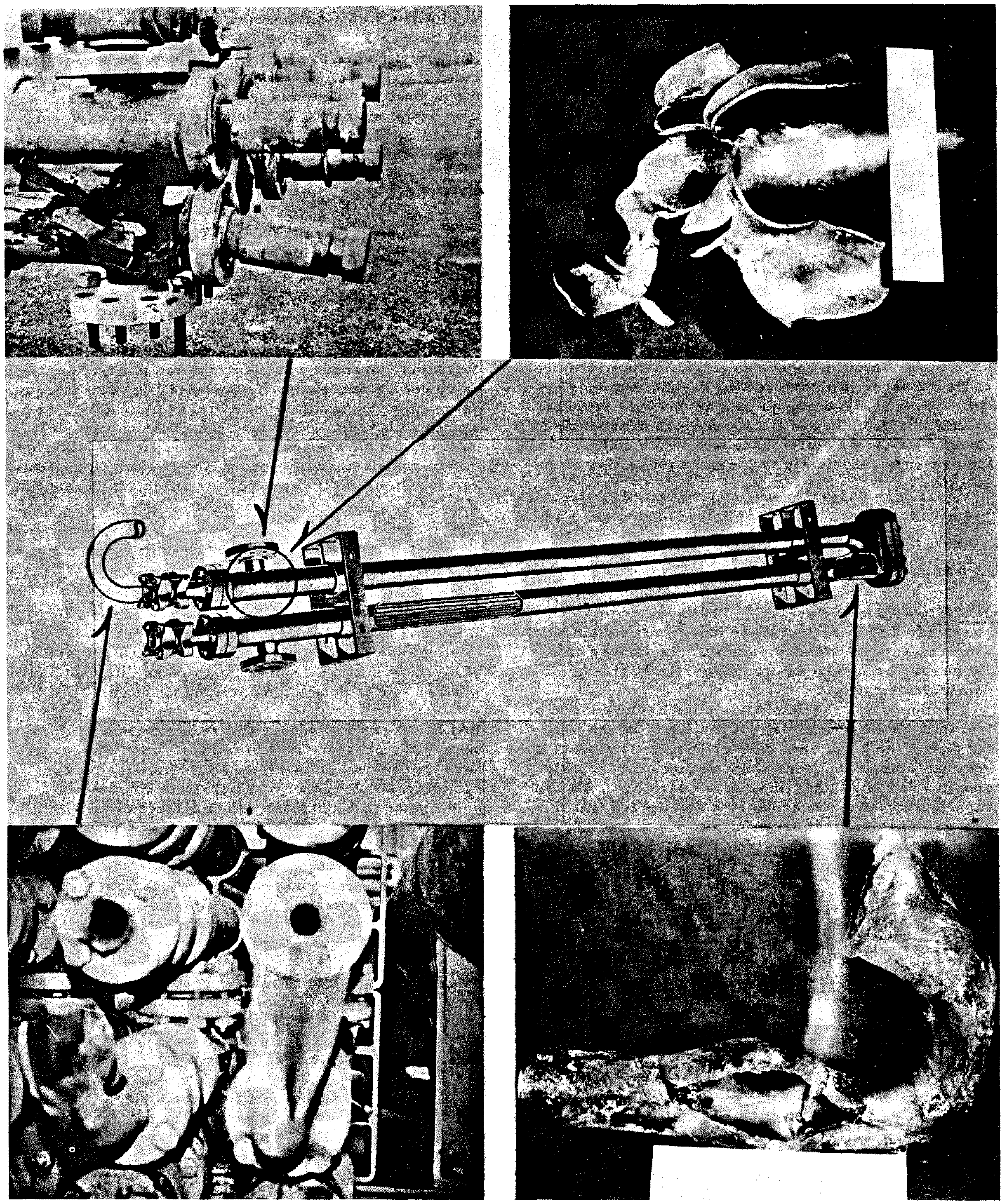

Figure 1 (center). Typical exchanger section. Aftercooler was made up of 8 sections, stacked 2 high and 4 across.

Figure 2 (upper left). Detonations in both parallel air passes ruptured both the tubing and the shell as shown.

Figure 3 (upper right). Detail of tube showing typical detonation type of failure.

Figure 4 (lower left). Detonations also occurred in the return bends connecting the second passes to the third passes.

Figure 5 (lower right). Pressure failures as shown above occurred in only one of the parallel passes.

is a certain distance in front. There may be, therefore, a certain time-lag between the passage of the pressure wave and the inflammation, which may itself be progressive.

Sustained reaction

Loison's hypothesis fits the observed condition of the equipment after the failure of the aftercooler. It appears entirely credible that the failure of the valve plate resulted in ignition of oil and/or deposits in the cylinder discharge passes or in the discharge surge drum. This combustion reaction was of sufficient intensity to create a pressure or shock wave that entered the aftercooler tubes. The temperature in this pressure wave was sufficient to vaporize the oil existing in a thin film on the tubing walls and create a flammable mixture. Ignition within the aftercooler tubing could have carried over from the original combustion reaction, or been caused by temperatures in the pressure wave above the spontaneous ignition temperature of the oil vapor-air mixture. This reaction, once begun, was self-sustaining as long as fuel was available, or until the geometry of the system was drastically changed (such as failure of the tube which could reduce the pressure sufficiently to prevent propagation of the reaction).

Two items are of particular interest here. First, there were two distinct detonations in each of the two parallel paths which occurred in exactly corresponding locations. As the air flow had separated into the parallel paths before the aftercooler, the initial reaction had to occur in or before the header as noted previously. Second, the pressure failures and the detonations occurred just before the vertical return bends where oil, condensed from the air, would tend to collect.

Revised design

In repairing the facility the U-tubes of the aftercooler were rearranged so that flow is in the top of the assembly and out of the bottom where it flows down to a knock-out drum. While one cannot eliminate the oil film on the tube walls, one can insure that there is no pocketing of lubricant and that all condensate, including oil, flows to a low point which is drained regularly. Success was also achieved in revising the valve design, increasing its expected life, and, thereby, decreasing the likelihood of a broken plate acting as a source of ignition. Cellulube is still being used in this unit. It has always been recognized that this lubricant is fire resistant, not fireproof, and is giving excellent service in all of the large reciprocating compressors.

DISCUSSION

JENSEN—Atlantic Research: I believe I understood you to say that in each of these tubes you could identify where there were two detonations. The figures show the peeling back, like an orange, certainly strong evidence of detonation.

Sustaining the detonation wave by the additon of fuel to it, by the mechanism of peeling it off the wall of the pipe, I think has been used previously to explain a very large scale accident which occurred at laboratories at Pratt & Whitney about four years ago. All the experts who were concerned with this agreed that this was a mechanism that could sustain the detonation which had originally been started by a fuel mist. Here the evidence is very clear, in this case the pipe was about 4 ft. in diameter which showed in places where the detonation wave had progressed and where failure had occurred in nodes.

JONES—Canadian Industries Ltd.: It seems to me that the two failures described as due to pressure are reminiscent of failures, that I have seen, where piping has ruptured as a consequence of local overheating, that is to say, where there is a combined effect of a local high temperature as well as high pressure. In general, if failure occurs around ambient temperatures there will be a lesser degree of the amount of bulging than when the pipe is hot. The reduction of area on the fractured edge is much larger with a hot failure than it is with a cool failure.

Now as best as I could see from the figures, it seemed to me that along the ruptured edges, the pipe had necked down to a relatively small cross section. I thought that, apart from being just a straight pressure failure, it would be a failure which might be described as due to the effects of both the pressure and some measure of heating. The location of the return bend is perhaps not inconsistent with this thought.

The second point I wanted to make concerns compressors. With four stages on air we go to about 600 lb./sq. in., this is the highest pressure I can think of in our air plant. I am wondering whether in going to 1,500 lb./sq. in. with four stages of compression on air, in effect one is relying substantially on the properties of synthetic lubricants in order to make this feasible or whether this is normal engineering practice.

BALL: There was substantial reduction in wall thickness at the pressure type of failure. I don't however have any information with me to indicate the percentage of area reduction. With regard to your second point, going to 1,500 lb. in the four stages was within the normal design criteria that we used. This is less than 2 pressure ratios per stage and, as long as the discharge temperature is reasonable and the stages balanced, is acceptable practice. We certainly were not relying, and never have relied, solely on the property of Cellulube to resist ignition. I think this would be a completely wrong approach.

WALTON—Sun Olin: You have postulated what is the fuel. What was the initiator? Was it heat from a broken discharge valve? Did you find a piece out of the valve which would indicate that it was the probable initiator of high temperature?

BALL: We never were able to find the piece that came out of the broken valve. However, the fact that the valve broke immediately before the reaction occurred —I would say within two minutes—is established by the fact that the safety valve in the third stage discharge began to blow. This would indicate that flow was not being maintained by the fourth stage and pressure was backing up into the third stage. This fact, that the valve broke just prior to the explosion, certainly suggests the valve failure as a likely cause of ignition.

WALTON: Was this a plate valve?

BALL: Yes.

WALTON: It looks as if the big thing here is the problem of valve breakage and so it seems that this is a focal point to work on.

BALL: We incidentally were able to increase the life of the valves that were in use in that compressor by two things: increasing the thickness of the plate and by reducing the lift.

DOYLE—Farmers Insurance Association: There are several different grades of Cellulube; I wonder which particular one this was? They have different degrees of fire resistance.

BALL: This was Cellulube 220.

Anonymous: What was the speed of the machine?

BALL: This machine operates at 327 rev./min.

Anonymous: What is the normal discharge temperature?

BALL: The fourth stage discharge had been running 67 to 73° on the inlet and from 292 to 308° on the discharge.

PAPENFUSS—Olin Mathieson: Was this a metal plate, metal seat valve?

BALL: Yes.

PAPENFUSS: I'd like to comment on our experience—though not an air compressor, I think the problem might be the same here—where the machines had been able to use plate and channel valves interchangeably. When machines are operating marginally too fast, our experience has been over 200 rev./min., you get into excessive plate breakage. Has this been a problem with this machine?

BALL: We had been having some difficulty with the plate life of this particular machine, and we had been able to more than double the life by the modifications that I have mentioned.

PAPENFUSS: Our experience has been we get more capacity on the same machine using the plate valve in place of the channel valve.

Anonymous: This may not be feasible in your case, but where we have an installation that uses different oils, we don't rely entirely upon a man reading the drum. As the drums come in, we have them around and through our production area, we add a certain dye. This allows the operator to have as a second defense, you might say, a visual check of what he's putting in if he doesn't want to rely upon the drum marking.

BALL: This seems to be a pretty good approach. These particular oils that we were using by their nature had different colors. The operators would be able to identify them simply by the color rather than by knowing what drum they did come out of.

BUDDENBERG—Collier Carbon and Chemical: Mr. Ball, I'd be interested in knowing if you periodically wash your discharge bottles and your aftercoolers, and if so, how frequently and what agent do you use. Also, have you changed any of your rules on design and operations as a result of this accident? In other words, how are you going to prevent it in the future?

BALL: We do not have any program for a periodic wash out of compressors or the discharge vessels. We have changed some of our design concepts slightly and some operating procedures. The main one I've already mentioned and that is preventing the oil from accumulating in the exchanger passages.

The original design had a tendency to pocket condensate at the return bends. I think it is significant that the pressure failures and the detonations occurred at those locations where we would assume—just by looking at the system—that we would have accumulation of fuel. So we have established strict standards and have included them in the standard specifications for compressor systems. We have also gone back through all of our existing systems and put in additional drains where we thought it was necessary.

ADRIAEN—Brockville Chemicals: I suppose you remove the CO_2 from the air; and if so, where and how?

BALL: On the high pressure air, the CO_2 is taken out between the second and third stages in the caustic system.

ADRIAEN: Did you find any deposit due to the caustic in any part of the machine; that is after the second or the third stage? I think that there is a certain decomposition of synthetic lubricant by the caustic.

BALL: In the portions of the system that failed, we did not find any unusual type of deposit that might have come from a decomposition of the Cellulube caused by caustic action.

HEPP—Sun Oil: Do you know of a decomposition reaction between the two?

ADRIAEN: Yes, we made some experiments in the laboratory which showed definite decomposition of the synthetic lubricant by caustic.

Anonymous: What does it decompose to?

ADRIAEN: I don't know exactly, these experiments are still being carried on. I understand these synthetic oils are esters of phosphoric acid and these phosphates seem to be decomposed in the cylinder by entrained caustic.

MESLOH—Pittsburgh Plate Glass: In answer to your question, Pete, we have run into this decomposition in our air plant. Caustic carried over into the third stage of our air compressor and we had immediate decomposition; our laboratories found that this happens as low as 150°F. The residue is a very heavy gunk containing phenol although it has no apparent corrosive properties.

HEPP—Sun Oil: At just which stage was this, after the third or the fourth stage?

BALL: Fourth stage.

HEPP: How long had this compressor been onstream with Cellulube, since it was originally put in Cellulube service.

BALL: The plant had gone on a stream early in 1958. It has been on Cellulube from the very beginning. In other words, this is not a system that had originally been on hydrocarbon oil and then had to be cleaned before going over to Cellulube lubrication.

HEPP: You mentioned a carbon deposit and I couldn't place this in the sequence of events; was this carbon deposit found afterwards as a result of the explosion or do you feel that these were decompositon products that are left during operations?

BALL: The carbonaceous appearing deposits that I mentioned were in the discharge chambers of the cylinder and in the discharge drum before the air had gone through the aftercooler itself. There was none of this type of deposit in the aftercooler.

HEPP: In the fourth stage, not the snubber, you found a carbon deposit?

BALL: Yes.

HEPP: Do you think it was a result of some combustion in that area that occurred after the fire or was that something which was laid down over a long period of time?

BALL: My impression would be that this material had been deposited from the normal operation.

HEPP: Did you by any chance analyze it for combined oxygen?

BALL: No, we did not.

HEPP: Have you any evidence that it's carbon-oxygen complex that's laid down for a long period of time?

BALL: No, we wouldn't have any of that material that came from the compressor at that time. I might also mention a paper that was published in Industrial and Engineering Chemistry, Product Research and Development, Volume 2, No. 1, March, 1963. This is titled, "The Effect of High Temperatures on Stability and Ignition Properties of Commercial Triaryl Phosphate Fluids." This research was done by the U.S. Naval Research laboratory in Washington. Although they are not identified as such in the paper, the materials tested were Cellulubes. The significant thing developed in this research, I believe, is summarized on the last page where they note that the carbonaceous material I spoke of is not really carbon at all. It is a breakdown product of the Cellulube that still maintains, to a very high degree, the high spontaneous ignition temperature of the parent oil. For example, the spontaneous ignition temperature of the parent oil is in the neighborhood of 1,000 or 1,050°. The spontaneous ignition temperature for the decomposition product is only reduced to 900 to 950°F.

BOLLEN—Dow Chemical of Canada: Was there a split or rupture or detonation on the inner pipe in that same location as the outer tube?

BALL: All of the failures were in the inner tubing, although I didn't indicate it as such on the diagram. There was failure of the water jacket where we had a detonation but not where we had the pressure type of failure. It might be interesting to note that on the rear end, back where we had the pressure type failures of the inner tube, we had a connection for a safety valve on the water side. The top works of the safety valve were blown out and through the roof, no doubt from the water hammer effect.

HEPP: Is anybody operating air compressors with caustic scrub with synthetic lubricant in the following cylinder? How much carryover is it going to take to destroy the lubrication in this cylinder and cause overheating.

MESLOH: We scrub at 90 lb./sq. in. gauge, the scrubbers being located between the second and third stages of our air compressor. We do not take any special precautions except that we do have a mist separator which is periodically checked for caustic carry-over. It takes a good bit of caustic to destroy the lubrication. There is one point that I might make. We originally used hydrocarbon oil for about two years and had no problem with caustic carry-over; however, since switching to Cellulube, there have been about three occasions on which caustic has been slugged into the third stage of the air compressor. A small amount of Cellulube is carried into the first scrubber which emulsifies forming a heavy, greasy film on the packing at the air inlet. Excessive velocities result, causing the caustic in the first stage scrubber to slug over into the second-stage unit, through the mist separator and third-stage suction drum. The resultant decomposition products must then be cleaned from the third-stage cylinder.

JONES—Canadian Industries Ltd.: This doesn't concern Cellulube, in particular, but we have an air plant and our desiccant and dust filter are on the 600 lb./sq. in. air stream of the plant. Our filter was a composite felt affair, which on one occasion caught fire and burned. We were rather intrigued because the burned steel framing, securing this felt assembly, looked as though it had been in an oxygen fire. It would be a function, I suppose, of the high partial pressure of oxygen in the 600 lb./sq. in. air stream. We attributed this to insufficient cooling of the activated alumina, which I believe is regenerated at about 500°F. If for one process reason or another you have to make a hurried change and get the activated alumina on stream before it is really cool, you would get hot air proceeding to your dust filter.