Low Temperature—II

Since the first commercial air liquefaction plant there have been probably hundreds of major accidents in units of this kind. Generally, the causes have centered around relatively few specific conditions. First, the particular properties of acetylene; second, the marked increase in the activity of oxygen at high concentrations and third, the low temperatures involved which erect barriers to detecting and correcting unusual conditions.

The following articles represent case studies of actual accidents. The advantages of this treatment are: first, we have a connected story for a particular installation; second, it's somewhat easier to follow than a series of comments on parts of different plants; third, it demonstrates how much can be learned by technical detective work; and fourth, it shows the interrelationship between various safety aspects of a plant.—**R. W. Rotzler**

Compressor explosion

C. W. Gibbs
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Investigation of damage caused by an explosion during a routine test warns compressor operators against explosive oil-air mixtures.

The only major disaster in the 88-year history of the Ingersoll-Rand Co. occurred recently during a routine shop test of a centrifugal booster compressor at the Phillipsburg, N.J. plant. This accident claimed the lives of 6 men, hospitalized 6 more for varying periods of time, and slightly injured 24 others.

Although this incident did not occur in an air separation plant or an ammonia plant, a description of the accident in this safety session is of value if it should serve as a warning for similar plant operations.

An investigation committee was created immediately to find out what caused the accident and to make recommendations to insure against any recurrence. This committee was composed of engineers from Ingersoll-Rand selected because of their experience and intimate knowledge of the equipment involved in this situation. They were assisted in their exhaustive studies by A. L. Brown, an expert on industrial explosions. In addition, various industries were approached to get the experience of others who might contribute to the thoroughness of the investigation.

The compressor being tested was the high pressure stage of a two stage unit which was part of an installation for an oil field at Kuwait. The installation was designed to compress natural gas for injection into the ground to accelerate the flow of oil from adjacent wells. The compressor was similar to a number that have been built by Ingersoll-Rand for many different petroleum and chemical industry applications and for nearly identical repressuring service on Lake Maracaibo, Venezuela. It was to be driven by a gas turbine coupled to a speed increasing gear. The compressor requires about 6000 hp to attain its rated performance.

Testing procedure

The test on this compressor was a standard and accepted method used to assure that the unit met all mechanical and performance requirements. It has been used widely throughout the industry for many years. This compressor had been run several times prior to the accident to prove it out mechanically. Other than vibration that was corrected prior to the final tests, the compressor ran well. Eye witnesses could report nothing unusual in the operation of the compressor. It had been running about six hours that day.

The test setup which is of interest is shown in Figure 1. Testing is done on a platform on which a special 22,000 hp steam turbine driver was permanently mounted, and served by a condenser located beneath the platform. A speed-up gear is driven by the turbine and the compressor on test is coupled to the gear output shaft.

Instruments for measuring speed, temperatures, pressures, and water flows were incorporated as required at various points in the testing loop.

A closed loop system (Figure 2) using air under pressure simulated the field conditions. The air leaving the compressor travels through a short length of pipe and then passes through a long tubular cooler in which water is circulated outside of the tubes to remove the heat of compression. After the air has been cooled to about room temperature—in this case 85°F—it passes through a high pressure throttle valve which reduces the pressure to inlet conditions. The throttle is adjusted by a test engineer to establish the desired discharge pressure and flow through the system. Before the air returns to the compressor inlet, it passes through a long length of straight pipe at the end of which is a nozzle-shaped orifice used for measuring the quantity of air flowing through the system. After passing through this measuring nozzle the air traverses another length of straight pipe and then turns upward to the inlet opening of the compressor. All of this closed loop piping was located underneath the compressor and platform.

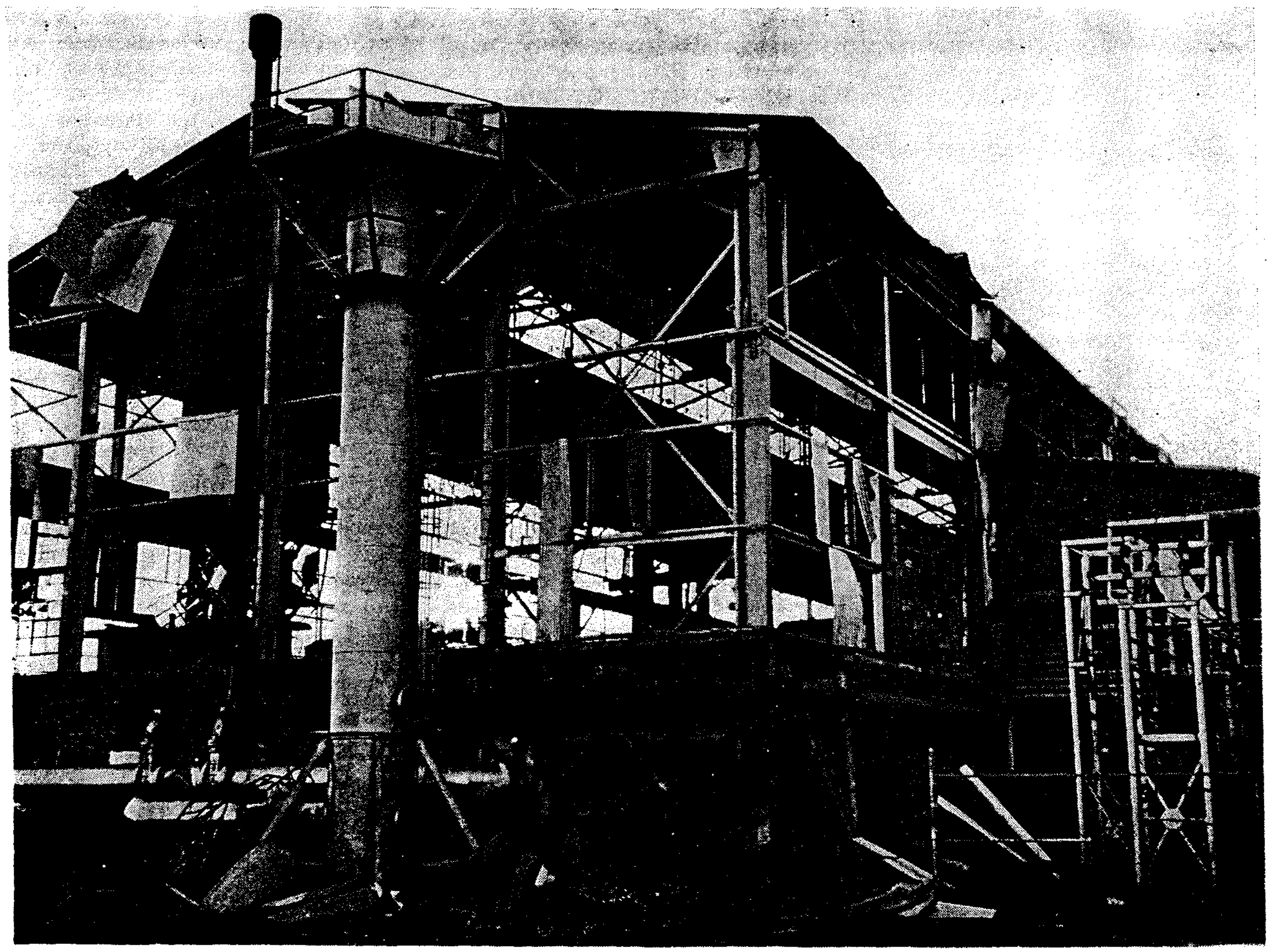
The loop piping was heavy seamless steel. The bursting pressure in the low pressure section was calculated to be approximately 7450 lb./sq. in. which gives a margin of safety of about twelve times the operating pressure of 600 lb./sq. in. In the high pressure piping the calculated bursting pressure at the weakest point is 11,000 lb./sq. in., providing a margin of safety of about six times the operating pressure of approximately 1700 lb./sq. in. No destructive detonation rupture occurred in this high pressure section of the loop system. The entire test loop had been hydrostatically tested immediately preceding its use for this test.

When air or any gas is compressed, its temperature increases, and limits based on long experience have been set for allowable discharge temperatures. In this case a maximum temperature of 400°F was established prior to the test.

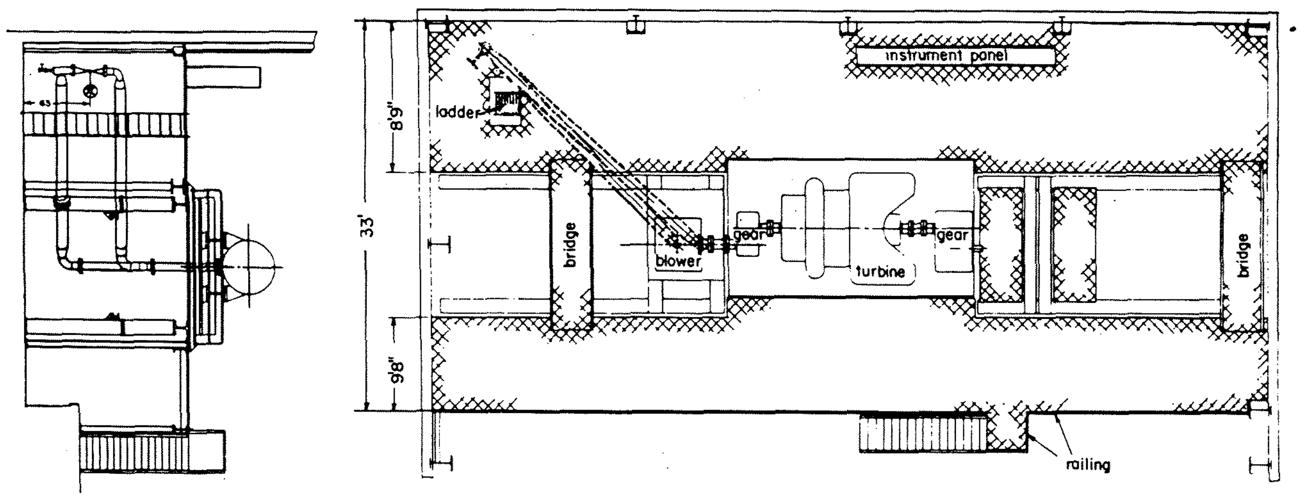
Water supplied to the cooler was arranged to operate from a main on the same circuit which supplied the water to the steam condenser. There was no loss of water supply to the cooler.

As a precaution against foreign matter remaining in the test loop, a drainage pocket and other drains are located at the bottom of the piping system. Accumulated water and any oil present were removed before each test run by blowing down with air until no accumulated liquid was observed in the discharge from the drains.

In a test system using dense air it is necessary to charge the system and also to maintain the prescribed inlet pressure—in this case about 600 lb./sq. in. An auxiliary compressor system consisting of a booster compressor supplied the necessary air through a small pipe to the test loop. A man at the test pit regulated the amount of air supplied by a small valve so as to maintain the desired inlet pressure. Standard procedure, which was observed, calls for blowing down the high pressure receiver near the booster compressor (technically known as a bottle) to remove moisture and lubricant continuously. Careful examination of this charging compressor system established definitely that



Damage to building housing the compressor testing facilities where accident occurred.



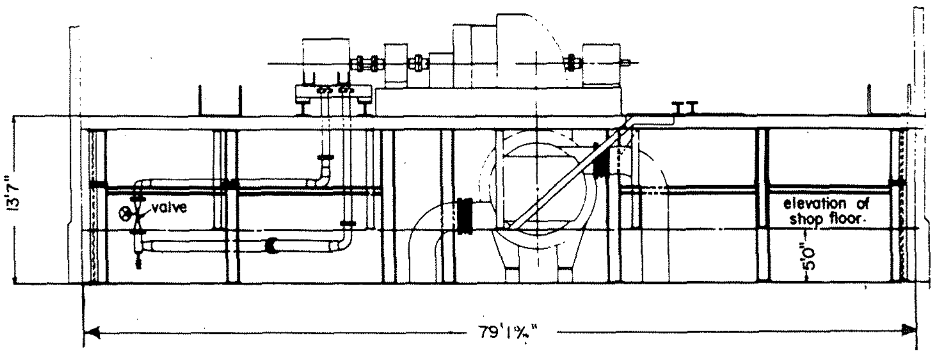


Figure 1. Standard test arrangement has a steam turbine mounted on platform to drive gear to which compressor to be tested is coupled.

it did not cause or contribute to the explosion.

Explosion description

All physical damage in the area resulted from the ruptures caused by detonations within the cool low pressure piping at two points in the horizontal run at the bottom of the test loop. The approximate locations of the ruptures are indicated on the diagram at points "X" and "Y". A third failure occurred at point "Z", but this was due to the severe bending force imposed by the detonations at "X" and "Y" rather than a local detonation.

An external view of the building shown in the introductory photograph will give you an idea of the damage done. Figure 3 shows the area where the test loop had been beneath the platform.

The committee assembled all of the parts that could be retrieved and studied them exhaustively. At point "X" on the diagram the heavy 12-in. pipe had been ruptured so that it was opened up like a banana peel. A detonation or explosion pressure of extreme intensity undoubtedly occurred in this region. Evidence of soot supported the conclusion that oil was present and had combined with the compressed air to form a combustible mixture.

At point "Y" in the diagram a second severe rupture occurred giving a similar banana peel appearance to the exploded pipe. In between the two ruptures a long secton of pipe was intact. This condition is typical of ruptures caused by detonation waves. They create a region of very high pressure, ignite and explode, and then travel at relatively low speed to a new region where this is repeated. This may be followed by successive waves of pressure at intervals along the pipe.

C. W. Gibbs has been with Ingersoll-Rand for 43 years, except for two years with Babcock & Wilcox and one year of Navy service during World War I. Most of his work with the New York company has been with special applications and process compressors. In recent years, Gibbs has been connected with the Compressor Engineering Department. He has been particularly involved with work on compressors for synthetic ammonia production.

In studying the reassembled parts positive evidence was found that the detonation wave had traveled from right to left on the diagram. This, of course, is opposite to the direction of the normal flow of air in the loop system. The findings also localized the damaging detonations in the cooled low pressure part of the loop system.

It is known that the low pressure air in the system at 600 lb./sq. in. was at a temperature of 85°F. Fires in compressed air systems occur occasionally and are practically always associated with the high temperature region at the discharge of a compressor. This fact is well known to the industry. Here, however, the ruptures and damaging detonations occurred in low temperature regions and not in high temperature regions. In view of the direction in which the pressure wave apparently traveled, it could only be concluded that a fire occurred somewhere in the compressor and the resultant shock wave traveled down the low pressure piping, gathering momentum until it detonated at the first point of rupture marked "X" on the diagram.

The compressor itself appeared externally unharmed. The heavy forged

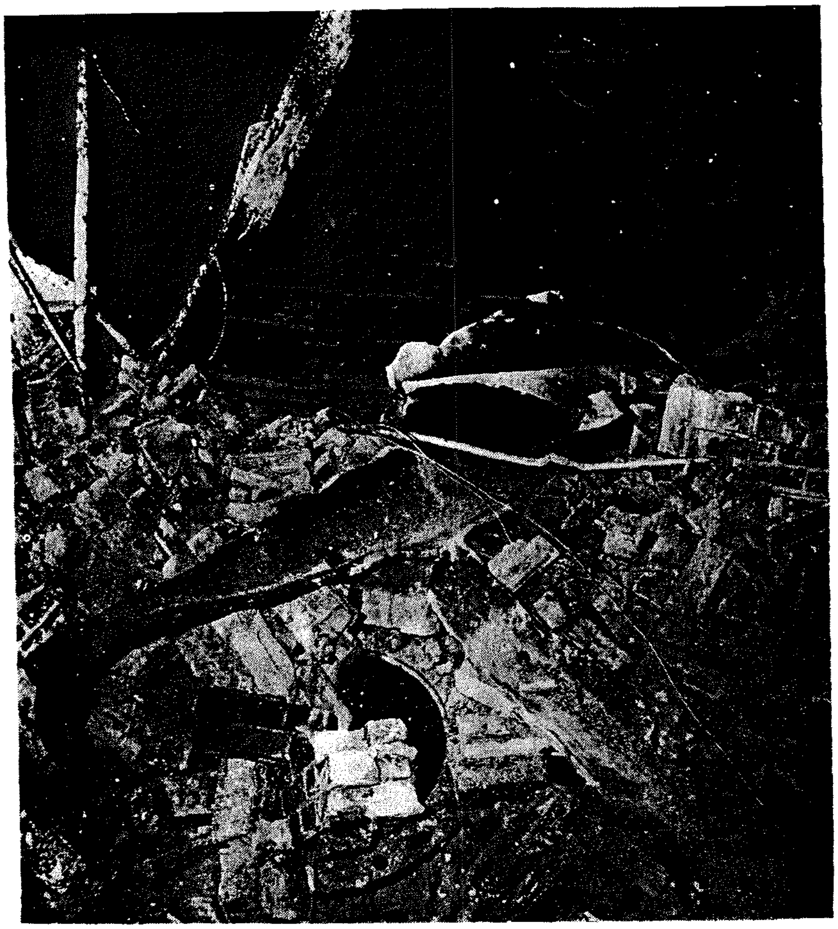


Figure 3. The extent of the damage to the test loop beneath the platform is shown in photograph taken immediately after the explosion.

steel casing and the inlet and discharge nozzles were all intact. The coupling which attached the compressor to the high-speed pinion shaft was completely broken and the pinion shaft was twisted, bent, and broken. The gear housing was also ruptured.

Internal damage to the compressor and its movement, caused by the explosion is believed to have created misalignment between the compressor and the gear, resulting in the coupling failure. The broken coupling on the gear could have produced sufficient unbalance to cause failure of the pinion shaft. This was the opinion of General Electric experts who assisted the committee. It was concluded by the committee that the damage to the coupling and the gear which drove it was a result of the explosion, not a cause.

Conclusion

After examination of the loop piping and the external parts mentioned above, the compressor was dismantled in the presence of the committee and the insurance companies. Many of the parts were damaged to such an extent that it was impossible to determine their condition just prior to the explosion. The oil seals that prevent the air or gas from escaping from the shaft opening in the compressor were in satisfactory condition as were the bearings. A few parts were rebuilt and tested in an attempt to duplicate the condition in which they were found after the accident. We were not able to duplicate the fractures.

After studying the results of these tests the committee concluded that the extreme damage to these parts could have occurred only as a result of the explosion. The committee decided, after studying the evidence, that it was probable that the ignition of an oil-air mixture occurred in the compressor. However, the condition of these parts made it impossible to determine the precise starting point and sequence of events.

The investigating committee was also instructed to make recommendations to insure against a recurrence of this accident. The recommendation was made and immediately put into effect that an inert gas, which will not support combustion, be used in place of air in all future testing of centrifugal compressors where it is possible for combustible materials to enter the closed loop. This we feel certain will prevent a recurrence.

Another point, emphasized by A. L. Brown, is the need of further knowledge regarding the effects of pressure and recycling on lubricating oils. Existing data, based on laboratory tests at atmospheric conditions, are not reliable for guidance in a closed loop test system or any similar system.

ACKNOWLEDGMENT

Ingersoll-Rand sincerely appreciates the help and interest of the following companies in assisting this investigation: Shell Chemical, Foster Wheeler, Allied Chemical, Standard Oil (Ind.), Esso Research and Engineering, DuPont, Air Products, Sun Oil, General Electric, as well as many others.

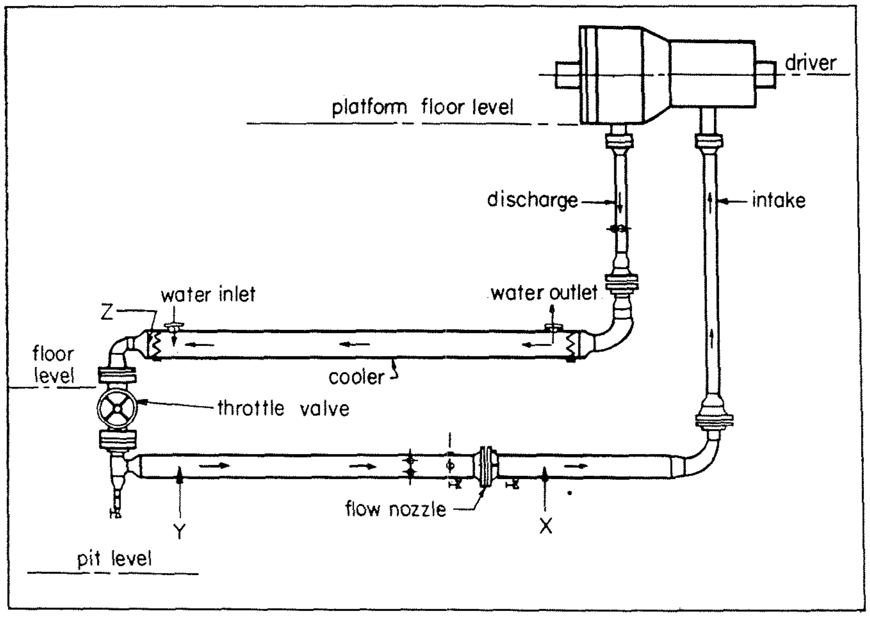


Figure 2. Flow diagram of compressor piping indicating sections where explosion damage occurred.