Failure of a Primary Waste Heat Boiler

Indications are that silica-based castable refractories lose insulating properties when used in reducing-atmospheres, and under the temperature-pressure conditions in the steam-methane section of an ammonia plant.

J. R. Attebery
Terra Chemicals International, Inc.
Sioux City, Iowa

In January, 1969, the pressure shell of primary waste heat boiler 101-C suddenly ruptured during normal operation in an M. W. Kellogg Co. ammonia plant. The resulting fire and sudden de-pressuirization of the process required an immediate plant shutdown. The fire, escaping from the external water jacket surrounding the vessel, was self-extinguishing as the reformer gas feed was cut off and the reformed gas was displaced by steam. There were no injuries and fire damage was minimal, limited primarily to instrumentation, electrical wiring, and insulation on nearby vessels. The 600 ton/day plant had been onsteam since June, 1967.

The primary waste heat boiler, located in the process immediately downstream of the secondary reformer, Figure 1, is the major source of heat recovery and steam production in this plant. The boiler recovers waste heat from the reformed process gas, producing 1,500 psig saturated steam. The reformed gas enters the shell at about 1,700°F to 1,800°F and about 400 psig to 500 psig. It leaves at about 900°F. The hydrogen partial pressure is approximately 100 psig to 200 psig. The 1,500 psig steam generated on the tube side is released in the steam drum with the auxiliary boiler and other waste heat boilers. It is a thermal circulation system with an elevated steam drum.

The shell of the waste heat boiler, approximately 28 ft. long by 51 in. inside diameter, Figure 2, is made of ASTM A-212 Grade B Firebox Quality Carbon Steel. The nominal shell thickness at the point of failure is 15/16 in. The shell of the vessel was internally insulated with 4½ in. of Insulag (trade name for a silica based castable refractory) and water jacketed on the outside. The refractory is protected from collapse and the erosive action of the gas by a ¼ in. thick stainless steel shroud. The sections fit together with slip joints.

To prevent hot gas from bypassing the heat exchange section and passing between the refactory and the carbon steel shell, conical gas shields (vapor stops) are welded between the pressure shell and the shroud. The shields are also constructed of stainless steel.

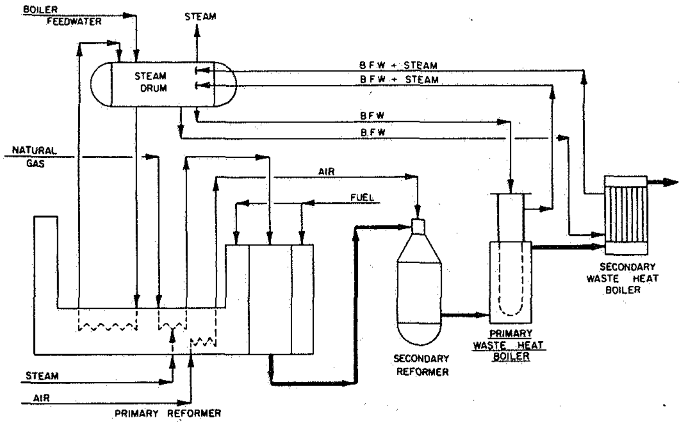


Figure 1. Process flow diagram.

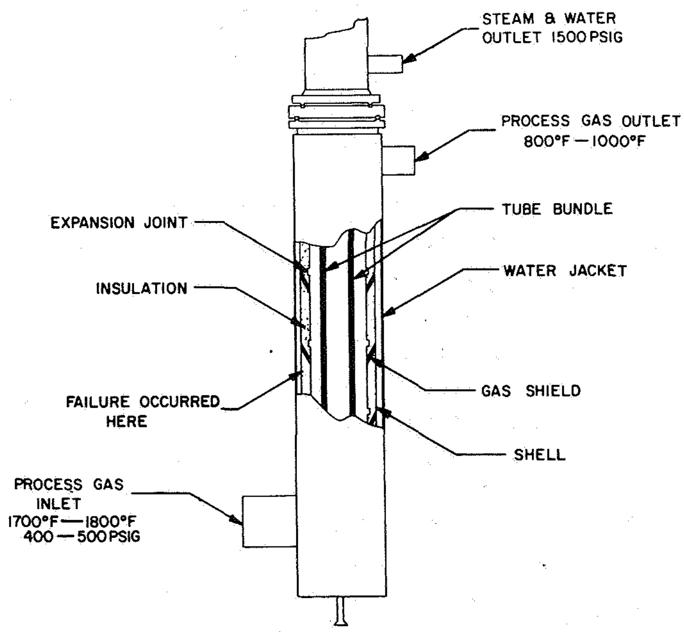


Figure 2. Primary waste heat boiler.

Sequence of events

On the day of the failure, operation had been normal with the exception of an intermittent low level alarm on the 101-C water jacket. Each time the alarm came on, the area operator observed the level sight glass and overflow. Even though the sight glass was full, and there was an overflow, the water flow had been increased because the jacket appeared to be steaming excessively. The quantity of vapor present was believed due to the low ambient temperature and atmospheric conditions. At this time the trouble was suspected to be in the low level instrument itself. The instrument department was contacted and, subsequently, removed the instrument to check it in the shop. Before leaving, the instrument technician and fitters observed the level in the sight glass to ascertain that it was full. Approximately 10 minutes after their departure, the shell ruptured.

The first indication of failure was a hissing, rumbling sound, clearly audible throughout the complex, and steadily increasing in intensity. Shortly thereafter, the suction pressure to the synthesis gas compressor started dropping and the natural gas flow indication to the primary reformer began increasing as the plant front end pressure dropped. The view of this area of the plant from the control room is obstructed by the compressor building.

The control board operator was beginning to shut the synthesis loop down when the production supervisor, returning from investigating the source of the noise, instructed him to immediately shut the plant down as there was a fire at the primary waste heat boiler water jacket. The plant was quickly shut down in the most expedient manner, leaving only about 40% of the design steam flow through the process and minimum firing on the furnace. After the steam safely extinguished the fire escaping from the water jacket, the process steam and all of the arch burners in the radiant section of the furnace were shut off. The remainder of the plant was secured as the search for the location of the failure began.

A window, cut in the water jacket where a bulge indicated the failure might be, revealed a vertical crack about 20 in. long and opened about 2 in. at its center, Figure 3. The failure was located approximately at the north-northwest side of the shell towards the secondary reformer. The crack started approximately 12 ft. 5 in. below the underside of the shell top closure flange and terminated about ½ in. into a circumferential weld. There were numerous small cracks parallel to the main fracture on both inside and outside surfaces. Most of the fracture was at an angle of 45° to the wall and had the general appearance of shear. There was also "necking" of the wall at the fracture. Surrounding the crack was a bulged area about 3 ft. dia.

The conical gas shield just below the rupture was torn loose from the pressure shell and the shroud slip joint adjacent to the rupture was separated about 3 in. Observation through the crack did not reveal any insulation present in the sections either above or below the torn gas shield. Inspection of the shroud after the tube bundle was removed revealed two small bulges about 12 in. above the inlet gas distributor and visible damage and distortion at each of the slip joints. The butt weld seam joining the bottom two shroud sections was damaged.

The tube bundle had only slight external damage, but several tie rods were broken, and two of the baffles and several of the baffle guides were bent due to rough handling during either the initial installation or removal of the bundle. The bayonet tubes were relatively clean with only a slight deposit of refractory or catalyst dust present on the external surface. Small pieces of insulation were present on the bottom baffle near the rupture area.

As the stainless steel shroud was removed, it was discovered that the castable refractory (Insulag) had deteriorated to the point where an estimated 50% of the vessel wall was unprotected. A small amount of insulation was found in the bottom of the water jacket. (During the failure, the overflow from the jacket was "black" in color indicating some of the Insulag had blown into the water jacket when the shell ruptured.) A significant amount of failed insulation was found covering the inlet tube sheet, in the channel head of the secondary waste heat boiler, and in the high temperature shift converter. The inlet distributor, vessel wall, hold down grating and raschig rings were also coated. Many of the raschig rings had the center completely filled with insulation, which had also penetrated an undetermined distance into the catalyst bed.

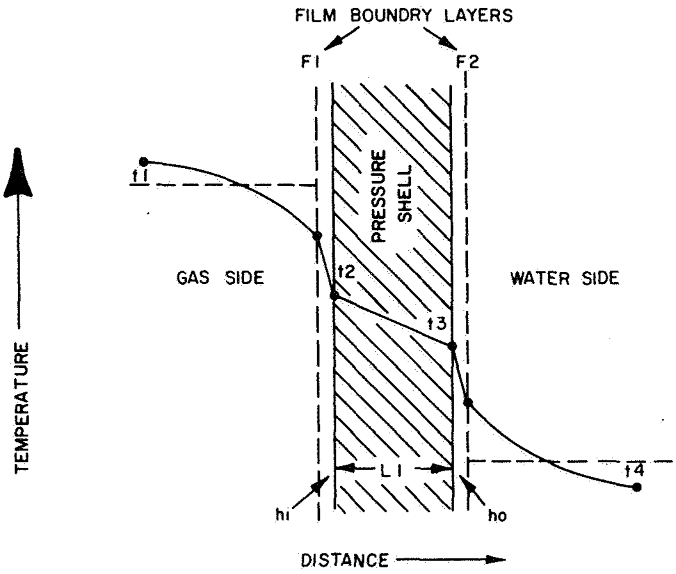
Figure 3. Vertical crack in the water jacket.

Investigation of the failure

Discussions with M. W. Kellogg and other ammonia producers revealed that at least three other failures in similarly designed equipment had occurred, and others had experienced problems with Insulag insulation. The three other failures were attributed to operation without water in the jacket.

Kellogg revised their specification for castable insulation for the primary waste heat boiler 101-C to "bubbled" alumina in December, 1967. This was to be used in place of Insulag or other siliceous type refractories *(1)*. No problems are apparent to date in lines or vessels using bubbled alumina.

We knew two facts which assisted us in investigating the failure. First, we knew water was overflowing from the jacket both before and during the failure, and second, that there were substantial insulation voids in the vessel. Calculations were made to determine the conditions necessary to have a temperature gradient across the pressure shell sufficient to cause it to rupture from overheat, Figure 4.



$$\frac{q}{A} = \frac{\Delta t}{\frac{1}{hi} + \frac{LI}{kAI} + \frac{1}{ho}}$$

Figure 4. Temperature gradients in forced convection.

With insulation intact and water in the jacket, external shell metal temperatures could not exceed 220°F to 250°F. Calculations were then made to determine metal temperatures assuming no insulation and nucleate boiling and no insulation with film boiling. With no insulation and nucleate boiling, the shell temperature would be about 950°F on the water side and 1,024°F on the gas side. With water scale on the outside, no insulation and film boiling, the external shell temperature would be about 1,000°F and the internal, 1,070°F.

The calculations indicate that failure cannot occur from overheat if water is in the jacket and nucleate boiling is occurring. They also indicate that metal temperatures can be high enough to cause failure from overheat if film boiling is occurring. Since we know from observation that the jacket was full and overflowing, we have theorized that "steam blinding" was occurring in the ruptured area due to the abnormally high heat flux and the transition from nucleate to film boiling. The continuous film of vapor virtually insulated the area and the heat transferred through the vapor film by conduction and radiation resulted in a temperature difference between the metal wall and the vapor-bound surface of the water sufficient to cause the rupture from overheat *(2)*.

A metallurgical examination of the rupture area determined the failure was due to a short-time, high temperature stress-rupture of approximately 100 hours duration at metal temperatures between 1,000°F and 1,200°F. The examination also determined that high temperature hydrogen attack did not cause the failure, but may have influenced it slightly. A sample taken from the rupture area was also examined and found to be normal with no apparent deterioration of metal properties.

A big disadvantage of the water jacket is that it is difficult to locate or determine the extent of a refactory failure in it when either a rise in water temperature or flow indicates a hot spot. Even though it is possible to reverse the transition from nucleate to film boiling, one may not know it is occurring and, in addition, the metal temperature cannot be reversed if sufficient turbulence cannot be created to break up the vapor film by increasing the water flow. Thus, continued operation may result in a major failure because the extent and magnitude of the hot spot is unknown.

One advantage of a water jacket is that it restricts thermal expansion of the vessel shell and thus minimizes gap formation between the shell and refractory liner that provides an opening for hot gas passage.

The next question to be answered was, why did we have insulation voids in a shop fabricated vessel assuming that it was adequately insulated in the shop? In our opinion, Insulag or other silica-based castable refractories will suffer degradation resulting in a loss of insulating properties when used in reducing atmospheres and the temperature-pressure conditions present in the steam-methane reforming section of the plant. Our experience has borne this out, not only with the primary waste heat boiler, but also in the transfer lines between the primary and secondary reformer and the secondary reformer and 101-C. These transfer lines are also water-jacketed and Insulag lined with stainless steel shrouds.

Insulag has a high silica content (ca. 52% as SiO_2 and a relatively high iron content (ca. 1%-2% as Fe_2O_3). Silica can become soluble, volatilize or react in the steam-gas atmosphere present and iron can react with carbon monoxide under high pressure reforming conditions *(3)*. Insulag, as cast, has a low density (about 30 lb./ft.^{3} after drying) and very little abrasion resistance. If the process gas passes behind the liner, erosion and refactory spalling may occur, carrying the insulation downstream and creating a hot spot on the unprotected vessel wall.

Shortly after the plant was onsteam, chromate inhibited cooling water was used for normal water supply to the jackets instead of steam condensate from the surface condenser. This source was used because the critical demand for demineralized water required the return to the utility plant off all steam condensate possible. A light scale found on the pressure wall was analyzed and found to be of typical composition expected from chromate inhibited cooling water.

Repair of the vessel

Before the vessel was opened for inspection and repair, the possibility existed that the refractory and shroud failure could have been caused by water impingement from a leaking boiler tube. Consequently, a new tube bundle was borrowed from Farmland Industries at Fort Dodge, Iowa, and installed. Our old tube bundle was later pressure tested and no leaks were found. The minor external damage to the baffles and tie rods of the bayonet tube bundle was repaired.

Repairs to the vessel were difficult because of the complicated rigging involved, the size and weight of the vessel, and the necessity of removing some of the structural members in order to remove the tube bundle and lower to ground level. In addition, low ambient temperatures reduced labor productivity and created additional problems.

After the vessel had been cleared, the 1,500 lb. flanged boiler feed water piping was removed and the entire top assembly containing the channel, tube sheet, and tubes was removed with the aid of a commercial rigger. The bundle was lowered to the ground and moved away from the work area. The total weight of the bundle, dry, was about 32 tons.

The stainless steel liner was removed in six sections by welding lugs on the inside of the liner and attaching cables. The conical gas shields were cut by air-arc gouge next to the vessel wall and each section was lifted clear of the vessel with an air hoist. After all six sections and remaining insulation were removed, a window 4 ft. x 4 ft. 9 in. was cut in the damaged area. A new patch of the same material (A-212 Gr B FBX) was rolled to 51 in. inside diameter. The new patch was 1 in. thick material as 15/16 in. plate was not available. The plate edges were ground to a double bevel with a matching bevel ground on the vessel wall opening. The plate was lifted into place, positioned and welded out.

The welding procedure used was E 6010 rod for root pass and E 7018 for weldout. A single root pass using a 1/8 in. rod was made. For the weldout, 12 passes were made (6 on each side) using a 5/32 in. rod. A pre-heat of 400°F was maintained during welding using a welding torch with a "rosebud" tip. The pre-heat was periodically checked with tempil sticks rated at 400°F and periodic checks were made during the course of welding with dye

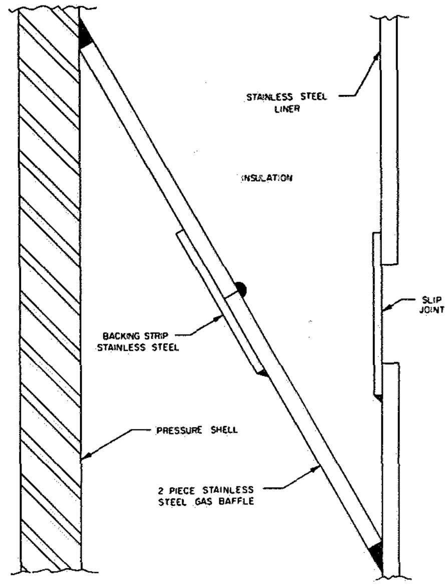


Figure 5. Modified gas baffle.

penetrant. After completion of the welding, the entire weld was radiographed. Two small slag inclusions found were ground out and repaired.

After welding was completed, the vessel was hydrostatically tested. Elliptical test heads were welded in the gas inlet and outlet nozzles. A test head for the top vessel flange was fabricated from the shipping container head and reinforced with 6 in. "H" beam strongbacks. Because of leaks developing in the gasket surface of the test head, a hydrostatic test pressure of only 580 psi was developed instead of the desired 675 psi. The water temperature for the test was 110°F-120°F. The top test head and the two elliptical heads were then removed and replacement of the shroud sections and insulation begun.

The shroud liner sections were straightened by rerolling and new gas shield members constructed, Figure 5. The external surface of the shroud and stub connections were covered with 3 layers of 1/8 in. thick cardboard held in place with masking tape. An exterior coat of aluminum paint was applied rather than shellac to prevent igniting the cardboard while welding. The liner was then lowered into the vessel, positioned, and bubbled alumina insulation poured into the annular space. When the area was full of insulation, the remaining piece of the gas shield was positioned and welded. The shell and insulation were kept at 60°F-80°F by the use of propane fired heaters piped into the external water jacket.

The bubbled alumina used for replacement was Greencast 97-L, which contains 96% to 96.5% Al_2O_3, with less than 0.1% SiO_2 and 0.1% to 0.3% Fe_2O_3. The density, when dried at 1,500°F, is 96- to 106-lb./ft.^{3}. The maximum usable temperature rating is 3,300°F. The application procedure recommended by A. P. Green and M. W. Kellogg was followed. The castable was mixed with 16% demineralized water by weight of the material for each pour with the exception of the small portion under the section of gas shield welded in after the pour. This small portion was mixed with 14% by weight of water to enable it to hold the approximate 60° angle. When the installation of the shroud and insulation was complete, the new tube bundle was installed and boiler feed water piping reconnected.

Curing and drying of refractory

The insulation was cured at 60°F-80°F for slightly over 72 hours as repairs were being completed by the use of the previously propane fired heaters connected to the water jacket.

The inlet temperature to the primary waste heat boiler was then raised 25°F/hr. to 250°F and held for 12 hours. This was accomplished by putting air through the primary reformer with the process air compressor 101-J. The maximum safe limit of 350°F air, in contact with reformer catalyst, was followed. The air was vented at the inlet of the high temperature shift with the shift converted blinded.

The air was then slowly backed out and replaced with steam, raising the temperature 50°F/hr. to 400°F. This temperature was held until no further evidence of boiling was reached, watching jacket water closely for excessive boiling. Drying was then considered complete and normal start-up procedure was initiated. Steam consdensate from the surface condenser was used for a short time after start-up until the demand for demineralized water again required the return to cooling water on the jacket water system.

Literature Cited

1. R. E. Dial, "High Alumina Refractory Materials for Gas Reforming," Air and Ammonia Plant Safety Symposium (September, 1967).
2. W. H. McAdams, Heat Transmission, McGraw-Hill, 3rd Edition (1954).
3. C. Edeleanu, "Materials Technology in Steam Reforming Processes," Proceedings of Material Technical Symposium organized by I.C.I., Ltd. (March, 1964).