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A Reliable New Check Valve for Harsh Gas Processing Applications

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Introduction

Over the past decade, a variety of filter designs based on porous ceramic filter elements have been developed to provide cleanup of particulate-laden flue gas at high temperatures and high pressures (HTHP). The most common filter design has been based on multiple rigid, cylindrical ceramic filter tubes placed in parallel across the process stream. The process conditions to which these filter designs have been exposed have taxed the capabilities of the ceramic materials used to construct the individual filter elements, resulting in periodic failures of a significant proportion of these filter elements. Because the components downstream of these HTHP filters can be extremely sensitive to even small amounts of entrained particulate matter, these failures have revealed the need for a means to ensure the cleanliness of the flue gas downstream of the filter in the case of catastrophic failure of some portion of the filter components. Consequently, the requirements of any system or safeguard device (SGD) designed to deal with these failures must be quite stringent.

Objective

In 1999, the Department of Energy's National Energy Technology Laboratory (DOE/NETL) issued a competitive solicitation (RFP No. DE-RP26-99FT40199) to develop suitable SGD's for inclusion in Hot Gas Cleanup (HGCU) systems envisioned for advanced PFBC and IGCC facilities. The criteria for a successful SGD design require that:

- the SGD must be able to operate with either PFBC ash or IGCC char with flue gases that may be either oxidizing (PFBC) or reducing (IGCC);
- in the event of the catastrophic failure of its filter element, the SGD must activate quickly and reliably, and once activated, provide a continuous barrier to prevent particles that breach its failed filter element from crossing the tubesheet;
- the SGD should have particulate emissions of zero ppm when in its active mode of operation, although low (~ 1-2 ppm) and or periodic emissions could conceivably be tolerated;
- at the time of filter failure, the SGD must be able to function with a dust loading of 2,000 to 20,000 ppm (or higher);
- the SGD must endure long-term operation at operating temperatures from 370 to 870 °C;
- the SGD must endure long-term operating pressures from 10.5 to 28 bar;

- the SGD design must be able to treat a nominal gas flow of 280 - 2800 actual liters per minute (lpm) when its filter is intact and the SGD is in its inactive mode of operation (in order to cover a wide variety of candle filter lengths and candle filter face velocities);
- the SGD must be able to activate with a nominal gas flow through it of 560 to 5600 lpm when a filter fails and SGD operation is initiated;
- the SGD must withstand repeated, vigorous, back-pulse cleaning events in its inactive and active operational modes;
- in its inactive mode, the SGD must not impede effective reverse-pulse cleaning of its intact filter element;
- the candidate SGD must be able to remain in either its inactive or activated condition throughout the variety of operating conditions liable to be encountered during normal HGCU filter operation (system startups and shutdowns, load changes, and variable temperatures and face velocities, etc.);
- the flow resistance of the SGD when in its inactive mode of operation (with an intact filter element) should be minimized; and
- the SGD design must be able to integrate into existing filter system designs in terms of seals, gaskets, fixtures, and assemblies.

In addition to these technical constraints, the most desirable SGD design should be inexpensive, easy to install, and easy to restore to its inactive mode during off-line servicing of the HGCU filter assembly.

Approach

Southern Research Institute (SRI) used its extensive experience with a wide variety of technologies associated with the capture of entrained particulate matter from flue gas streams to propose a unique SGD design in response to DOE/NETL's solicitation. In order for an SGD to meet the criteria listed above, it must be able remain inactive, and then to activate only in response to the conditions it experiences immediately following the failure of the filter element it is designed to service. When a filter element undergoes catastrophic failure, two main events occur. Because the breach of the ceramic filter element (and its associated filter cake, if any) provides a localized, much lower resistance flow path across the filter assembly's tubesheet, gas flow through the inactive SGD immediately increases greatly following a filter element failure. In addition to this change, dust-laden gas enters the portion of the filter element remaining on the tubesheet. Without the advantage of additional sensors to detect and identify the failure of a particular filter element, one or both of these two events must be able to trigger the activation of the SGD. It is possible to envision static SGD designs that act as a secondary filter, or particle trap, in the event of filter element failure. However, because reliably capturing and retaining particles in an SGD requires suitably small pores, the passage of clean gas in the inactive mode would lead to an unacceptable pressure drop penalty, as well as potentially interfering with effective reverse-pulse cleaning. There is also the possibility that an SGD that functions as a particle trap might be susceptible to reentraining previously captured particles when exposed to the force of periodic reverse-gas pulses. Based on these factors, the design of SRI's SGD (discussed in detail below) makes use of the increase in gas velocity through the SGD associated with a filter element failure to trigger SGD activation. Once this approach was selected, the challenge was to generate a design for a mechanical check valve that would function reliably and predictably at the extremely harsh conditions found in HGCU filters.

Project Description

The concept of SRI's check valve, or SGD, is quite simple. Although other applications, arrangements, and features are possible, a single dedicated SGD can be installed at the outlet of each filter element, where many filter elements that are at risk of failure are arranged in parallel (Figure 1).

As can been seen in Figure 1, the sealing plug within the body of the SGD acts like a stopper that is moved into position to close the opening above a particular filter element in the event of the failure of that element. Once the plug has closed this opening, it is secured in its closed position by the action of the locking balls. The entire device can be constructed of any machinable material(s) deemed suitable for other components in the process stream. The prototypes tested to date have included an aluminum proof-of-concept version, and two additional units constructed from 310 SS. For these prototypes, the locking balls (as shown in Figure 1 and discussed in more detail below) were made of 316 SS (for the aluminum version) or Si_3N_4 (materials from which off-the-shelf balls can easily be obtained).

In its inactive mode, the position of the sealing plug allows filtered flue gas to pass upwards through the SGD, while also allowing the easy downward passage of periodic reverse-gas cleaning pulses. In the configuration shown in Figure 1, the top hole in the body of the shell includes a spherical sealing surface lapped during manufacture to mate with the spherical top surface of the sealing plug when the SGD is activated. The form of the sealing plug is essentially a lower cone joined to a segment of a sphere at the upper, large end of the cone. The design weight of the sealing plug is established by its dimensions and the density of the material from which it is constructed. The sealing plug is supported by three spherical locking balls that in turn rest on a conical surface inside the lower portion of the shell. Grooves are cut into this conical surface under each ball to guide its downward movement when the SGD is activated. A shallow spherical indentation around the circumference of the plug at the height where the balls contact the plug in the inactive mode helps to hold the plug and balls in their inactive positions during installation, and in the presence of normal vibrations that may be experienced in the filter vessel. In addition, these balls contact the inner wall of the shell in the SGD's inactive mode to further secure them against vibration. The details of this design minimize the contact area between components of the SGD that must move when the device activates.

In the event of a catastrophic failure of its filter element, the increase in the velocity of the gas at the plane (A-A) of the annular orifice between the sealing plug and the interior wall of the shell generates an upward force sufficient to lift the sealing plug vertically off the three locking balls. The upward movement of the sealing plug is guided by an alignment pin that is axially mounted to spokes attached to the top of the shell. Because this pin fits only loosely in the central hole of the sealing plug, the upward motion of the plug is guided by only intermittent contact with the pin, rather than a continuous sliding action, which would most likely be problematic at HGCU environmental conditions. When the sealing plug is lifted off the three locking balls (located at 120° intervals around the circumference of the plug), the balls then roll down the grooves in the shell until they become trapped between the conical surfaces of the lower shell and the sealing plug. The slopes of the conical surfaces are set to be nearly parallel so that any downward force applied to the top of the sealing plug following SGD activation will be transferred very nearly through the centers of the locking balls and to the SGD shell wall. The dimensions of the sealing plug, shell and locking balls are set so that under no conditions can the balls pass beyond the bottom of the sealing plug and fall out of the SGD. The fact that the pressure on the lower side of the sealing plug following activation is normally higher than the pressure above the plug provides even more assurance that the sealing plug remains fully elevated, and in contact with the sealing surface of the shell.

It is obvious from examination of the physical components of the SRI SGD that its shell must be made in at least two pieces, so that the sealing plug and locking balls can be inserted during assembly. The configuration shown in Figure 1 includes a circular, compressible gasket between the two pieces of the shell, which are joined at the flange used to mount the SGD to the tubesheet. Other means of joining the shell pieces during assembly, including welding, could conceivably be used.

THEORY OF OPERATION

To take full advantage of the capabilities of the SGD, the conditions necessary to generate the lifting force needed to elevate the sealing plug into its activated position must be predictable and reproducible. In addition, as mentioned above, the device must be able to remain in its inactive state while being exposed to normal fluctuations in process conditions (flow, gas temperature, etc.) inherent in any industrial process. In the inactive (i.e., normal) mode of operation, the upward flow of filtered flue gas provides an increased pressure in the lower portion of the SGD, having a magnitude determined by the velocity v and the density ρ of the gas according to Bernoulli's term $\frac{1}{2}\rho v^2$, as shown in Equation 1,

$$\Delta P = \tfrac{1}{2}\,\rho(v/C_d)^2 \qquad (1)$$

where C_d is the discharge coefficient of the annular orifice (a value determined to be about 0.75 for the design shown in Figure 1).

The typical conditions under which the SRI SGD would activate in the event of a isolated filter element failure in a conventional HGCU filter can be generically described (Figure 2). A sufficiently high upward force, generated by the dissipation of pressure across the annular orifice, must be applied to the sealing plug to initiate activation of the SGD. As Equation 1 defines, this force is proportional to the density of the gas and the square of its velocity through the annular orifice described above. The weight of the sealing plug and the cross-sectional area of the annular orifice between the plug and the shell can be adjusted in the design process to set this threshold of activation at the desired level. Identifying the proper activation threshold requires some knowledge or estimate of the operating conditions at the point in the process where the SGD will be located (usually the filter tubesheet). Proper selection of the activation threshold will ensure that the only condition sufficient to activate the device will occur when its filter element fails. In Figure 2, the activation threshold (17.5 mbar) is about five times the normal pressure drop across the annular orifice (3.75 mbar), and almost three times the maximum foreseeable value for the process. (This maximum value is roughly based on operation at an HGCU filter when its most extreme and abnormally high filtering velocity was momentarily experienced.) By setting this threshold above the maximum foreseeable value for the intended process, a safety margin against unintended activation, as identified in Figure 2) is established. In the case of the failure of its filter element, the magnitude of the pressure differential across the tubesheet determines the gas velocity through the SGD. Therefore as the threshold of activation is increased, the minimum tubesheet pressure drop at the time of filter element failure, below which the SGD will not activate, is also increased (see Figure 2). The relationships governing the activation of the SGD allow a wide "window of activation". However, balancing the insensitivity to process upsets with the ability to activate with a low tubesheet pressure drop, must involve the process operators in the SGD design. As the magnitude of the normally expected pressure drop across the filter element at risk of failure increases, a much wider latitude can be exercised in setting the limits of the SGD's window of activation.

Results

SRI has designed, fabricated, and tested three prototype SGD's under the research sponsored by DOE/NETL. The first prototype, P1, was constructed of aluminum and validated the general concept of the device. Once the threshold of activation of P1 was reached, the sealing plug rapidly moved into its fully closed position (Figure 3). As noted on the figure, the rate of decay observed in the pressure upstream of the SGD was due to leaks in the system other than across the seal between the plug and the SGD shell.

Based on the success of P1, a second prototype, P2, was then fabricated (Figures 4 through 7) and tested. This evaluation included characterization of the performance of P2 at ambient conditions at SRI's laboratory in Birmingham, Alabama, and extensive tests (at ambient temperature and HTHP conditions - about 815 °C and 5.8 bar) conducted in the Small Pressure Vessel (SPV) at DOE/NETL's High-Temperature Gas-Stream Cleanup Test Facility (HTGSCTF) during June and July, 2000.

This high-temperature prototype SGD, which was constructed from 310 SS and used locking balls made of Si_3N_4, performed very well. Activation of the device was repeatedly achieved at ambient and HTHP conditions. The SGD activated quickly and completely, and remained activated (closed) when exposed to vigorous reverse-gas cleaning pulses. Post-test visual inspection of the seal formed by the SGD at ambient and HTHP conditions suggests that the device formed a total barrier to the passage of particles, and also to the flow of gas. (Quantitative determinations of the quality of the seal formed at HTHP conditions were limited by the system configuration and by the nature of the readings available with the PCME, an electrodynamic particle charging sensor manufactured by PCME, Inc. To the extent provided by the PCME device used to provide relative measures of outlet mass levels at the HTGSCTF, the activation of P2 quickly and consistently formed a high-quality seal.) In several of the tests, the device was activated by a gradual increase in flow across the tubesheet (Figure 8). As can be seen in this figure, activation occurred quickly once the activation threshold was exceeded.

The tests at DOE/NETL also demonstrated that, in its inactive mode, the SGD was able to withstand the most energetic reverse-gas cleaning pulses available with the HTGSCTF with no apparent effect. The threshold of activation for P2 was consistent for almost all the test runs performed at both ambient and HTHP conditions. In addition, when inactive, the device offered very little resistance to the flow of filtered gas (ΔP across P2 was less than 3.7 mbar at a flow of 850 lpm). Although the test designed to assess the effect the SGD had on cleaning effectiveness had to be aborted due to filter element failure (discussed below), there is every reason to believe that P2's low resistance to flow in the forward (normal) direction translates to an equally low interference with the effectiveness of reverse-gas cleaning pulses.

One of the HTHP tests at DOE/NETL was designed to determine if the inactive SGD could withstand vigorous, repeated reverse-gas pulses and remain in its inactive mode. This test run was also intended to compare the effectiveness of the cleaning of a filter element fitted with P2 to the degree of cleaning experienced by another element operated in parallel without any SGD. The configuration for this run included one of the SPV's three filter element locations fitted with a conventional ceramic filter element with no SGD (location A), the second location having a conventional ceramic filter element with P2 positioned above it (location B), and the third element location (location C) blanked off. However, after several hours (and eight 20-minute filtration and cleaning cycles) of HTHP testing (at about 815 °C and 5.8 bar), the filter element under P2 failed catastrophically, breaking off completely near the tubesheet, and falling into the SPV hopper. The failure was attributed to the thermal and/or mechanical force of the reverse gas pulses. Although this unplanned filter element failure cut short this run, it provided an excellent opportunity for the SGD to activate following an on-line failure of its filter element. Immediately following the failure of the element under the SGD, P2 activated, completely closing off the flow of gas through its filter element location. Operation of the HTGSCTF continued through another three filtration and cleaning cycles. The closure of the SGD left the SPV tubesheet with only one of its three element locations actively collecting the PFBC ash reinjected upstream of the SPV. Therefore, the accumulation of ash and the increased face velocity experienced by this single remaining filter element ultimately caused the tubesheet pressure drop to reach system limits, and the system was shut down. The system vessel pressure, tubesheet pressure drop, and readings obtained with the PCME during this run were recorded by DOE personnel (Figure 9).

Examination of the data obtained by DOE/NETL's data acquisition system and the PCME monitor provides a fairly detailed log of the specific events that occurred around the time the filter element at location B failed. The activation of P2 is apparent by noting the increased rate of accumulation of tubesheet pressure drop following the cleaning event that occurred at about 14:00. Because the flow through the SPV and the ash injection rate remained the same even after P2 activated, the face velocity through location A was doubled to 10.2 cm/sec (location C was blanked off for this run). The PCME also indicated a brief emission of ash at about 14:00, which is what would be expected if a small amount of particle-laden gas passed through the SGD as it was activating. The three subsequent peaks in the PCME readings at 14:20, 14:40, and 15:00 represent the resuspension and reentrainment of ash that passed through to the clean side of the tubesheet as P2 activated, but settled out on the various surfaces above the tubesheet. The agitation of this ash by subsequent reverse-gas pulses would cause some portion of it to be reentrained during each cleaning event, but the total amount reentrained would gradually diminish as the supply of ash that deposited above the tubesheet was depleted. The PCME data shown in Figure 9 agree with this sequence of events.

A third prototype SGD, P3, was fabricated and has undergone limited evaluation at SRI's laboratories and at the Power Systems Development Facility (PSDF). Although the principle of operation of P3 is the same as the first two prototypes, the design of P3 differed in some ways from the earlier versions. (Due to patent disclosure limitations, the details of these differences cannot be included here.) In the bench-scale tests conducted at SRI, P3 was activated repeatedly with an ambient air flowrate of about 2550 lpm. The PSDF evaluation was conducted at HTHP conditions (around 400 °C and 15 bar, with the PSDF operating in gasification mode). One objective of this evaluation was to determine whether the SDG would remain inactive (open) through typical process startups, process variations, and shutdown procedures. P3 was installed in series between an intact filter element and a pore-plugging failsafe for two PSDF gasification periods of operation conducted in the spring of 2002. Although there were minor process upsets during these periods, P3 remained in its open position during the startup and shutdown procedures as well as during some minor process variations.

The second objective of the PSDF evaluation was to manually activate the device during HTHP operation. The approach used for this manual activation was the direct injection of high pressure nitrogen into the interior of the filter element below P3. It was hoped that enough of the injected nitrogen would travel upwards through P3 (and the other failsafe above it) to trigger the activation of P3 without inducing the failure of the filter element. Measurements of the pressure drop across P3 and the other failsafe during the injection of the nitrogen indicate that for two seconds there should have been a sufficient amount of the injected gas passing through the failsafes to activate P3 (rather than exiting backwards through the filter element). However, P3 remained open through several nitrogen injection trials. The reason P3 did not activate during these trials is not certain, although the difference in the design of P3 (compared with the first two prototypes) may require that a sufficiently high flow of gas pass through P3 for longer than the two seconds available in these trials. Bench-scale tests of activation performed at SRI following the PSDF test runs determined that P3 was still able to activate with approximately the same ambient air flow as during initial testing. Further bench-scale and/or pilot-scale testing may be performed to clarify these results.

Application

Applications for U.S. and international patent coverage have been filed for all of the features shown and discussed above, as well as other features that have been envisioned to enhance the operation and increase the fields of application of the device. The design of this check valve should allow each unit to be easily reused. The valve design can also be scaled up or down to handle different ranges of flows. Depending on the particular process conditions, one check valve could be arranged on a manifold to service several flow streams. The low pressure drop across the device may also allow check valves to be installed in series, if process control issues warrant this type of arrangement. With proper selection of the threshold of activation, the valve could also be designed to shut on a reversal of flow. Because the activation of the device depends on characteristics of flows common to gases and liquids, SRI's check valve could also be installed on liquid transport lines. The basic design described in this paper can serve as a check valve with the potential to provide reliable service in environments where no other check valves can function. Because this design has the capability to be completely constructed from any machinable material suitable to the intended process, it may become an enabling technology for other high-temperature gas processing applications, including fuel gas cleaning for fuel cells, and high-temperature fuel gas conversion processes.

Future Activities

In order to fully exploit the potential of this check valve design, it would be beneficial to perform additional evaluations of prototype units installed on as many of the various processes and configurations identified above as possible. Parameters of interest include material of construction, makeup of the gas (or fluid) to be controlled, more extreme operating temperatures and pressures, and scaling the design to a broad range of flows. Also, additional design features have been conceived that should enhance and expand the potential fields of application of this check valve. These features, which are currently under patent review, should also eventually be evaluated in bench- and pilot-scale installations.

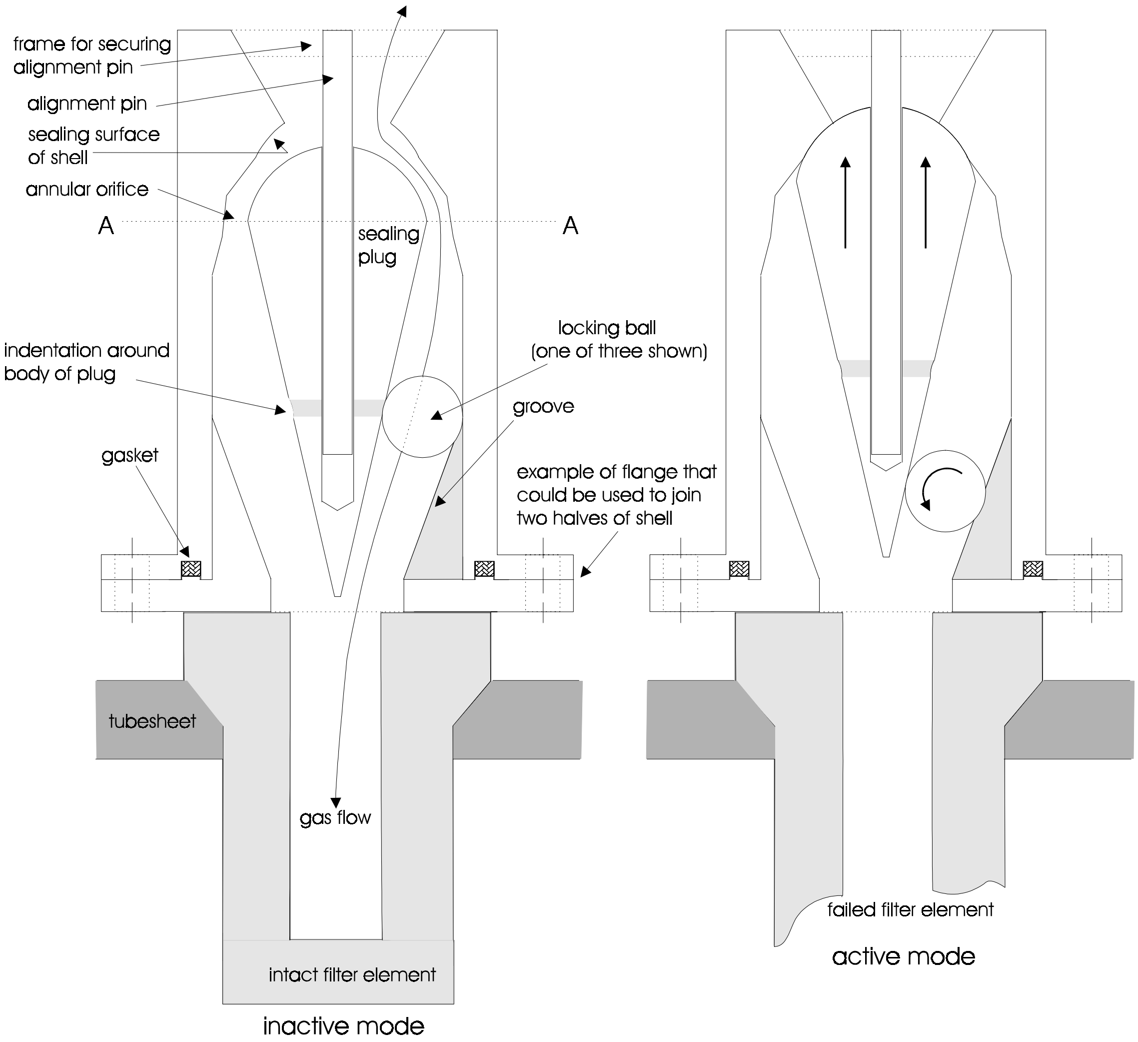

Figure 1. Schematic of SGD operation illustrating the activation of the SRI SGD when its filter element undergoes catastrophic failure. (Details of the installation of the filter element and the SGD to the tubesheet are not shown.)

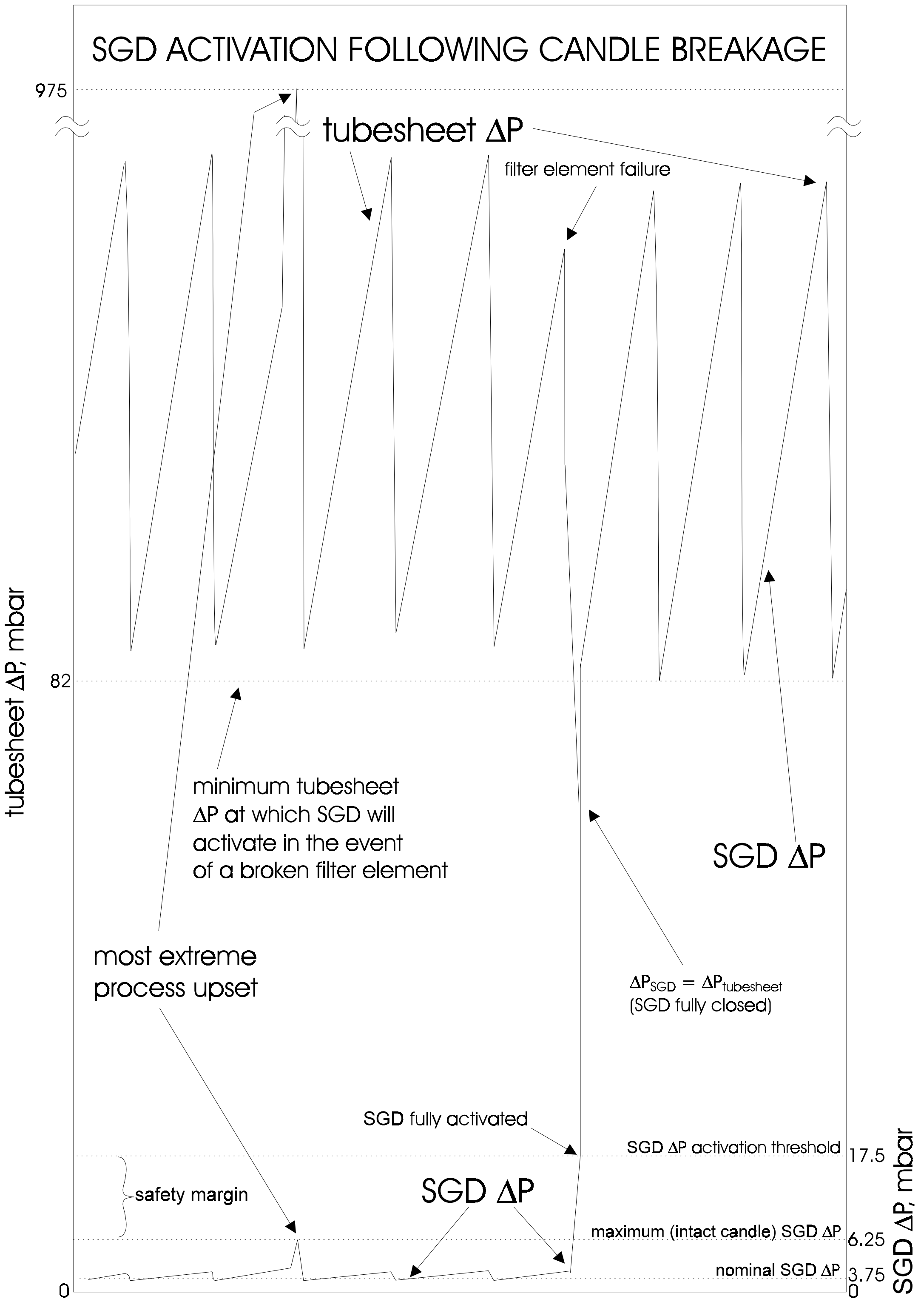

Figure 2. Idealized relationships between the pressure drops across the tubesheet and an SGD before, during, and after the failure of a filter element and the resultant activation of its SGD.

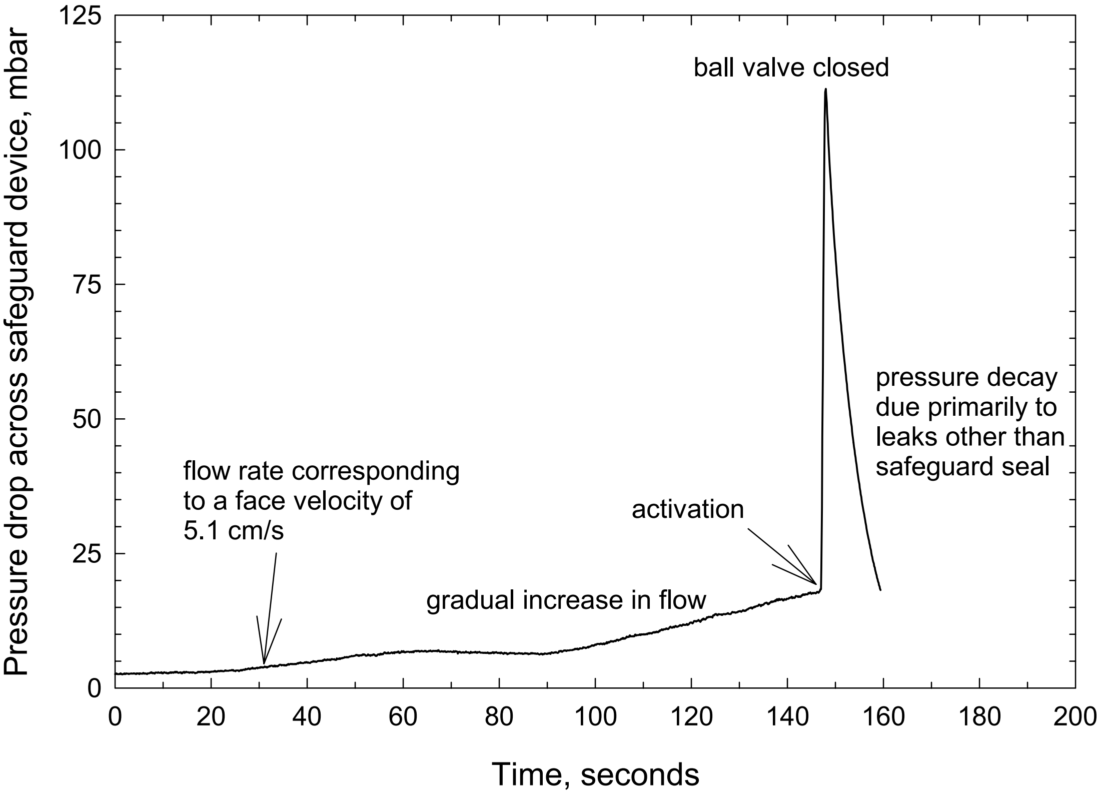

Figure 3. Activation of P1 induced by a gradual increase in flow. Activation occurred at ambient conditions at a flow rate of about 1950 lpm.

Figure 4. Complete P2 assembly.

Figure 5. P2 sealing plug and locking balls.

Figure 6. Sealing plug in its inactive position supported on the three locking balls positioned in the lower shell.

Figure 7. Lower shell showing the vertical channels used to maintain the 120° spacing of the three locking balls during activation.

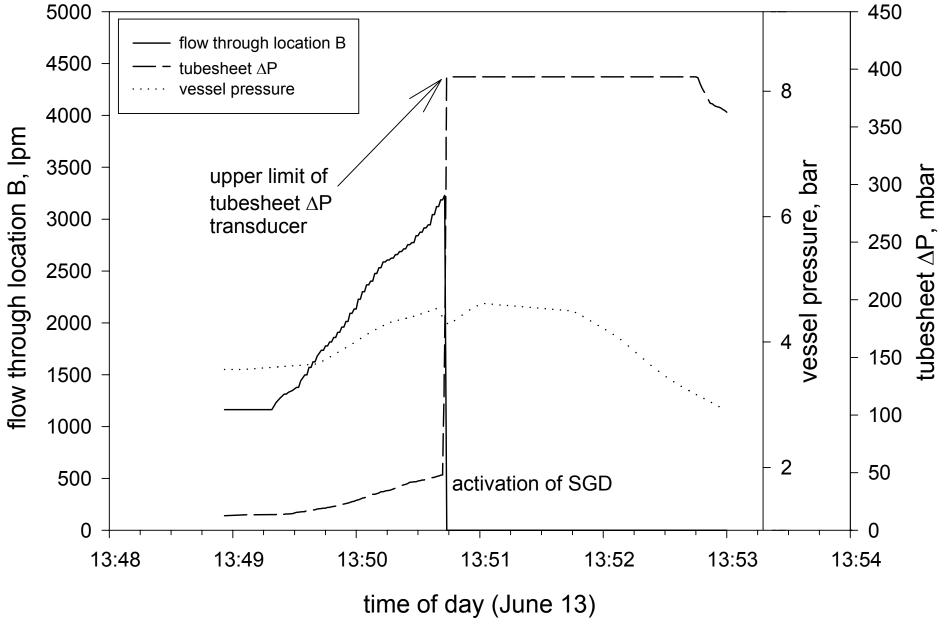

Figure 8. Data showing the activation of P2 at 1547 °F. The flow rate through the SGD at location B on the tubesheet has been adjusted to estimate the effect of the pressurization of the SPV. For the HTGSCTF to generate sufficient flow through the SGD, the SGD was located in parallel with a small orifice at location A. The remaining location, C, on the tubesheet was blanked off. Activation of the SGD forced all of the system's gas flow through the small orifice, resulting in the high tubesheet pressure drop evident after SGD activation. System flow was then manually reduced to decrease the tubesheet pressure drop to manageable levels.

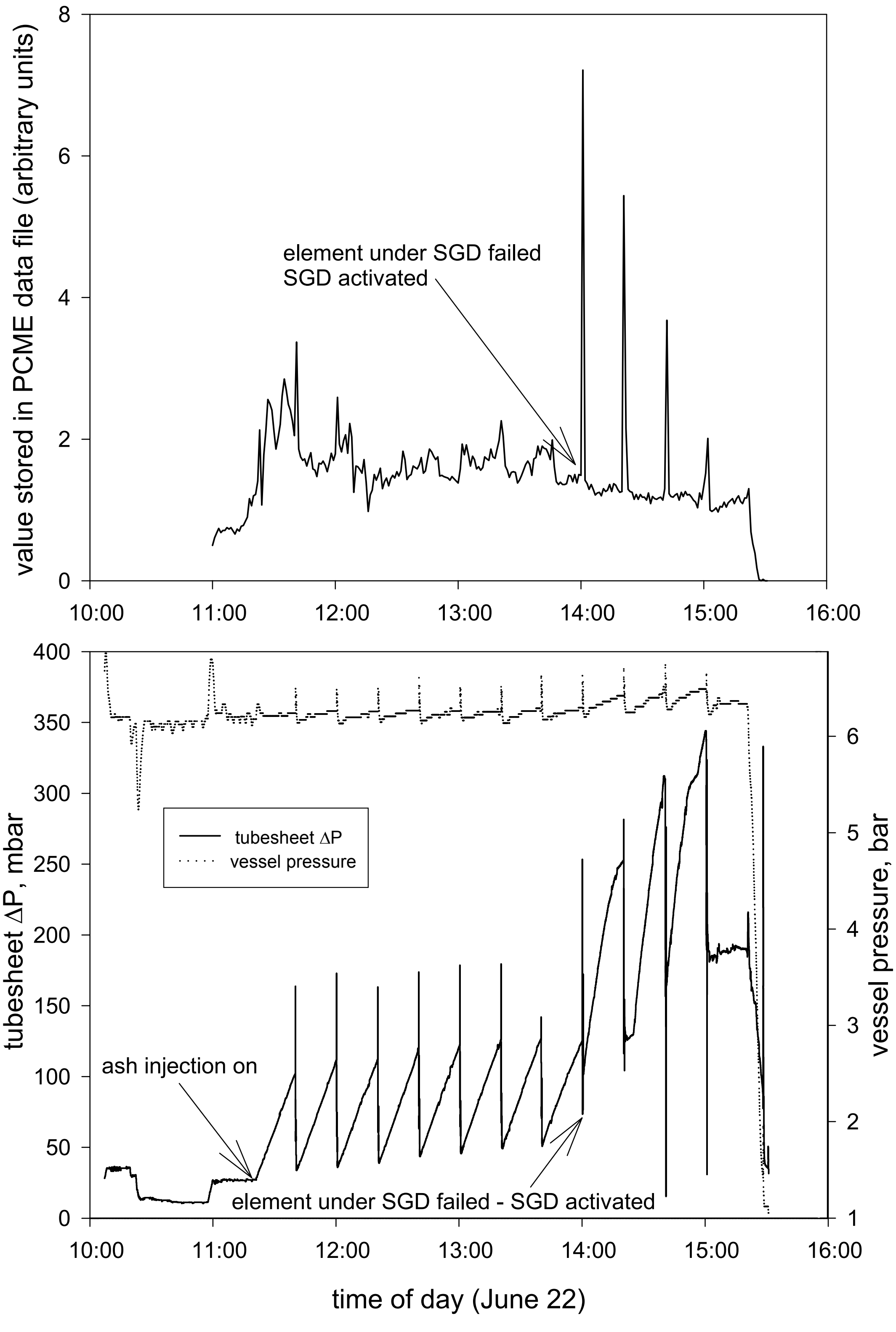

Figure 9. Summary of PCME readings, tubesheet pressure drop, and SPV pressure for the HTHP run in which P2 activated following the failure of its filter element.