Fuel Flexibility in Gasification

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Abstract

In order to increase efficiencies of carbonizers, operation at high pressures is needed. In addition, waste biomass fuels of opportunity can be used to offset fossil fuel use. The National Energy Technology Laboratory (NETL) Fluidized Bed Gasifier/Combustor (FBG/C) was used to gasify coal and mixtures of coal and biomass (sawdust) at 425 psig. The purpose of the testing program was to generate steady state operating data for modeling efforts of carbonizers.

A test program was completed with a matrix of parameters varied one at a time in order to avoid second order interactions. Variables were: coal feed rate, pressure, and varying mixtures of sawdust and coal types. Coal types were Montana Rosebud subbituminous and Pittsburgh No. 8 bituminous. The sawdust was sanding waste from a furniture manufacturer in upstate New York. Coal was sieved from -14 to +60 mesh and sawdust was sieved to –14 mesh.

The FBG/C operates at a nominal 425 psig, but pressures can be lowered. For the tests reported it was operated as a jetting, fluidized bed, ash-agglomerating gasifier. Preheated air and steam are injected into the center of the bottom along with the solid feed that is conveyed with cool air. Fairly stable reactor internal flow patterns develop and temperatures stabilize (with some fluctuations) when steady state is reached. At nominal conditions the solids residence time in the reactor is on the order of 1.5 to 2 hours, so changes in feed types can require on the order of hours to equilibrate. Changes in operating conditions (e.g. feed rate) usually require much less time. The operating periods of interest for these tests were only the steady state periods, so transient conditions were not monitored as closely.

The test matrix first established a base case of operations to which single parameter changes in conditions could be compared. The base case used Montana Rosebud at a coal feed rate of 70 lbm/hr at 425 psig. The coal sawdust mixtures are reported as percent by weight coal to percent by weight sawdust. The mixtures of interest were: 65/35 subbituminous, 75/25 subbituminous, 85/15 subbituminous, and 75/25 bituminous. Steady state was achieved quickly when going from one subbituminous mixture to another, but longer when going from subbituminous to bituminous coal.

The most apparent observation when comparing the base case to subbituminous coal/sawdust mixtures is that operating conditions are nearly the same. Product gas does not change much in composition and temperatures remain nearly the same. Comparisons of identical weight ratios of sawdust and subbituminous and bituminous mixtures show considerable changes in operating conditions and gas composition. The highly caking bituminous coal used in this test swelled up and became about half as dense as the comparable subbituminous coal char. Some adjustments were required in accommodating changes in solids removal during the test. Nearly all the solids in the bituminous coal sawdust were conveyed into the upper freeboard section and removed at the mid-level of the reactor. This is in marked contrast to the ash-agglomerating condition where most solids are removed at the very bottom of the gasifier. Temperatures in the bottom of the reactor during the bituminous test were very high and difficult to control.

The most significant discovery of the tests was that the addition of sawdust allowed gasification of a coal type that had previously resulted in nearly instant clinkering of the gasifier. Several previous attempts at using Pittsburgh No. 8 were done only at the end of the tests when shutdown was imminent anyway. It is speculated that the fine wood dust somehow coats the pyrolyzed sticky bituminous coal particles and prevents them from agglomerating quickly. As the bituminous coal char particles swell, they are carried to the cooler upper regions of the reactor where they re-solidify.

Other interesting phenomena were revealed regarding the transport (rheological) properties of the coal sawdust mixtures. The coal sawdust mixtures segregate quickly when transported. This is visibly apparent. To prevent bridges and ratholes from developing in the lowest coal feed hopper, it is normally fluidized. When feeding the coal sawdust mixtures the fluidizing gas was turned off to prevent segregation. The feed system worked as well with no fluidizing gas when using the mixtures as it did with fluidizing gas and only coal. In addition, it was inadvertently discovered that greatly increased pressure above the feeder resulted in greatly increased flow with the mixtures. Increased pressure above the feeder with coal only results in quickly plugging the feed system. Also, it was learned that addition of sawdust reduces the system loss during conveying compared to coal only. This is in spite of overall smaller particle sizes with the coal sawdust mixtures.

Introduction

State of the art power systems using advanced turbines are limited to pressure ratios of about sixteen to one. It would be thermodynamically advantageous to extend the operating pressure ratios of these systems higher. Pressure ratios of thirty to one are believed to be achievable. However, limited performance data is available to properly evaluate the feasibility of such undertakings. Key technical issues and uncertainties need to be resolved prior to designing these higher-pressure systems.

Several advanced concepts involve the use of a carbonizer, pyrolyzer, or gasifier to partially convert a solid carbon fuel into combustible gas and semi-processed solid fuel components. Specifics of high-pressure (between twenty and thirty atmospheres) operations of these units is of limited availability. There is a particular paucity of information regarding fuels that are mixtures of coal and biomass. In addition, if the purpose is to enable numerical simulations of these high-pressure systems well instrumented, characterized and monitored testing is required.

There are considerable amounts of unutilized or underutilized fuels of opportunity that are biomass in origin. Sawdust, tree bark, waste paper that cannot be recycled, poultry litter, soy bean stalks, and rice husks are among the many that are potentially useful and plentiful in some areas. These fuels have limited useful shelf lives in their discarded states. They decay. If methods can be found to put these waste products to good use, considerable benefit to the nation’s energy situation can be achieved.

Objective

In order to assure that inherent scale-up problems (e.g. surface to volume ratios involving heat transfer from non-adiabatically heated equipment) do not influence experimental results, equipment larger than bench scale is needed. Pilot scale equipment is typically used to generate the experimental data that can be used to reliably design demonstration scale processes. The process must be sufficiently instrumented so that good control of flows, pressures and temperatures is assured. Additionally, safety and environmental protection are possible only with well-operated processes.

The precision required for information that is to be used in numerical modeling also requires considerable data to be accurately acquired. Sophisticated, capacious data acquisition systems are expensive but when combined with the newer distributed control systems they provide reliable, powerful tools to simultaneously control and monitor the unit operations of coal conversion processes.

The task was to simulate carbonization with various operating parameter changes at high pressures (twenty to thirty atmospheres). Operating parameter changes of interest were pressure, solid feed rate, solid feed type and gas feed composition. In order to avoid second order interactions, it was necessary to vary one test parameter at a time about a base case of conditions. The conditions of interest were only steady state operating periods. When making some parameter changes (such as reactor pressure), time to achieve steady state is relatively quick. Careful monitoring of product gases, temperatures and reactor bed differential pressure instruments can indicate whether or not conditions have “lined out”. Since there is always some drift and cycling in internal reactor conditions, it is often somewhat subjective that steady state has been reached. Considerable experience with the system being used is necessary for an informed and reasonable assessment.

It is not a trivial undertaking to co-feed mixtures of coal and biomass into high pressure vessels, particularly if good mixing is required. If synergistic benefits are to be obtained from intimate contact of the separate feeds, they must be thoroughly mixed and the delivery system must assure that segregation does not occur. With feeds as different as biomass and coal, the sizes and shapes of the particles is very important.

Approach

The National Energy Technology Laboratory (NETL) has an existing pilot scale size Fluidized Bed Gasifier/Combustor (FBG/C) that has been reported previously (Strickland, et. al, 1988, Kanosky 1990, Kanosky, 1991). Use of this reactor to simulate carbonization was the objective of the work reported here. The focus of this paper is that part of the test program which involved the co-feeding of various coal and biomass mixtures into the gasifier.

The experimental system was identical to that used for the coal only testing. A simplified schematic of the FBG/C is shown in Figure 1. Since the biomass testing was an integral part of the test program, the strategy was to maintain conditions as closely as possible to that of the base case, with biomass feeds being the test variable. This presented problems in that coal and biomass have considerably different heating values. In addition, cellulose molecules (as well as the other organic compounds in living matter) are not as robust as coal. Cellulose fibers are much more fragile in the thermal extremes of a gasifier than the highly interconnected molecules depicted in the many model coal molecules that have been proposed.

When comparing conditions in fluidized gasification systems it is important to maintain similarities in bed particulate loading. Devolatilization and pyrolysis occur quickly relative to the gas-solid reactions in the oxygen deficient zones of the reactor. In particular the water-char reaction is quite slow. If changes in coal feed rates are significant and all other parameters are held constant, the bed inventory will change over time accordingly. It then becomes difficult to determine when steady state has been reached because the bed changes very slowly over time.

Since the heating value per unit mass of biomass is much less than the heating value per unit mass of coal a larger volume of biomass must be used to equal an equivalent amount of coal. The densities of the mixtures vary inversely with more biomass. In addition, the mixtures higher in biomass will have a disproportionately high heating value (compared to coal only) if the strategy is to keep the coal feed rate comparable. Thus, one is adding a disproportionate amount of thermal energy in that case and conditions are not similar.

In order to avoid the oxymoron condition of transient steady state great care must be taken in evaluating just which are the significant dominant or controlling parameters. It is not possible to have only one parameter change at a time with the biomass mixtures. So compromise was required to reach some target coal/biomass mixture feed rate. However, it must be remembered that the primary purpose of the test program was to provide modeling data and as such each test segment was independent of the others in that regard.

Project Description

The NETL FBG/C was operated as an air blown, ash agglomerating, jetting fluidized bed gasifier for the tests reported here. The coal/biomass mixtures were premixed in drums and loaded into the Coal Silo for pueumatic conveying into the Coal Batch Hopper (see Figure I) in batches. The Batch Hopper is normally filled and then brought up to the pressure of the Feed Hopper directly below it. The valve between the vessels is then opened and a load of feed is dumped into the Feed Hopper. Under normal operations with coal only the Feed Hopper is isolated from the Batch Hopper and the Feed Hopper is fluidized to prevent bridging, ratholing, or plugging. It is well established that this procedure causes segregation of particles by density. In order to avoid this in the coal/biomass mixtures the Feed Hopper fluidizer was turned off. Otherwise, all procedures for coal only feeds were followed.

At the bottom of the Feed Hopper is a rotary Pocket Feeder that controls the solids feed rate by varying its rotational speed. The Feed Hopper is normally kept at a slightly higher pressure than the bottom of the reactor to insure no back-flow in the feed line. At the bottom of the Pocket Feeder the solids are entrained in an air stream and conveyed into the axial center of the reactor as shown in Figure 2. The coal/air stream is in the center of an annular flow of preheated air and steam. The strategy is to keep velocities high in this region in order to quickly convey the solid particles out of the hot zone where the highly exothermic oxygen reactions are primarily occurring. Average coal char particle residence times in the reactor for normal operations is on the order of 1.5 to 2 hours.

Solids are removed in three places. The very bottom of the reactor collects the agglomerated high ash particles. The first freeboard section has a port (the Overflow) to remove smaller particles. The final solids removal is in the Cyclone in the product gas stream of the gasifier. Gas is cleaned up and sampled downstream of the Cyclone. The primary gas analyzer is a Perkin Elmer magnetic sector mass spectrometer with backup by an Ametek quadrupole residual gas analyzer and with periodic bottle samples checked by gas chromatograph. Gas analyses are reported on a dry basis from the primary analyzer.

Figure 2 shows the locations by number identifier of reactor internal thermocouples (TE) and differential pressure ports (PDT). Internal thermocouples are at varying distances into the bed and at different angles. All pressures, temperatures, flows, gas compositions, etc. are scanned by the Moore Products APACS/ProcessSuite distributed control/data acquisition system on about a one-second interval (depending on conditions). The system allows real time plots of all key process variables and historical trends are always available.

The solid feeds used for these tests are described in Table 1. The Montana Rosebud subbituminous coal was the base case coal. The Pittsburgh No. 8 was from a local mine. The biomass was sanding waste sawdust from a furniture manufacturer in upstate New York. The sawdust had been pelletized and was re-pulverized and screened by NETL personnel. All feeds were kept dry. The coal sawdust mixtures on a percent by weight basis were:

85% subbituminous coal/15% sawdust
75% subbituminous coal/25% sawdust
65% subbituminous coal/35% sawdust
75% bituminous coal/25% sawdust

Table 2 gives the key steady state operating conditions of the base case and coal sawdust mixtures. Reactor pressure for all tests was 425 psig. The 65/35 case shown in Table 2 indicates only 55 lbm/hr of coal feed. This was limited because the Pocket Feeder was at its maximum delivery rate.

Results

The most striking overall observation was that very little difference could be discerned when comparing the base case to all the subbituminous coal mixtures. The bituminous coal mixture was markedly different in significant aspects from all the subbituminous coal tests. Results are presented in graphical form in the attached figures that show reactor temperatures, reactor differential pressures and key product gas analyses for the steady state periods. All curves in all the data figures appear as thick lines. This is due to typical drift and cycling of readings during a test. Sharp vertical dislocations are due to operational changes and instrument aberrations. It should be noted that there is more variability in the bituminous test for all figures. That is reactor conditions were not “lined out” nearly so well as in all the subbituminous coal cases. This was mostly due to us having to learn how to operate the gasifier with the bituminous coal. All previous attempts with the Pittsburgh coal resulted in nearly immediate clinkering and shut down.

Figures 3, 4, 5 and 6 show thermocouple readings at the bottom of the reactor. TE-733 in Figure 5 is not shown on Figure 2, but it is at the level of TE-700 and TE-701. Figures 3,4, and 5 clearly show that the gasifier is running much hotter at the bottom with the bituminous coal mix than it is with all subbituminous coals. The trend is continued in Figure 6 (slightly higher up) but is less pronounced. Temperature plots at the top of the vessel show that the differences in subbituminous coal and bituminous coal temperatures are insignificant.

Figures 7, 8 and 9 show hydrogen, carbon monoxide and carbon dioxide gas analyses for the steady state periods of operation. The carbon dioxide plots are essentially the same. There is slightly less hydrogen for the bituminous case. However, the carbon monoxide analyses show markedly lower carbon monoxide concentrations for the bituminous case.

Figures 10, 11 and 12 show differential pressure readings of the gasifier internals at the respective locations shown in Figure 2. Note the much lower differential pressure in the reactor bottom (PDT-707) for the bituminous coal case. This trend continues for PDT-708 (reactor middle) but is more mitigated at the top of the vessel. The reason for this behavior is that the bituminous coal swelled up and became much less dense. Very little char was removed through the bottom drain (Underflow in Figure 2). Nearly all the solids were removed through the Overflow outlet. It was eventually dumped every fifteen minutes instead of every hour to keep up with the quickly accumulating inventory. Table 3 compares Overflow solids for the base case (subbituminous coal only), the 75%/25% subbituminous coal mixture and the 75%/25% bituminous coal mixture. The larger particle size and greatly reduced density for the bituminous coal are clearly shown. The differences in particle size were readily apparent with a visual comparison.

As noted above there was no successful prior operational experience with the bituminous coal. The greatest concern was for the high temperatures at the reactor bottom (where clinkering occurs). Numerous tweaks were attempted to control the temperature there but none worked well. Frequent dumping of the Overflow seemed to have some limited effect. The test was terminated when the feed tube plugged with an unscreened pellet of wood. It is speculated that addition of the sawdust caused inert fine particle coating of the hot, plastic bituminous coal particles preventing them from agglomerating as they would with coal only.

Not indicated in any of the data plots was the markedly different transport/rheological behavior of the coal mixtures compared to only coal. As noted above, the Feed Hopper is always fluidized with coal only and for the coal sawdust mixtures it was turned off. There were no operational problems with the Feed Hopper during any of the coal mixture tests. In addition, when calibrating the Pocket Feeder for the coal mixtures the Feed Hopper differential pressure instrument was inadvertently raised from a few psi to about 50 psi. Not only did this not result in the kind of plugging that would inevitably result in this equipment if coal only were being fed, it resulted in a dramatic increase in solids flow rate. While not recorded as official data, the increase in solids flow rate was so great that it could only have been the result of significant alterations in the packing factors of the particles inside the cup in the Pocket Feeder. It must also be remembered that during these calibrations the fluidizing gas to the Feed Hopper was also off.

The FBG/C is equipped with an extensive venting and particulate control system. During Pocket Feeder calibrations using only normal coal it is noted that about five percent of the solids are lost to the particulate collection systems. In the case of the coal/sawdust mixtures this was reduced to about three percent.

Application

The Results of the work reported here show that considerable synergistic benefits can be obtained from use of intimately mixed coal and biomass. Not only are flow properties greatly improved, but coals that were not possible to use previously can be utilized. In addition, there is considerable potential for using waste fuels of opportunity such as waste sawdust, bark, poultry litter, etc. These fuels are essentially free except for costs of transport and handling.

It is only speculation why the sawdust alters the transport/rheological properties of the coal so inordinately and prevents clinkering of the bituminous coals in the FBG/C. However, it is possible that very small particles of cellulose from any source could have similar effects. If it is discovered that waste paper products that cannot be recycled have similar properties to the sawdust we used, considerable improvements in similar gasification processes are possible.

References

Strickland, L. D., R. B. Reuther, J. M. Rockey, “Design Features and Early Operating Experiences with the METC 6-inch Diameter Fluidized Bed Gasifier”, Fifth International Pittsburgh Coal Conference, Sept. 12-16, 1988, Pittsburgh, PA.

Kanosky, J. P., “METC’s Fluid-Bed Gasifier (FBG)”, Tenth Annual Gasification and Gas Stream Cleanup Systems Contractor’s Review Meeting, Aug. 28-30, 1990, Morgantown, WV.

Kanosky, J. P., “Fluid-Bed Gasifier for Hot Gas Cleanup Units”, Proceedings of the Eleventh Annual Gasification and Gas Stream Cleanup Systems Contractor’s Review Meeting, Aug. 1991, Morgantown, WV, pp. 499-503.

Feeds Used:	Montana Rosebud (Subbituminous) Coal	Pittsburgh #8 (Bituminous) Coal	Furniture Sawdust (Niagra/Mohawk #1)
Proximate Analyses (%wt, as rec'd)			
Moisture	3.46	2.28	11.62
Volatile	38.59	37.90	72.46
Fixed Carbon (by diff.)	49.02	52.96	15.21
Ash	8.93	6.86	0.71
Ultimate Analysis (%st, as rec'd)			
Moisture	3.46	2.28	11.62
C	64.27	72.89	43.80
H	4.51	5.14	4.87
N	0.95	1.20	3.07
O (by diff.)	15.95	9.18	35.88
S	1.93	2.45	0.05
Ash	8.93	6.86	0.71
Others (as rec'd)			
Cl-, ppmw	NA	<10	400
NH+4, ppmw	33.4	NA	NA
Cu+2, ppmw	26.0	NA	NA
Zn+2, ppmw	248	NA	NA
Mineral carbon, %wt	0.14	0.07	0.03
Gross Heat Value, Btu/lbm	11,209	13,235	7,498
Density, lbm/cu ft (Helium)	94.22	84.24	89.86
(Bulk)	43.11	43.15	NA
Sieve Sizes (mesh)	-14 +60	-14 +60	-14
Ash Fusion Temperature, ^{O}F			
(ID)	2,300	2,120	NA
(ST)	2,320	2,140	NA
(HT)	2,340	2,200	NA
(FT)	2,420	2,400	NA
Free Swelling Index	1.0	7.5	NA

Table 1. Analyses of Feeds Used in Biomass Testing

	Base Case	85/15 Subbit	75/25 Subbit	65/35 Subbit	75/25 Bitum
Total Feed rate (lbm / hr)	70	95	90	85	90
Coal Feed rate (lbm / hr)	70	81	67.5	55	67.5
Sawdust Feed rate (lbm / hr)	0	14	22.5	30	22.5
Convey Air (scfh)	1600	1600	1600	1600	1600
Reactor Air (scfh)	1025	1025	1025	1025	1025
Steam (lbm / hr)	60	60	60	60	60

(Reactor @ 425 psig)

Table 2. Steady State Operating Conditions

		Base Case	75/25 Subbit	75/25 Bitum
Bulk Density (lbm / cu. Ft.)		13.13	15.99	7.96
Screen Size (Cumulative Percentage)				
Passing	Retained on			
	35	8.99	10.59	78.37
35	45	15.46	17.97	86.21
45	60	23.61	25.27	91.27
60	80	36.32	34.40	94.42
80	170	59.70	59.97	96.11
170	325	71.93	82.76	97.14
325	PAN	100	100	100

Table 3. Overflow Solids Comparison

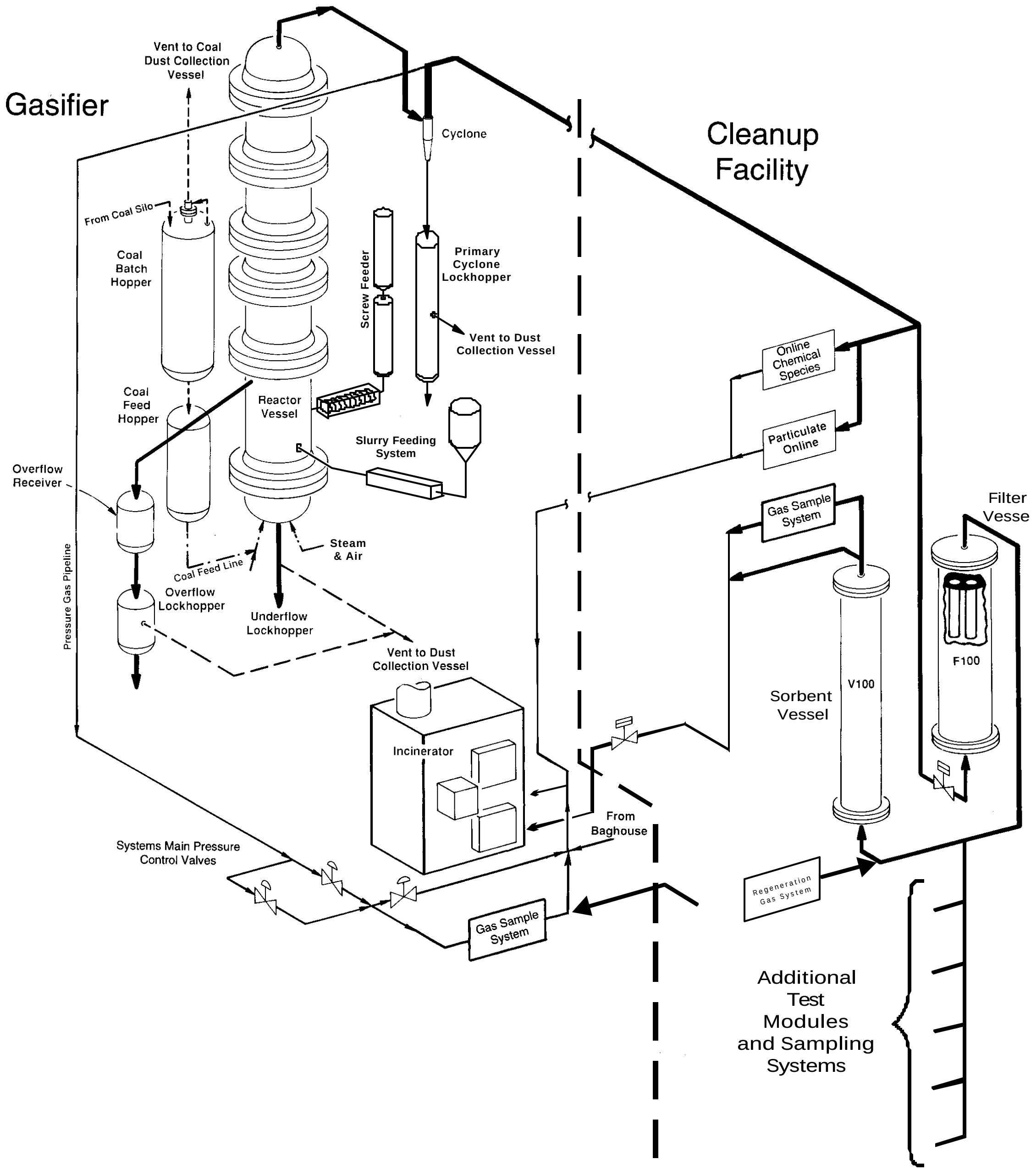

Figure 1. NETL FBG/C Facility

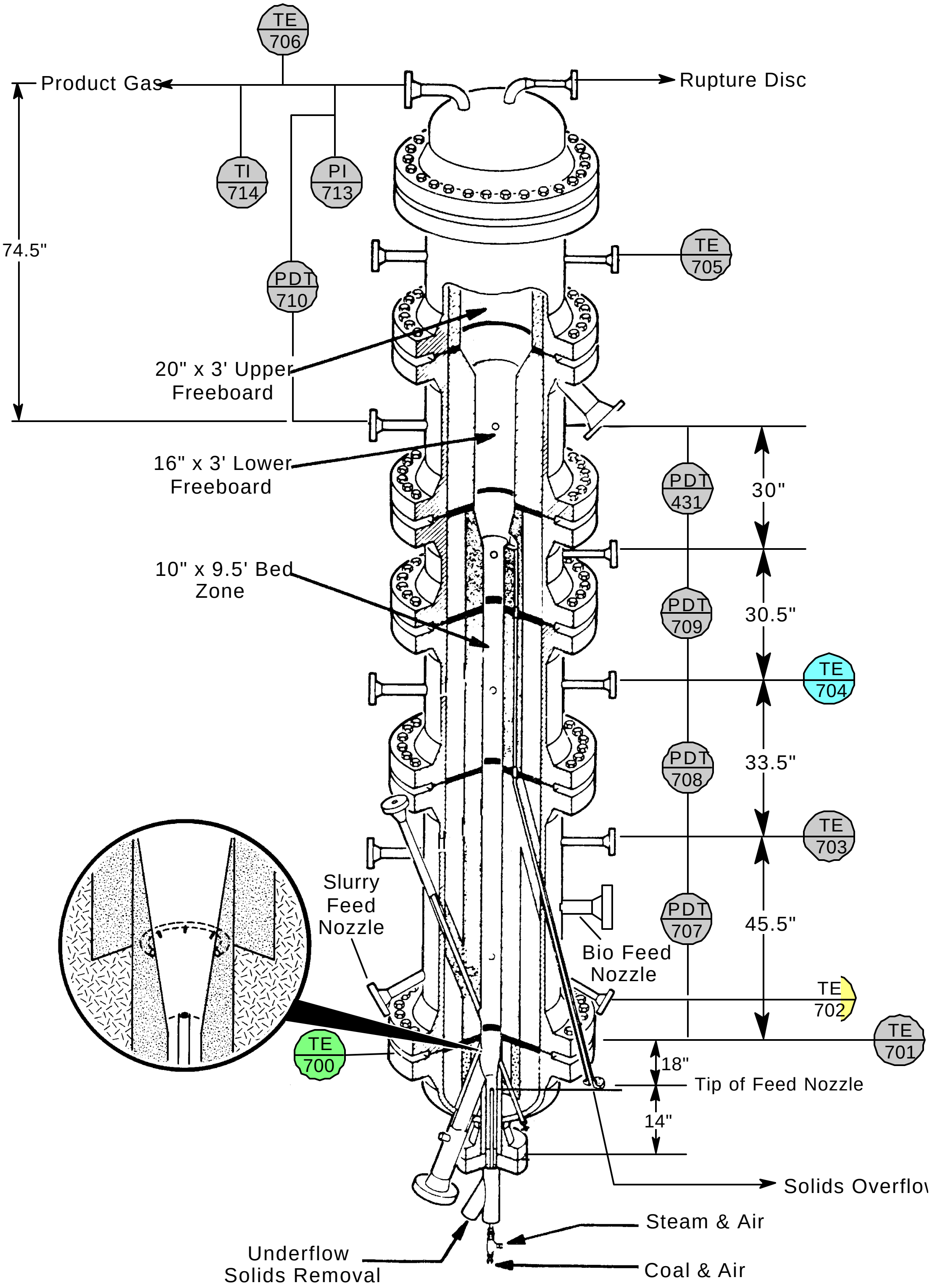

Figure 2. FBG/C Thermocouple and Differential Pressure Tap Locations

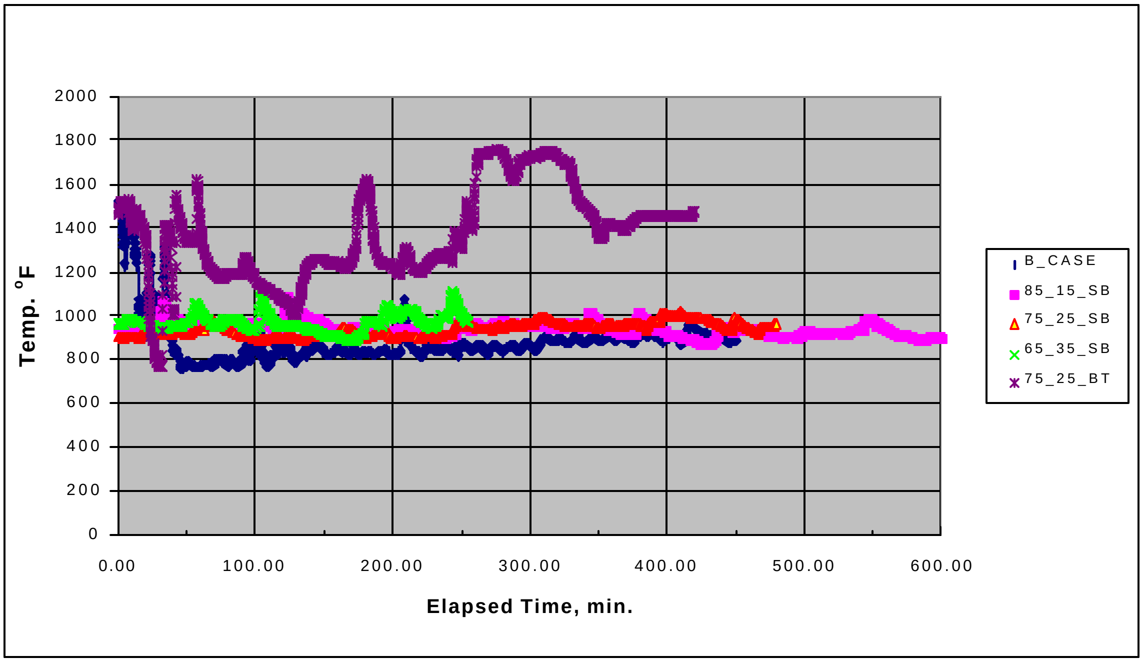

Figure 3. Comparison of TE-700

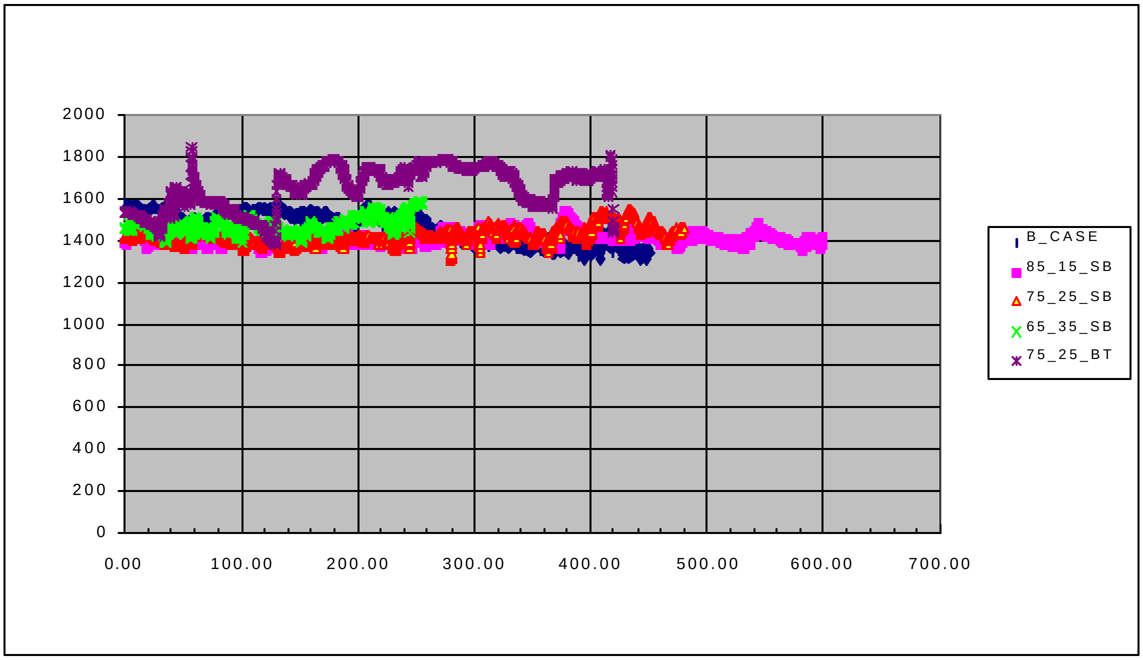

Figure 4. Comparison of TE-701

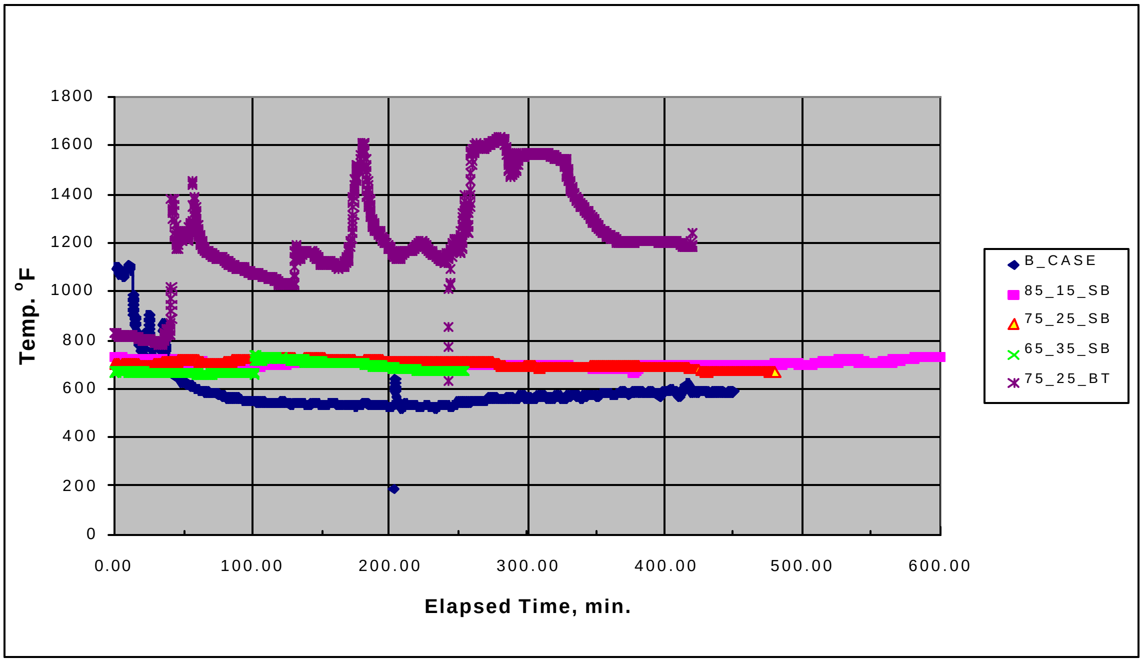

Figure 5. Comparison of TE-733

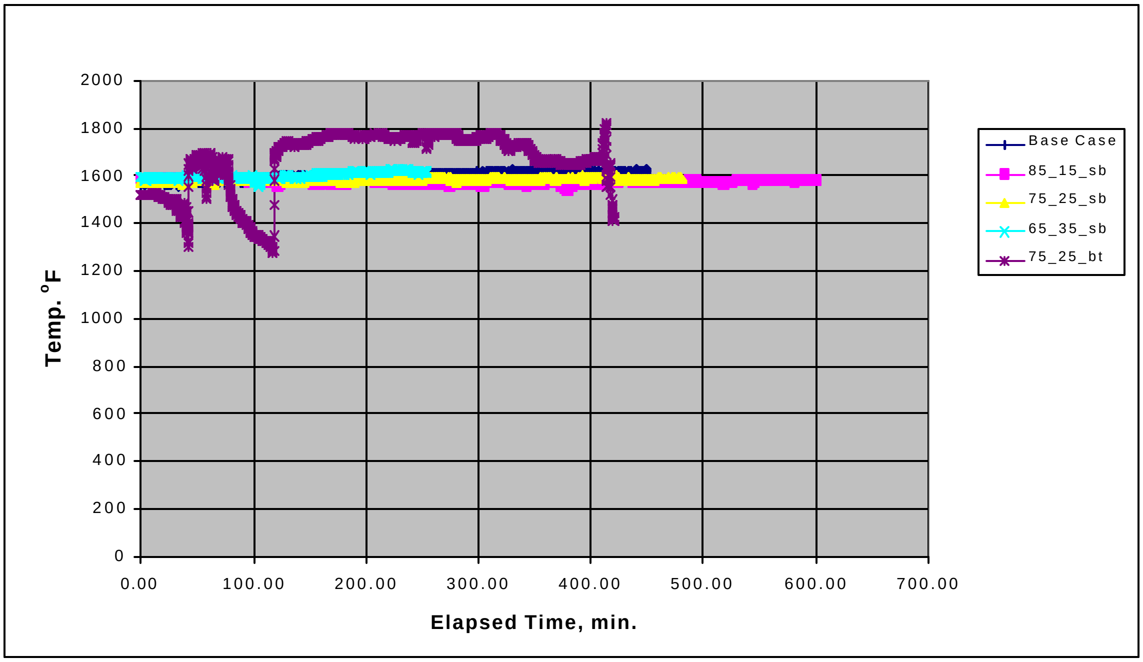

Figure 6. Comparison of TE-702

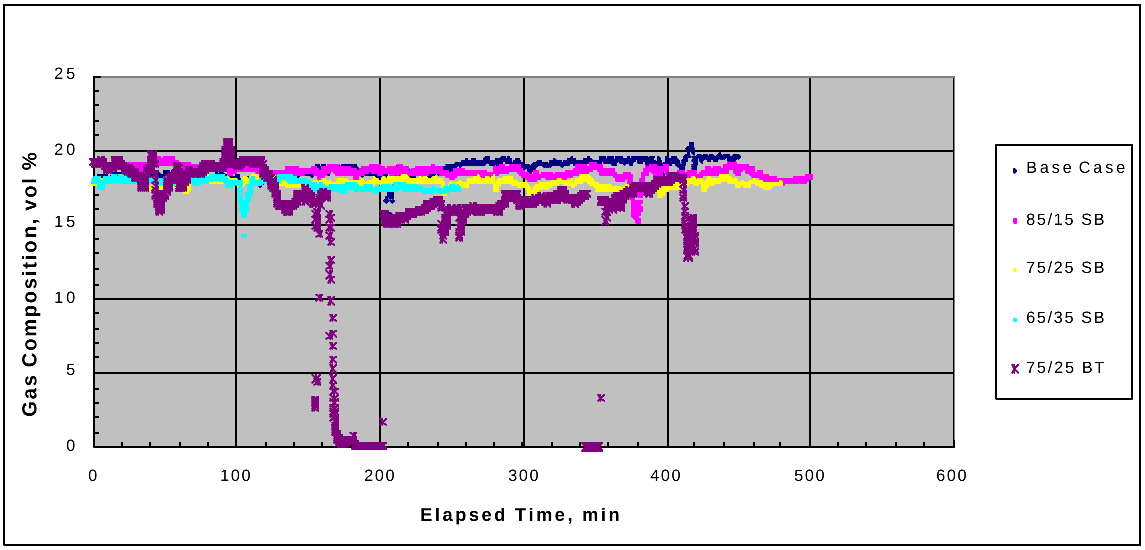

Figure 7. H_2 Comparison

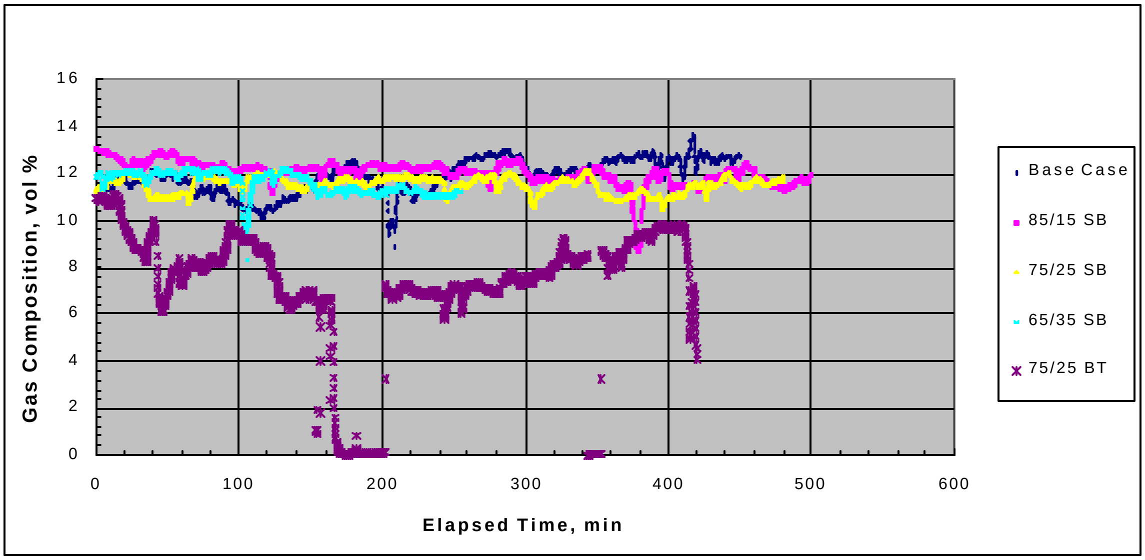

Figure 8. CO Comparison

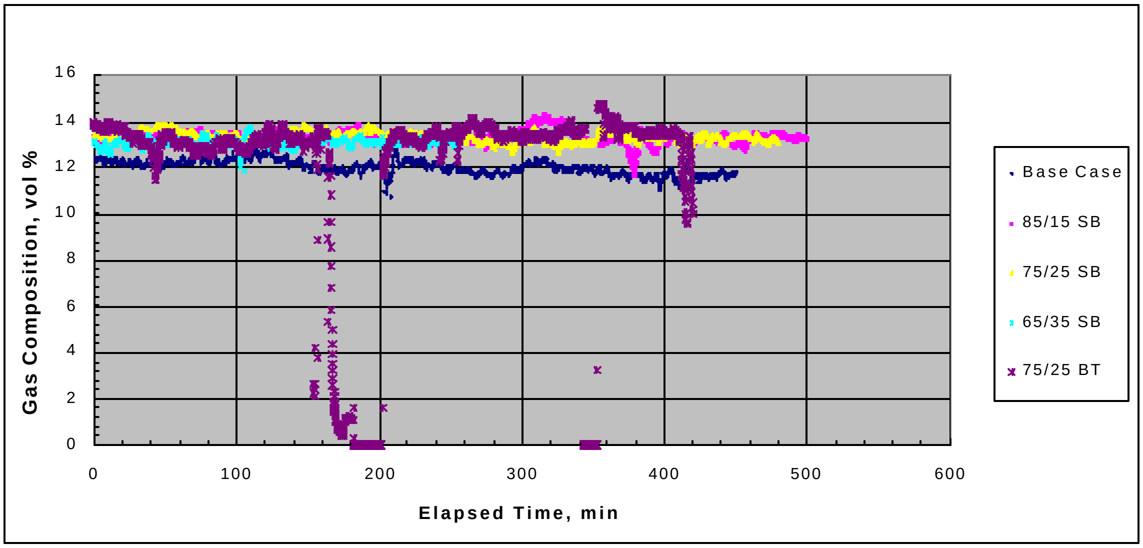

Figure 9. CO_2 Comparison

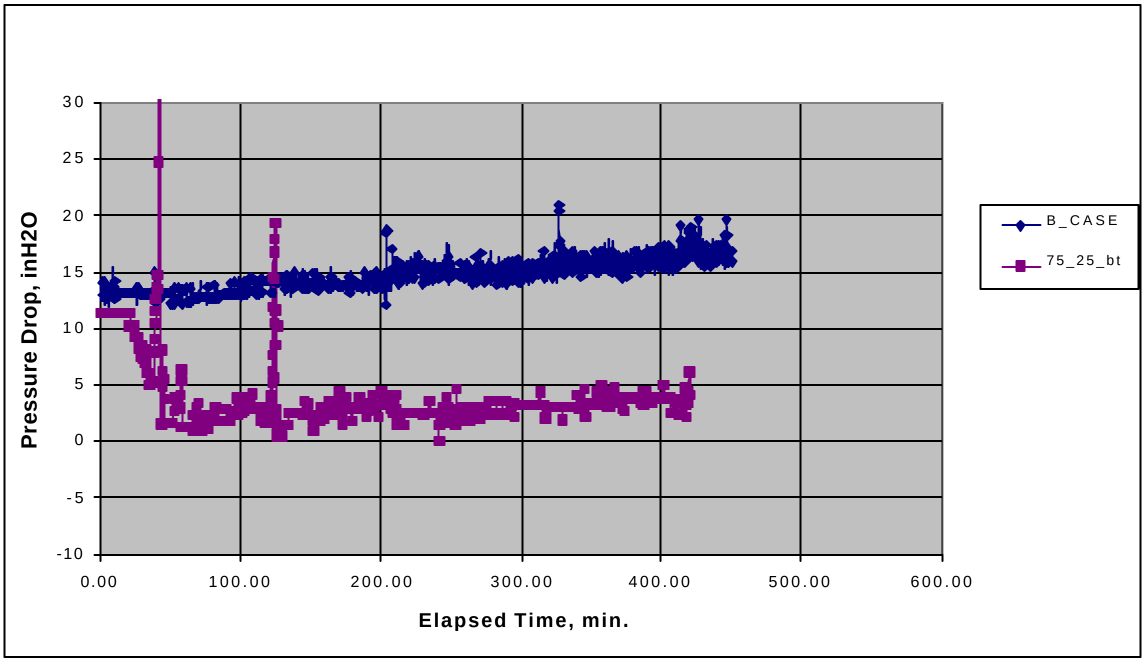

Figure 10. Comparison of PDT-707

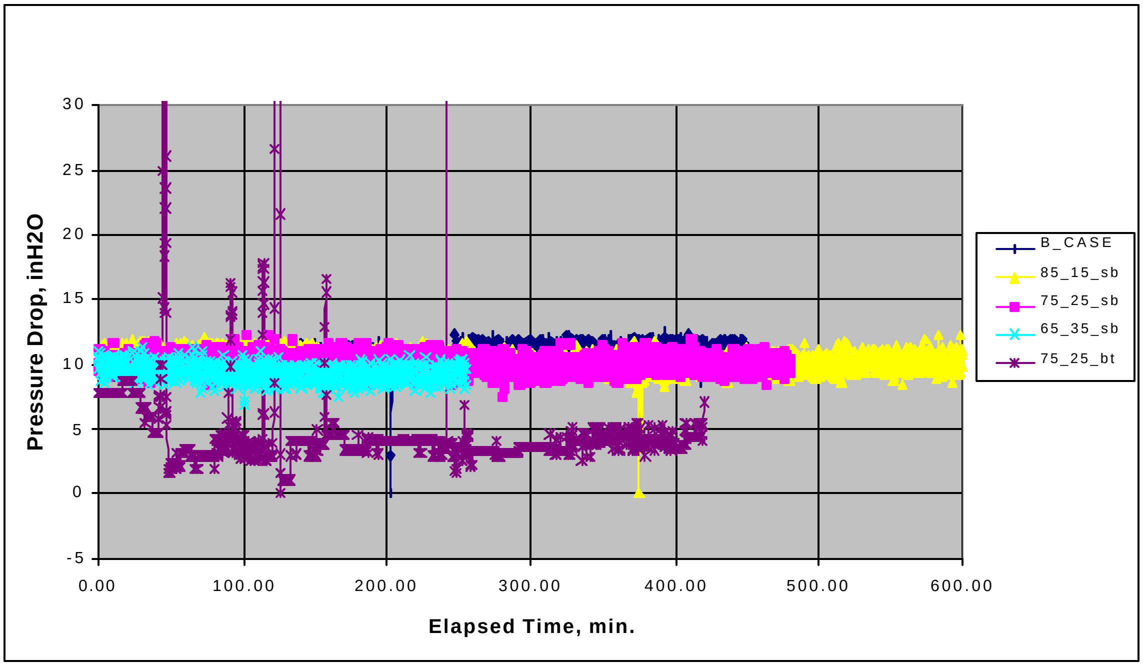

Figure 11. Comparison of PDT-708

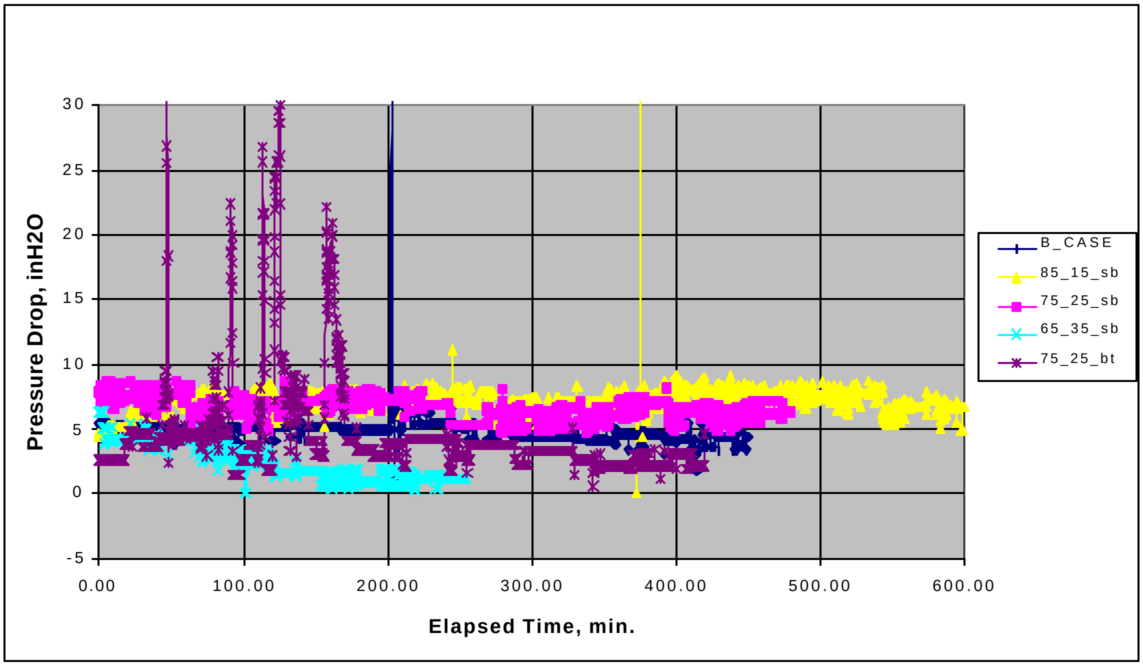

Figure 12. Comparison of PDT-709