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Asphalt DSR prediction and control

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Much has been written about crude column product separation by APC (advanced process control) but very little about vacuum column APC. Why? VDU (vacuum distillation unit) separation is important, especially in asphalt mode, when vacuum pitch is sold as a premium product, and controlling asphalt quality is high on the list of economic priorities. Our guess is that such APC applications have not been reported because of inability to infer asphalt qualities, and without such inference vacuum column APC would not be effective. Recently we had the opportunity to set up asphalt quality inferential models at two refineries, and this paper describes the inferential techniques and shares the inferential performance data. The refineries have agreed to this publication but requested anonymity. Hence we call them refinery A and refinery B; both are located in North America.

Refinery A is a land-locked refinery and throughput is limited by asphalt sales. The product grades vary from shingles to road asphalts. Refinery B runs mostly road asphalt by blocks and only from certain crudes. In summer asphalt is the most lucrative refinery B product.

Asphalt quality is typically measured by the DSR (Dynamic Shear Rheometer) apparatus, where the number reported as G*/sine(delta) is a measure of viscosity at a given temperature. Our DSR inference relies on the knowledge that asphalt viscosity correlates with average boiling point and density. The average asphalt boiling point is estimated from column measurements, but for density we need the aid of a density analyzer. Without online density measurement DSR inference is not plausible.

Refinery A had installed a density meter and developed asphalt DSR inference several years ago but the model was less than perfect. It would predict OK for a few days, and then suddenly would have to be biased substantially, even when the crude had not changed. That had caught us by surprise. What was going on here? Operation has not changed much but the lab test is suddenly showing a different value? The fog lifted when upon studying the DSR test we realized it is carried out at several defined temperatures of 46, 52, 58, 64 or 70 ºC, the specific test temperature being a part of the asphalt grade specifications. During asphalt runs the schedulers switch grades often, and then indeed, carried out at a different temperature the lab test would yield a different result. The operator, not being aware of the change of DSR test temperature, views the sudden lab – inference discrepancy as a sign of problematic inference and turns off the APC.

The vacuum column configuration

Figure 1 shows a typical vacuum column configuration. Reduced crude feed comes from the atmospheric crude column through a furnace and into the flash zone. There are two distillate products: LVGO (light vacuum gasoil) and HVGO (heavy vacuum gasoil). LVGO is diesel range material, going into the diesel pool. HVGO is FCC or hydrocracker feedstock. There is a possibility to also draw vacuum wax, though normally wax is circulated back to the furnace to improve the separation. As is common in vacuum column designs, the draws are from total draw trays. Part of the draw is pumped around through heat exchangers to cool the column, another part is pumped down as reflux, and a third part is taken out as product.

Density measurement

As shown in figure 1, due to density meter temperature limitation asphalt is cooled to a temperature of about 420-470 ºF before being measured. Density is a function of temperature and we need to correct the raw density reading to a standard temperature of 60 ºF before using it in out DSR correlation. The laboratory also measures asphalt density at 60 ºF, and that permits comparison of the analyzer corrected density against lab values. Figure 2 is a six months trend of density related measurements. The orange line is raw density as measured online (VBAPI_A). The magenta line is the density meter temperature (TVDEN) on the right hand scale. The blue line is our correction of the density meter to 60 ºF (VBAPI_M), and the green squares are lab tests of asphalt density (APIVB_L). The corrected density meter reading more or less trends with lab density though that agreement is not perfect. One might expect slow drifts and a need to occasionally bias the density reading and/or DSR correlation.

The GCC inferential package

GCC (generalized cut-point calculations) is a well established inferential package for wide cut fractionators such as CDU (crude distillation unit) and VDU. GCC uses column measurements to first identify the TBP (true boiling point) curve for the feed, and then it estimates product cut-points. Being a first-principles based model GCC has performed better than other methods, and in addition it has the ability to infer cut-points during crude switches. Several GCC related papers have been published [for example 1, 2, 3, 4, 5, 6, 7], and it is not the object of this paper to cover additional GCC sites beyond saying that HVGO cut-point is predicted well. That is important for the asphalt inference because HVGO back end cut-point is identical to asphalt front end cut-point. Figure 3 is a one year trend of HVGO 98% point inference model (HVG98_M) against lab tests (HVG98_L). HVGO98% is predicted from HVGO cut-point, and the high fidelity of this prediction indicates that the HVGO cut-point is well estimated. That trend is for refinery A. We cannot show the equivalent refinery B trend because refinery B does not test the HVGO distillation curve.

Is the front end asphalt cut-point good enough for this inference? Viscosity is after all a function of asphalt average boiling point. In calculating asphalt average boiling point our model assumes the asphalt effective back end cut-point to be 800 ºC. Given that asphalt effective endpoint is indeed around 800 ºC the magnitude of crude to crude inferential variation is fairly small.

DSR modeling

There is a way to consider DSR lab tests carried out not only at one temperature in isolation but also at other test temperatures. Given the sensitivity of viscosity to temperature, there is a certain temperature called TE, such that if the DSR test were to be carried out at TE the test result would have a value of precisely 1.00 KPA. The DSR – temperature model we are using is:

$$LN[G^*/\text{sine(delta)test}] = B * [1/TE - 1/Ttest] \qquad [1]$$

Where Ttest is the test temperature in ºK and G*/sine(delta)test is the DSR outcome of that test.

With knowledge of coefficient B, equation 1 permits calculation of TE from DSR test result at any temperature. Refinery A tests the same asphalt sample at different temperatures and for a given test sample the TEs calculated from test results at different temperatures should be identical. Thus, even if the viscosity – temperature relation is not precisely known the many lab tests at different temperatures give us the opportunity to calibrate the temperature influence.

Figure 4 tests this concept, covering 20 days of TE calculations. The lab tested samples at 46 (TE46_L), 52 (TE52_L), 58 (TE58_L) and 64 (TE64_L) ºC. The reported DSR results are very different at each temperature because viscosity is quite sensitive to temperature, but the calculated TE values co-inside within half a degree. The fifth green square lab value in figure 4 (DSR_L) is a laboratory calculation of TE based on interpolation among the several test results. Finally the blue trend of figure 4 is a TE inference as a function of VGO cut-point and asphalt density readings. While not perfect, this inference tracks the lab well and can reliably be used for control.

DSR inferential performance

Figure 5 illustrates refinery A inferential model performance over the same 20 days compared to lab data at 58ºC test temperature. The blue line and orange squares of figure 5 are trends of DSR inference and DSR lab test, both at 58ºC. The blue line inputs are shown in brown and green. Brown is the asphalt density measurement after temperature correction to 60ºF. Green is HVGO cut-point inferred by GCC (right scale), ºC. API and cut-point often trend as mirror image, where the gravity changes as a result of cut-point change, but the mirror image is not perfect because gravity can also change with crude type, and refinery A continuously changes the crude mix.

Figure 6 is a typical refinery B five day trend. Referring to the right hand scale, the orange diamonds are DSR test temperatures, the red triangles are temperature TE, calculated from the lab DSR test result data whereas the heavy purple line is our TE inference. On the left hand scale, green squares are DSR test results, and finally the blue line is our DSR inference as calculated from our TE model and lab test temperature.

DSR control performance at refinery B

The complexity of refinery B MVPC (multi-variable predictive controller) is beyond the scope of this paper. Suffices to say that there are many product quality inferences, as well as many constraints, and the MVPC manipulates both the atmospheric crude column and vacuum column together. Changes in the crude column affect asphalt quality and to achieve the desired DSR both AGO (atmospheric gasoil) and HVGO draw must be manipulated. AGO is the lowest draw of the atmospheric column and changes of AGO affect vacuum column feed and asphalt quality. Figure 7 is a five day trend illustrating how DSR control is accomplished. During these five days several grade switches took place. DSR inference is shown in green, which compares well against lab DSR test results in red diamonds. Upon grade switches both the inference and lab result jump, not because of any process change but simply because of the change of test temperature. The TE value itself actually does not change until column conditions change. Anyway, upon that inference jump the APC controller reacts quickly, changing the main manipulated variable: AGO draw (orange) and HVGO hot reflux (blue), bringing DSR to target. Vacuum diesel draw is shown in magenta. It often moves as mirror image of AGO, but that mirror image is not perfect, indicating that other changes have occurred, for example crude quality drift due to a non-uniform crude tank.

Conclusions

We have demonstrated that with knowledge of HVGO cut-point and asphalt density one can infer asphalt DSR. In our case HVGO cut-point is a GCC inference whereas the density is measured by an on-stream analyzer. Our inferential procedure involves the following steps.

1. Obtain an inferential estimate of HVGO cut-point, a GCC model calculation
2. Obtain a current asphalt density reading and asphalt analyzer temperature
3. correct the analyzer density reading to 60ºF
4. Estimate TE, the temperature at which asphalt DSR would be precisely 1.00 KPA
5. Obtain the lab DSR test temperature appropriate for the asphalt grade
6. Use equation 1 to convert TE into G*/sine(delta) at the test temperature

While this procedure is not trivial we have shown that good inferential precision is achievable.

Further we have integrated the DSR inference into a large MVPC, manipulating both the crude and vacuum columns. In addition to controlling all distillate properties at targets, subject to equipment constraints, we have also achieved effective control of asphalt DSR. Asphalt is one of the most profitable refinery products and its precise quality control has a value of several million dollars annually.

GCC Literature

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Figure 1. Vacuum column configuration

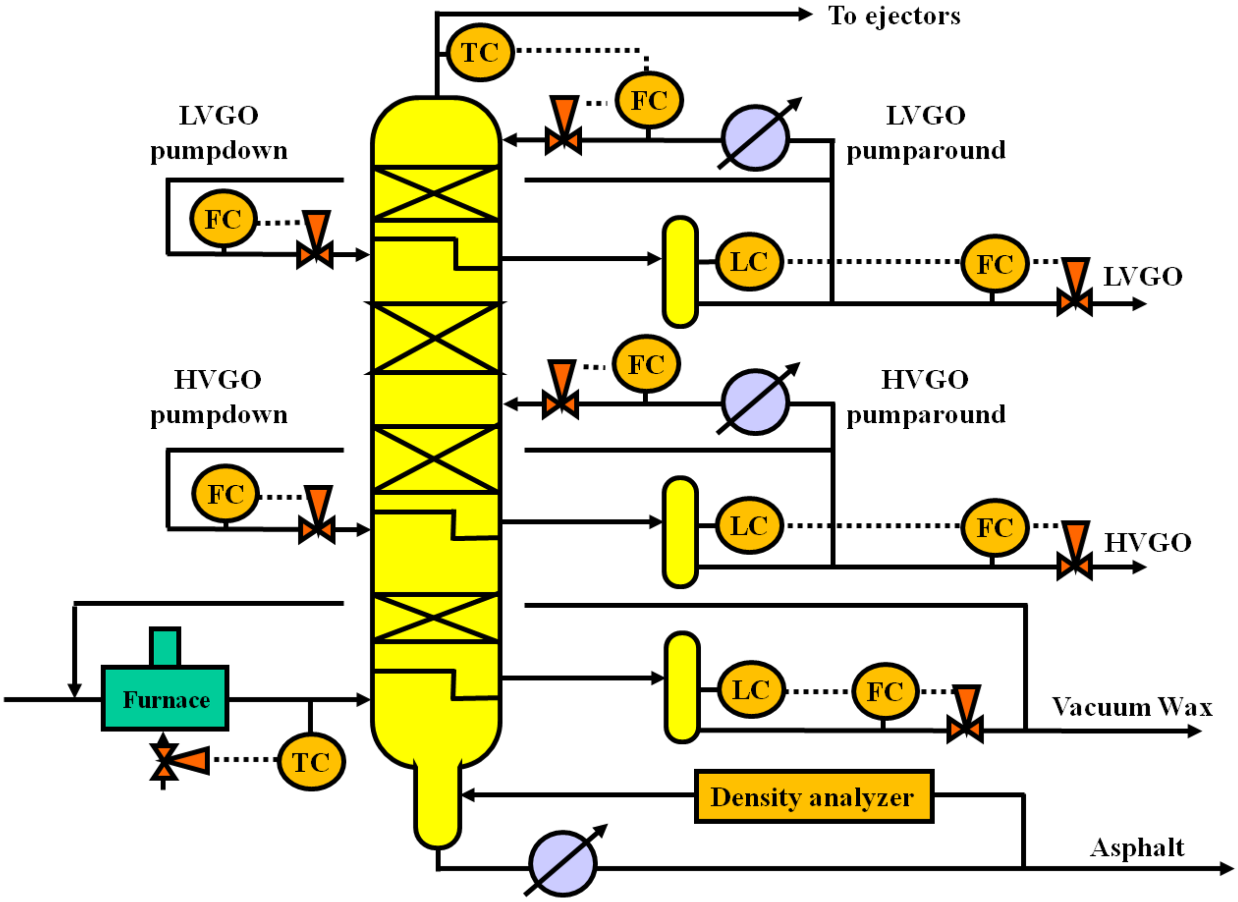


Figure 2. Correction of asphalt density from instrument temperature to 60 ºF

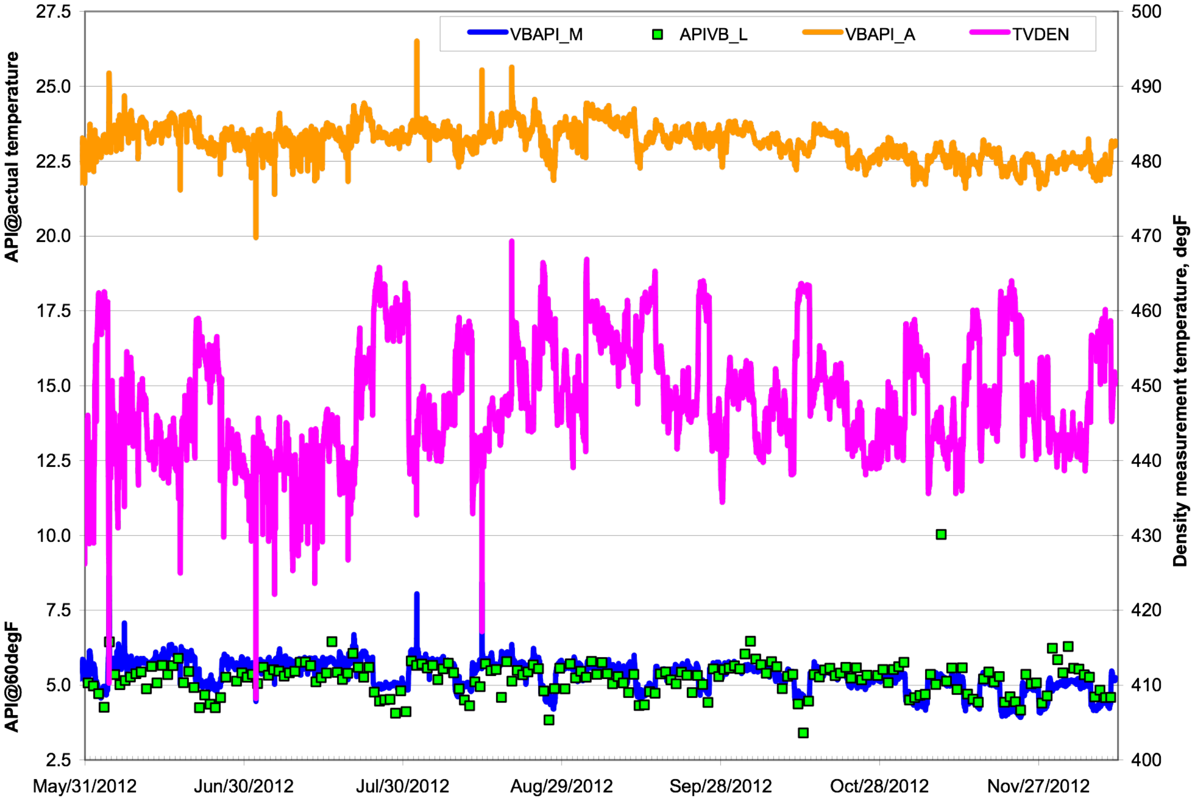


Figure 3. Inference of VGO 98% point for one year compared against lab data at refinery A

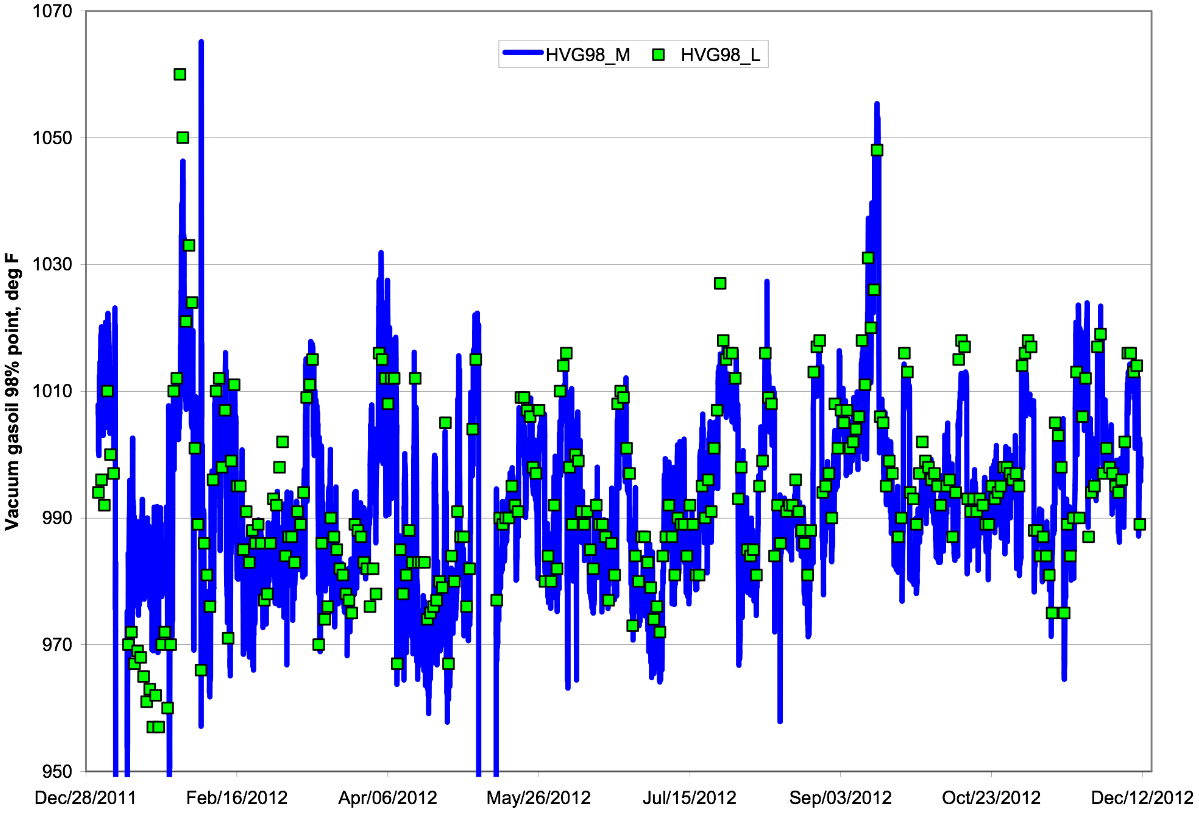


Figure 4. Refinery A inference of TE (temperature at which DSR would be 1.00 KPA) versus lab results

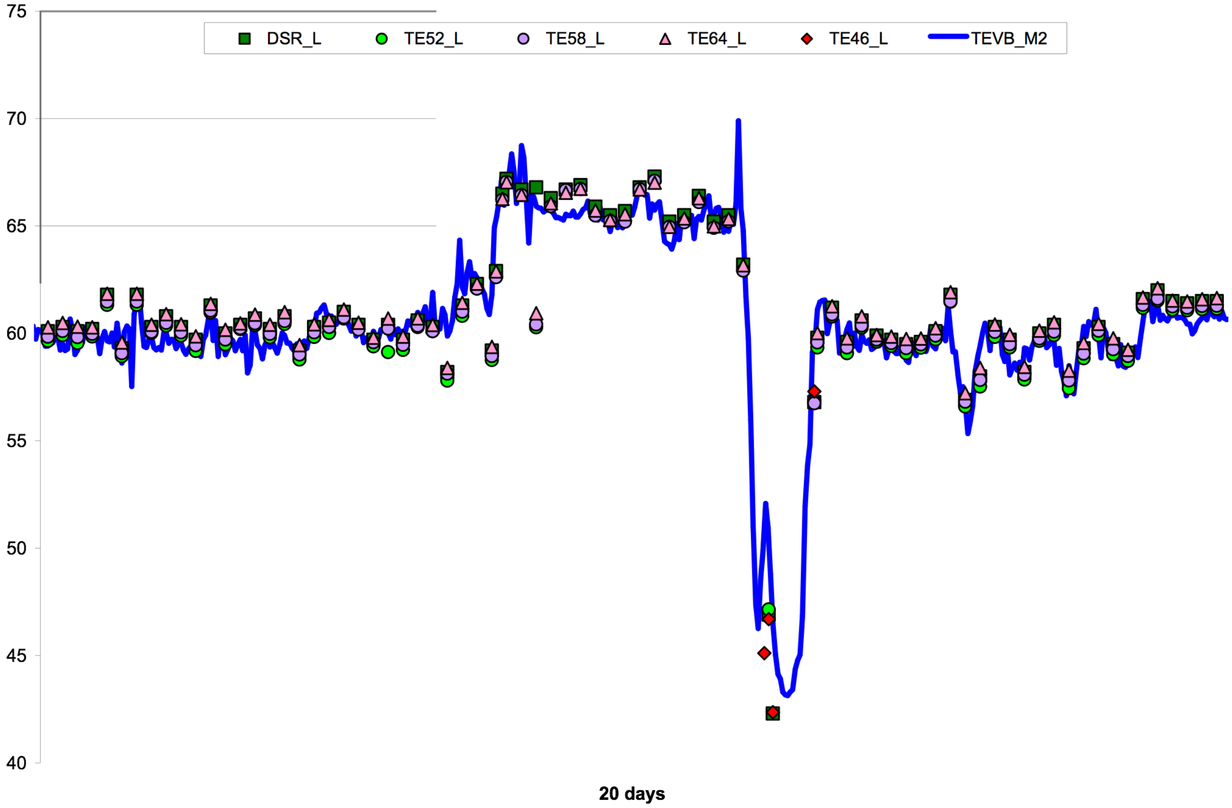


Figure 5. Refinery A inference of G*/sine(delta) @ 58 ºC

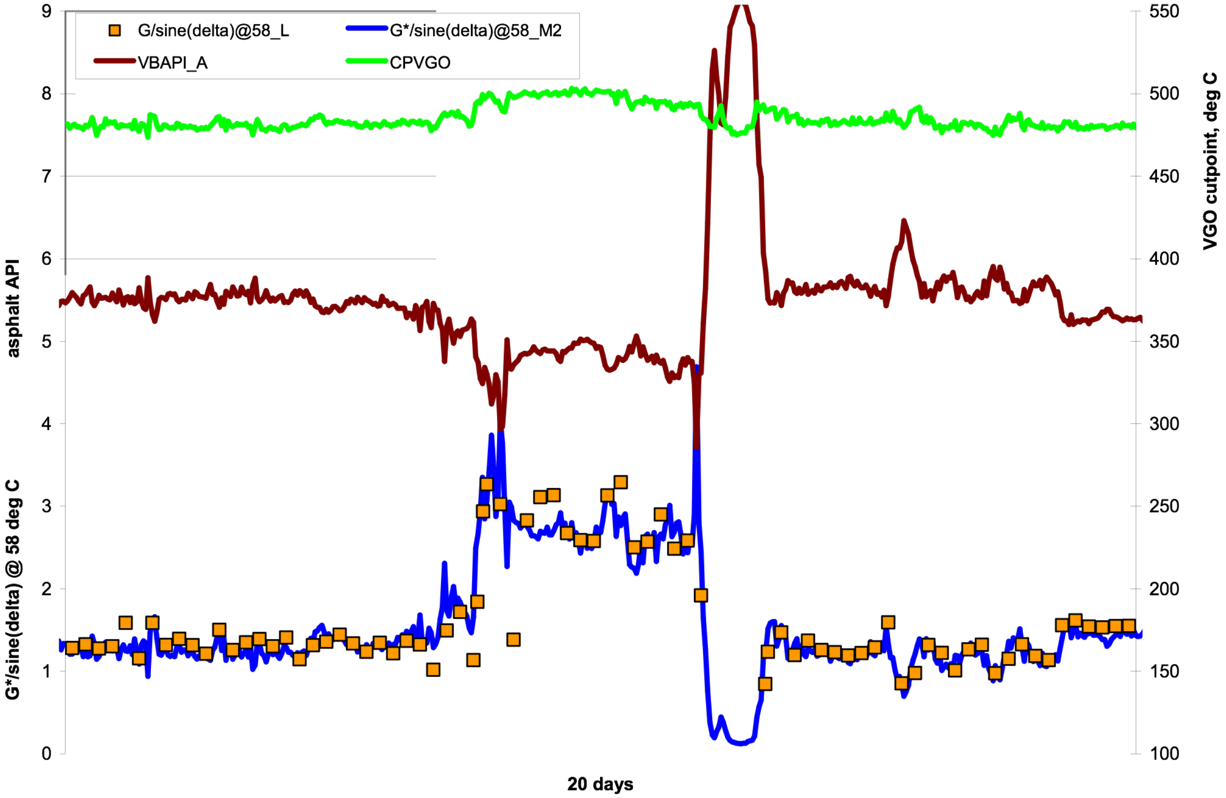


Figure 6. Refinery B inference of TE and DSR

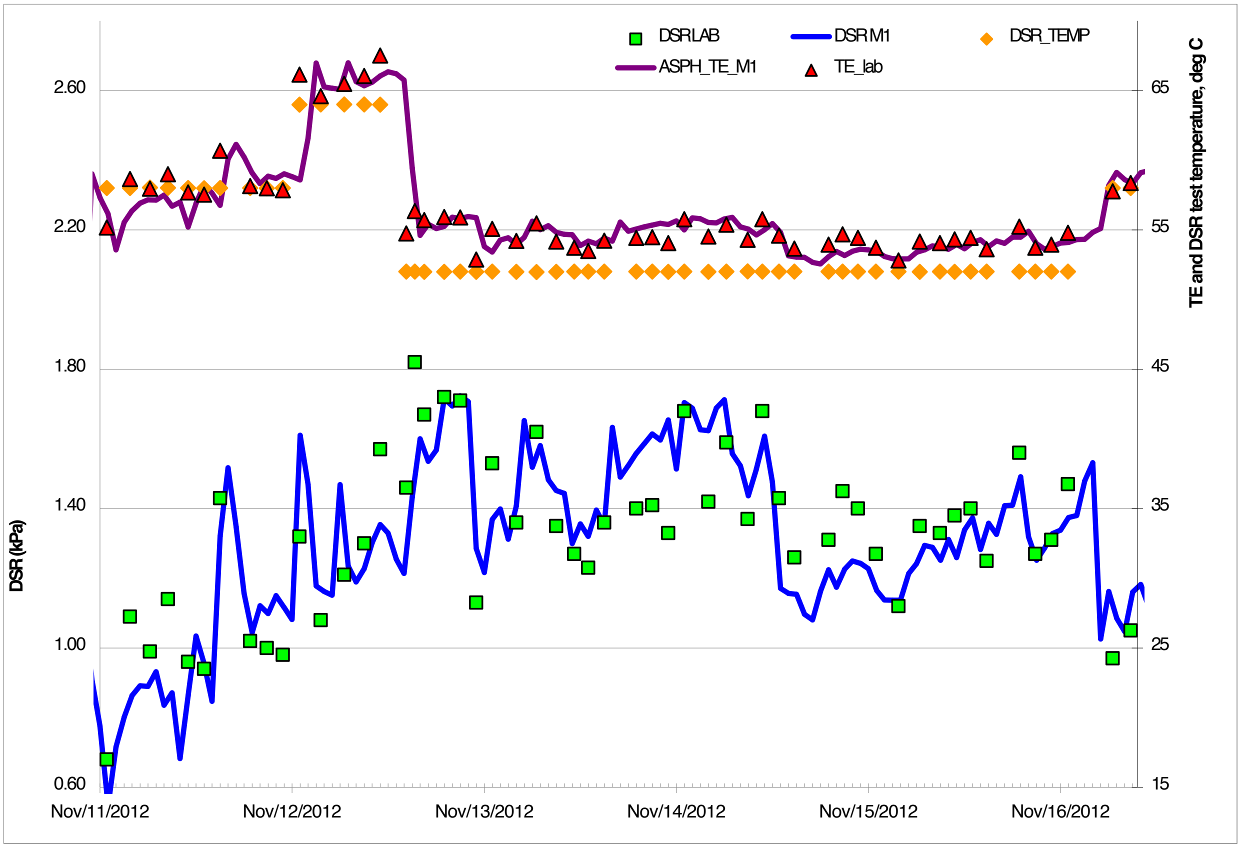
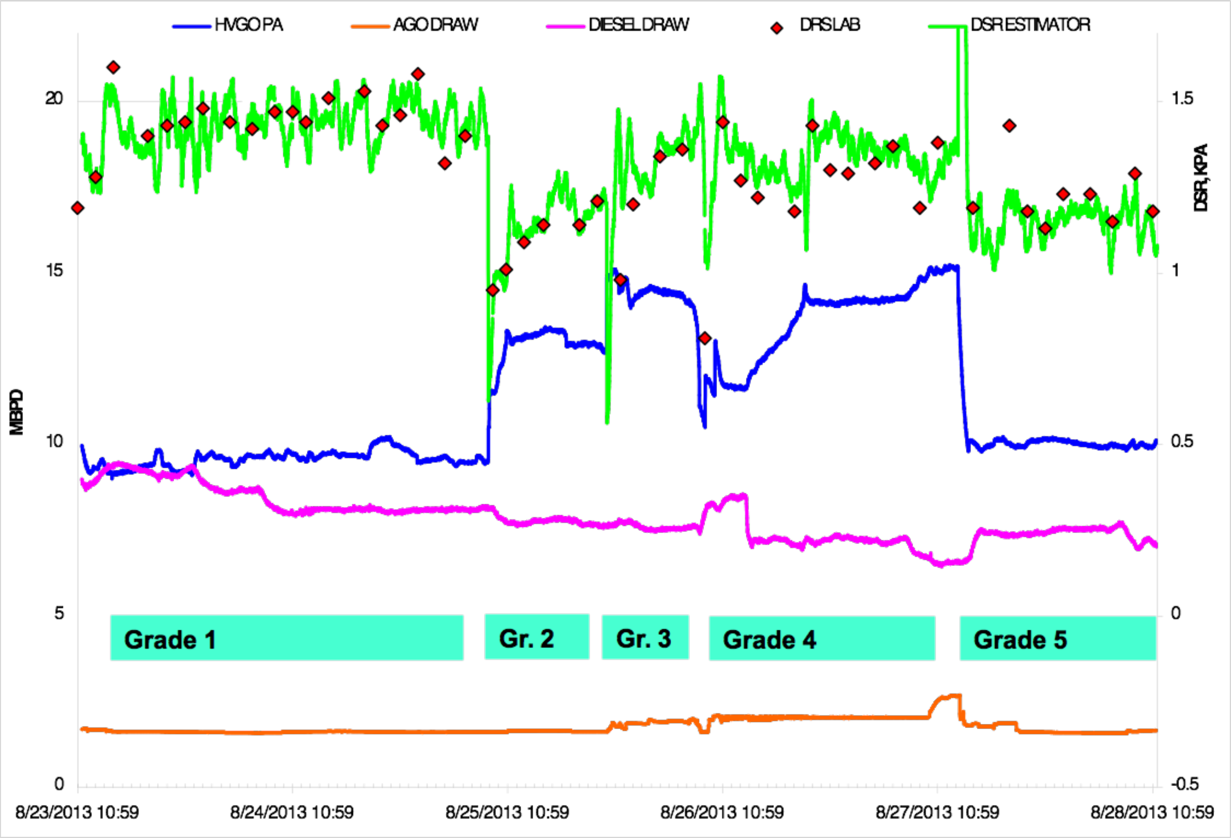


Figure 7. Refinery B DSR control trend


HVGO PA
AGO DRAW
DIESEL DRAW
DRS LAB
DSR ESTIMATOR
MBPD
DSR, KPA
20
15
10
5
0
1.5
1
0.5
0
-0.5
Grade 1
Gr. 2
Gr. 3
Grade 4
Grade 5
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