

FEED CHARACTERIZATION AND DEEPCUT VACUUM COLUMNS: SIMULATION AND DESIGN

Impact of High Temperature Simulated Distillation

Scott W. Golden

Glitsch, Inc.
4900 Singleton Boulevard
Dallas, TX 75212

Dan C. Villalanti

Triton Analytics Corp.
16840 Barker Springs #302
Houston, TX 77084

Gary R. Martin

Consultant
712 Canyon Ridge Drive
Euless, TX 76040

Presented at the
AIChE 1994 Spring National Meeting
Atlanta, Georgia, April 18-20, 1994

Session on Modeling of Petroleum and Petrochemical Process I:
Steady-state Plant Simulation, Optimization and Analysis

Paper 47a

Copyright © S.W. Golden, D.C. Villalanti, and G.R. Martin, April 1994

SUMMARY

The recent petroleum refinery industry trends toward deepcut crude vacuum column revamps have resulted in several units that have not met their product recovery and operating objectives. Deepcut revamps recover the highest boiling range vacuum gas oil recoverable by conventional distillation.¹ Most of these designs were based on standard refinery laboratory distillation tests (ASTM D1160 or D2892)^{2,3} and extrapolated 1000° + F degree distillation data. In some cases, the units have had operating problems that required shut-downs to modify the column equipment. Poor vacuum column feed characterization⁴ as well as inadequate column modeling techniques caused these problems.

The vacuum column feed distillation shown in Figure 1 can be improved by using gas chromatographic ASTM D2887⁵ and high-temperature simulated distillations (HTSD). The critical laboratory analytical advances have been in the development of HTSD gas chromatography.

High Temperature Simulated Distillation (HTSD) is a relatively new method that basically extends method ASTM D2887 determination of the boiling range distribution of

hydrocarbons to a final boiling point of about 1400°F. By using recent advances in capillary GC column and stationary phase technologies, together with either programmed temperature vaporization (PTV) or on-column injection techniques, adequate separation from C₅ to C₂₀ normal paraffins allows characterization of petroleum products from about 97°F to 1380°F.

The simulated distillations improve the accuracy of heavy oil TBP distillation curve accuracy over conventional tests or extrapolation. The TBP curve is used to generate the individual pseudocomponent normal boiling point (NBP). The NBP is used in conjunction with one of the generalized K-value correlations like Grayson-Streed or BK-10 to calculate vacuum column flash zone vaporization.

Deepcut vacuum unit modifications improve gas oil yield. The higher vacuum gas oil yield associated with deepcut improves refinery margins. The amount of additional gas oil is a function of the processing conditions and the quantity of recoverable gas oil in the feed. Improved distillation data from the ASTM D2887 and the HTSD method in conjunction with nontraditional simulation techniques allows the standard commercial process flow sheet

distillation models to better match the measured plant operating data from deepcut projects. Using improved analytical techniques will improve heavy vacuum gas oil yield prediction and the prediction of process design stream flows.

With an accurate computer model the prediction of the high cutpoint vacuum column design is possible. An example of a deepcut unit designed with the standard methods, D-2892 true boiling point (TBP) distillation will be presented in the first case study. A second case study shows a deepcut design using HTSD data as well as modeling techniques that are a modification to the conventional methods. Vacuum crude units ideally have 4- to 5-year run lengths. Operating reliability cannot be ignored.

DEEPCUT

The term deepcut vacuum column operation has no standard definition, and one refiner's deepcut operation is another's typical operation. The authors' definition of deepcut is a heavy vacuum gas oil (HVGO) TBP cutpoint of 1100+ °F degrees on a light crude and 1050+ °F on high-metals Venezuelan type crude oil. More than one definition of HVGO cutpoint is used in the industry.⁶ One definition uses the ASTM D1160 distillation data converted to TBP distillation data^{7, 8} of the HVGO and vacuum residue streams to calculate the cutpoint. This definition is inadequate for high cutpoints, and it predicts different cutpoints for two different types⁹ of crude vacuum column operations yielding an equivalent vacuum residue yield. Here, the HVGO TBP cutpoint is defined as the temperature on the whole crude TBP curve (Figure 2) that corresponds to the cumulative distillate yield.

TBP DISTILLATION

Accurate feed characterization is essential to deepcut vacuum column design. The selection of the correct laboratory techniques for a particular stream analysis is necessary prior to a controlled plant test run. There are standard laboratory techniques for day-to-day control of the refinery operations. These are not adequate for deepcut vacuum column revamps. The modern laboratory analytical techniques of simulated distillation by gas chromatography produces high-temperature distillation data; however, these techniques require diligence in laboratory quality control.

Standard laboratory distillation tests

The standard refinery distillation test on the vacuum column products and feed is an ASTM D1160 distillation. An ASTM D2892 can also be used to generate the vacuum column product and feed distillations. A few refiners use ASTM D2887 simulated distillations which are limited to material boiling below 1000°F at atmospheric pressure. There are some refiners performing HTSD, but many refiners have outside laboratories run simulated distillations on an as-needed basis. Ultimately the data from these tests, in conjunction with the unit material balance, is used to characterize the vacuum column feed.

The maximum distilling flask temperature of any of the

laboratory distillation analyses is limited to the temperature at which the oil begins to crack. Cracking temperature is crude-oil dependent; however, some oil cracking generally begins around 680-700°F. The heaviest oil must be distilled under an absolute pressure of 2 mmHG or less. Therefore, the oil characterized by the distillation tests has a maximum boiling point of approximately 1050°F at atmospheric pressure. On some crude oils, the maximum temperature (converted to atmospheric pressure) is 1000°F or less, due to oil cracking, and as high as 1070°F on some stable crude oils. Material boiling above the cracking temperature is not characterized correctly and the recorded temperatures do not reflect the actual temperature of the oil at the volume percent recorded.

Unless the ASTM test procedures are rigorously followed and the laboratory equipment and procedures meet the test standards, the results from the test will be inconsistent. The conversion technique from vacuum to atmospheric is also a source of error. These conversions will lose accuracy unless the test is run at 2, 10, or 100 mmHG.

As noted in method ASTM D2887, the boiling range distribution obtained from GC simulated distillation is essentially equivalent to those obtained by true boiling point (TBP) distillation (i.e., method ASTM D2892). The less efficient (one plate) laboratory distillation methods—ASTM D86 and ASTM D1160—are not equivalent to TBP and GC simulated distillation. In addition, the generation of reliable data using the physical distillation methods, especially at higher temperatures, requires careful operation, significant time and cost, and experienced operators. For these reasons, HTSD can offer significant improvements in precision, turnaround time, and cost.

HIGH TEMPERATURE SIMULATED DISTILLATION (HTSD)

As mentioned in the summary section, HTSD is basically an extension of ASTM method D2887 for the boiling range distribution of hydrocarbons by GC. By proper choice of GC conditions and equipment, separation from C₅ to C₁₂₀ n-paraffins is routinely done to calibrate the GC elution time to the atmospheric equivalent boiling point (AEBP) of the paraffin (as described in API Project 44).

To accomplish the goal of eluting heavy materials up to the equivalent of C₁₂₀ at or below the maximum column temperature requires a careful choice of chromatographic conditions, the most important of which is the stationary phase film thickness. Typical films used in the HTSD vary from 0.05 to 0.15 micron. The resulting phase ratio (volume of the column versus volume of the stationary phase) commonly exceeds 1000 for a 0.53 mm I.D. capillary column. This high phase ratio permits the elution of materials from the column at up to 500-600°F below their AEBP. For instance, the elution of C₁₁₀ n-paraffin (B.P. 1351°F) occurs at about 800°F column temperature.

A consequence of the conditions necessary for HTSD is a limited concentration capacity of the column due to the small amount of stationary phase. This requires appropriate dilution of the standards and samples (usually in CS₂). A condition of accurate HTSD data is careful operator evaluation of the system performance due to loss of

stationary phase at high temperature (i.e., resulting in loss of film and sample capacity) and the unavoidable buildup from residue containing samples of nonvolatile materials such as metals, asphaltenes, etc. in the injector and column.

Because of the highly inert conditions of high purity fused silica GC columns, the gentle injection techniques, and the short time at maximum temperatures, little or no evidence of cracking is normally seen in HTSD.

Because of the column breakdown (bleed) during the final portion of an HTSD analysis and the need to dilute the sample to approximately 1-2%, a blank GC run using only the solvent is recorded in the data system. This solvent blank run is then subtracted from all subsequent runs. This blank subtraction accomplishes two important goals: 1) it removes the signal present from the solvent (which could deter from an accurate light end determination) and 2) the column bleed is compensated. The assumption during this process is that the solvent blank and the column bleed profiles are constant during the calibration and sample analyses. It is the HTSD operator's duty to verify this to meet the criteria for statistically meaningful results.

The final step in HTSD calibration is the analysis of a reference oil that has been physically distilled by method ASTM D2892 (TBP). The HTSD analysis results are compared to the TBP results and a statistical analysis of the difference determines if the HTSD is in specification.

Quality control and quality assurance for HTSD

As in any analytical method, the statistical analysis of quality control sample is essential in determining the accuracy and precision of the method. In the case of HTSD, Triton currently uses about five different types of samples which represent closely the type of samples that our clients submit. These include:

- Lube feed stocks
- Heavy California crude
- Hydrotreated residue
- Gulf of Mexico crude
- Blend of physically distilled gas oils.

After 10-15 HTSD analyses have been gathered on each sample, the mean and standard deviation of the temperature vs. percent off, or the amount off at a specified temperature, is determined. Using an X-type control chart, any excursions beyond ± 2 or 3 standard deviation limits will signal an out-of-control range method. Appropriate maintenance and corrective action is triggered before a refinery sample is reported.

FEED CHARACTERIZATION

A petroleum refinery feeds atmospheric residue to the vacuum column where most 650°F minus boiling range material is removed by the atmospheric distillation. The atmospheric residue is composed of an undefined mixture with components boiling between 400-2000+ °F, in the case of some heavy crudes. Historically, crude oil distillation curves have been generated via an ASTM D-2892 TBP procedure or by blending the product streams characterized by standard refinery analytical laboratory tests of ASTM D86 and D1160. In the last few years refiners have begun to use

simulated distillations. One of the above methods is used to produce the TBP curve from which the pseudocomponents are derived.

Pseudocomponent breakdown

The pseudocomponent breakdown of a complex mixture of hydrocarbons¹⁰ requires the atmospheric residue be “cut up” into components whose physical properties can be estimated by one of several techniques. The distillation test methods all have some limitations resulting from both the test method limits and the complex nature of the hydrocarbon mixture. Crude oil—and more specifically the heavy end of the crude—contains complex mixtures of aromatics, long-chain paraffins, large naphthenic compounds, and sulfur- and nitrogen-containing compounds.

Accurate TBP distillation is required to properly assess the following aspects of deepcut vacuum column revamps:

- Project economics - Gas oil yield
- Design - Process flows
- Reliability - Wash zone coking.

The feed TBP curve is used to generate the NBP of the individual pseudocomponents. The NBP is used in conjunction with a generalized empirical method like Riazi and Daubert's¹¹ two-parameter equation to calculate molecular weight, refractive index, etc. The characterization parameters are used by a generalized correlation like Erbar's modification to Grayson-Streed or BK-10 to calculate the equilibrium K-values. Therefore, the TBP distillation curve is the starting point for the prediction of the flash zone conditions for a given cutpoint. The impact of the specific generalized parameter correlation is beyond the scope of this paper; however, they also have a significant impact on deepcut vacuum column design.

Economics - Gas oil yields

The justification for a deepcut revamp is improvement in the vacuum gas oil yield and reduction in the lower value vacuum residue product. Heavy vacuum gas oil is usually fed to a fluid catalytic cracker (FCC), and the vacuum bottoms is used to produce fuel oil, asphalt, or thermal cracker feedstock. The value of vacuum gas oil as FCC feedstock and vacuum residue as coker feedstock is refinery-dependent. However, the margin is generally \$4.00/bbl or higher. Predicting the correct gas oil yield of a deepcut operation at an acceptable product quality is integral to project economics. The deepcut vacuum column revamp must increase feed enthalpy to increase gas oil yield. The quantity of material vaporized is highly dependent on the feed characterization. Table 1 presents a comparison of total vacuum gas oil yields from two different feed characterizations of the West Texas Intermediate (WTI) crude oil. The calculated gas oil yields are significantly different for the same flash zone conditions. The data presented is from an actual deepcut vacuum column operation.

Table 1 - Feed Characterization

	(West Texas Intermediate)	
	Design	Actual
Total Gas Oil (% Feed)	93	88
Vacuum Residue (% Feed)	7	12

Design - Process flows

The cutpoint of a deepcut vacuum column revamp sets the major equipment design. The enthalpy required to vaporize the heavy oil requires high temperature; therefore, the unit operation is more severe in terms of major equipment impacts. The major equipment includes the fired heater, heat exchangers, column internals, pumps, piping, and controls. The TBP distillation affects the equipment design. The enthalpy of the feed sets the fired heater duty, the feed vaporization in the flash zone affects the column packing selection, and the quantity of superheat in the vapor leaving the flash zone affects the wash oil system (line size, control valve, and wash zone spray distributor).

The TBP distillation curve determines the amount of vapor generated in the flash zone for a given set of conditions. The slope of the distillation curve in the area where the deepcut gas oil is recovered increases, depending on the crude oil origin. For a given molecular weight, sulfur-containing compounds boil at a higher temperature. The crude oil TBP shown in Figure 2 is West Texas Intermediate (WTI) crude. The whole crude curve was synthesized by blending the product streams from an operating unit, using conventional physical distillation tests, simulated distillations, and the unit material balance. Table 2 shows the slope variation as the oil gets heavier.

Table 2 - TBP Distillation Slope*

(WTI Reduced Crude)	
Cut NBP	Slope
1050-1075	30.5
1075-1100	34.8
1100-1125	41.9
1125-1150	64.0

* Degrees/Vol. % crude

The HVGO and vacuum residue were characterized by HTSD. The slope of the TBP distillation curve increases as the oil gets heavier. The gas oil yield and the flash zone temperature predictions improve as the accuracy of the TBP curve improves. Many times the flash zone prediction from

the models is significantly different from the plant data. Inaccurate crude vacuum unit feed distillation results in incorrect prediction of flash zone conditions. The flash zone conditions in a deepcut vacuum column will vaporize a significant amount of oil, boiling up to 1300°F. Figure 3 shows the TBP distillation curve of the overflash from one unit designed for 100% Maya crude oil atmospheric residue. Only 10-15% (assumes no entrainment) of this oil can be characterized by either an ASTM D2887, D1160, or D2892. Overflash liquid on light crude deepcut operations (such as West Texas Intermediate, North Sea crudes such as Statford, and West African crudes like Bonny Light) will have a TBP 50% point of 1200°F and an endpoint above 1400°F.

The heaviest portion of the vacuum column feed distillation must be generated by HTSD. Crude vacuum column simulated product yield predictions, process equipment design, and plant operating reliability associated with deepcut projects are improved because of the better vacuum unit feed characterization associated with the HTSD. Vacuum residue HTSD improves the characterization of the 1000+ °F portion of the vacuum column feed. The 1000+ °F material is the source of the recovered distillate and overflash in the deepcut revamped columns.

Reliability - Wash zone operation

The wash zone of the crude vacuum unit has been the source of reliability problems on some deepcut revamps. Remember, the purpose of a revamp is to increase gas oil yield. This implies minimum overflash because the feed enthalpy is maximized (oil cracking limit) on many of these units, and low overflash is the only way to recover the incremental gas oil because of the process flow scheme. As the feed enthalpy is increased, the volatilized contaminants increase in the flash zone vapors. On many revamps the wash zone efficiency^{12,13} must be optimized to maintain yield and gas oil quality. The prediction of overflash is dependent on feed characterization and the simulation method utilized.

Several columns revamped for deepcut operation have been shut down to replace coked wash zone beds. Wash zone coking goes through several stages, but the unit's run time is usually less than six (6) months.

1. Initially, coke formation increases column pressure drop with no apparent impact on gas oil quality. Unless the pressure drop is monitored closely (and it should be following a deepcut revamp), it usually is not noticed. An increase in wash zone pressure drop of 2 mmHG (measured by manometer) is an indication of coke formation.

2. As coking progresses, the packing free area is reduced to the point that black oil is entrained. The HVGO product quality begins to degrade. Microcarbon residue and metals increase. This usually occurs when the pressure drop reaches 4-5 mmHG.

3. Eventually the column must be shut down because yield losses and product quality become unacceptable. When the pressure drop reaches 6-8 mmHG the HVGO product asphaltene content becomes very high.

There are several potential causes of wash zone coking. The major causes of coking on deepcut operations are listed below:

- Process design - Incorrect design wash oil rate

- Operational - Too low overflash
- Equipment - Poor design.

The wash zone coking on five (5) projects that have been thoroughly investigated were caused by poor process design. In these projects, the design wash oil flow rate was too low. The quantity of overflash was very low and for practical purposes was zero. The required wash oil rate to meet the design overflash was 2 to 3 times the value predicted in the original designs.

The design TBP distillation curves were not accurate. In one case, simulated distillation data was available, but the designers used their database crude assay for the crude blends. When the test run data simulated distillations were used (in conjunction with modified modeling), the simulation predicted plant operation very well.

SIMULATIONS

Many engineers routinely perform computer simulations of their vacuum column operations to evaluate performance. The computer model is used for the following:

- Analyze current operation (prior to revamp)
- Predict deepcut operation process conditions
- Evaluate post-revamp performance test run.

The importance of good vacuum unit design and operation to the overall plant performance has been documented in the literature.^{14, 15, 16, 17, 18} The computer models for crude vacuum column simulation have been commercially available for twenty years or more. Vacuum column feed TBP characterization by high-temperature simulated distillation (HTSD) is replacing the older distillation test methods. The empirical thermophysical property calculation methods have been improved, and the property prediction methods of the heavier oil fractions boiling above 950°F are being updated. When a deepcut revamp is being considered, the model must be more than just a tool—it must be correct!

Figure 4 shows a typical crude vacuum column arrangement. The computer model of an operating column must correctly reflect the actual operating data, otherwise the model is not accurate. Deepcut operation is then predicted from the base case model. Without an accurate model of the plant data, it is difficult to correctly assess the future deepcut operation. There are inherent inaccuracies in the model due to feed characterization problems with the heavy oils, extrapolation of the thermophysical property generator data, and difficulties in modeling the physical realities of the unit. In spite of these limitations, the model should accurately predict the column yields so the project economics can be properly assessed prior to the revamp. The design deepcut revamp stream flow rates must be correct or the unit operation will not operate reliably.

The revamp of a deepcut vacuum column requires pre-revamp tests to determine the model accuracy and post-revamp test run to evaluate the critical operating parameters. Many times these test runs are performed to check the contractor's yield guarantees. A test run is very important after the unit is revamped to evaluate operating parameters such as actual overflash (not metered overflash).¹⁹ If there is a problem with little or no overflash, this is the time to take corrective action, not when the bed cokes up. When an

unscheduled column shut-down is required, everyone is very unhappy.

Real vacuum columns

A typical computer model is shown in Figure 5. The model assumes the vapor/liquid mixture entering the column is in equilibrium. Many times the feed is flashed in an ideal stage in the flash zone. The simulation results from these models underpredict the required wash oil flow rates by a factor of 1.5 or more. The deepcut vacuum column is designed, started up, and operates until the wash zone cokes. The unit is then shut down!

The computer model of a deepcut vacuum unit must reflect the process impacts of the following:

- Transfer line
- Flash zone
- Slop wax collector
- Wash zone internals.

Transfer line

The fired heater increases the vacuum column feed enthalpy consistent with yield objectives. The transfer line carries the two-phase oil to the column. The pressure drop in the transfer line is a function of the velocity, the physical properties of the oil, and the physical layout of the transfer line. The transfer line has pressure drop; therefore, phase change is continuous from the furnace outlet to the column flash zone. The temperature drop from the furnace to the column depends upon the transfer line pressure drop. A well designed transfer line will have less than 3 psi pressure drop, depending on the length. The two-phase feed enters the vacuum column flash zone where the liquid and vapor are separated.

The two-phase fluid in the transfer line has several possible phase regimes, depending on the flow parameter in the line. In most of the possible flow regimes, the vapor and liquid are not uniformly mixed. The transfer line of a vacuum column has very low residence time and poor vapor/liquid contact; therefore, the two phases are not in equilibrium. The vapor entering the vacuum column flash zone is superheated and the degree of superheat depends on furnace and transfer line design and operation.

Flash zone

Figure 6 shows a schematic of the flash zone of a crude vacuum column. The liquid/vapor feed enters the column and experiences pressure drop at the column feed nozzle. The feed stream liquid and vapor are partially separated by some kind of vapor horn or other device such as a multi-vane distributor.

The realities of commercial units need to be addressed. The feed enters the column through a tangential or radial feed nozzle at velocities between 200 ft/sec and sonic velocity (approximately 460 ft/sec). The flash zone conditions are therefore non-ideal. There is a quantity of oil that is physically entrained with the rising vapor. This quantity of entrainment varies depending on the transfer line velocity, column diameter, flash zone internals, and flash zone height.

However, there is always some entrainment to the wash section of the column, and this cannot be avoided. In many instances, the entrainment exceeds the overflash.¹⁹ The liquid being removed from the slop wax tray on many units is primarily entrainment.

Slop wax collector

The slop wax collector tray above the flash zone (below the wash section) ideally should de-entrain any of the vacuum residue that reaches this point in the column. The slop wax collector should be specifically designed for de-entrainment. The overflash liquid mixes with the entrainment. The flash zone temperature is considerably higher (30-70 degrees, depending on overflash rate) than the overflash liquid. Mixing of the entrainment and the overflash results in vaporization. The quantity of vaporization is a function of the overflash and entrainment rates, temperatures, and slop wax collector tray pressure drop. The metered overflash temperature is a very good indicator of the percent of entrainment. On some operating units the temperature difference between the flash zone and the metered overflash is very small. Low overflash (or very high entrainment) can be inferred from this temperature difference.

Wash zone internals

Ideally, the wash zone internals should only have to fractionate the volatilized contaminants and de-entrain residue. However, the wash zone must first de-superheat the rising flash zone vapor. The vapor/liquid in the transfer line are not in equilibrium, and the vapor is superheated. The wash zone must remove the superheat. Many times the actual amount of overflash on a given operating column is a fraction of the design. The reason is partially related to the vapor thermal condition entering the wash zone (as well as feed characterization).

ALTERNATE SIMULATION METHOD

Computer models must match the observed plant data, otherwise the simulation is at best wrong. When a vacuum column revamp has been based on an inaccurate computer model, the results could be a plant that operates for only six (6) months before it is shut down. Our proposed alternate simulation method is presented in Figure 7. This model has been found to match plant data very well. The assumptions used in creating the model may be incorrect, but the model results closely match observed deepcut vacuum column operation.

The major assumption used in creating our model is that the vapor/liquid feed to a vacuum column are not in equilibrium. Our assumption here is that the vapor/liquid leaving the furnace or entering the column (or anywhere in between) are in equilibrium. The vapor and liquid are separated in a flash operation at the conditions chosen. The superheated vapor is fed directly to the bottom of the wash zone. The liquid from the flash is separated into entrainment which enter the wash section. The majority of the feed liquid enters the flash zone. The flash zone is assumed to be an ideal stage.

The superheated vapor and entrainment enter the wash section of the column at the temperature of the flash. The liquid in the flash zone has sufficient residence time to equilibrate with the vapor generated by the pressure letdown. The flash zone vapor is fed to the wash zone.

The slop wax tray is modeled as an equilibrium flash (high residence time). This simulates what happens when the entrainment and overflash mix on the slop wax collector tray. By modeling the column in this manner, the vapor entering the wash zone consists of superheated vapor from the transfer line, vapor generated from the entrainment and overflash mixing.

Note Slop wax collectors typically have 2-3 mmHG pressure drop because of vapor maldistribution from the flash zone and vapor from the transfer line liquid due to pressure drop across the feed inlet (or transfer line).

Many engineers have experienced the problem of incorrectly matching the measured flash zone temperature with the plant data. In part, this is due to the model structure. The conventional method of simulating the vacuum unit is to model the column as shown in Figure 5, where the flash zone is simulated as an ideal stage.

A comparison of two simulations, one using HTSD and the other using ASTM D2892, was performed to highlight the differences. The flash zone temperature and pressure are identical for each case.

1. Conventional model - D2892 feed analysis
2. Alternate model - D2887 and HTSD.

The results of these two simulation methods are presented in Table 3. Important revamp design and operation issues of gas oil yield and wash zone operation are presented. Observed plant operating data is more closely approximated by the nontraditional simulation. The feed characterization and modeling techniques are important when designing a deepcut vacuum column. This is a very important issue when considering a deepcut design, although there has been some debate on whether feed characterization or modeling are important.²⁰

Table 3 - Simulation Comparison

	Original Design ⁽¹⁾	HTSD Plant Simulation ⁽²⁾	Plant Data
Total gas oil yield, (% of feed)	93	86	88
Wash oil rate, bpd	4,500	8,200	9,500
Overflash rate, bpd	2,200 ⁽³⁾	1,500 ⁽⁴⁾	1,500 ⁽⁴⁾

(1) Conventional Simulation Methods - D2892 Analysis
(2) Alternate Simulation Method
(3) No Entrainment
(4) Metered Overflash, include 600-bpd Entrainment

**CASE 1- POOR RELIABILITY
FEED CHARACTERIZATION BY ASTM D-2892**

A deepcut vacuum column was designed to operate at a heavy vacuum gas oil (HVGO) TBP cutpoint of approximately 1150°F. The initial design work for the system was done using a crude assay whose atmospheric residue TBP distillation curve is shown in Figure 8. The vacuum column was designed to operate at a top column pressure of 4-5 mmHG. This is at the limit of a conventional three-stage vacuum ejector system. The column design flash zone pressure and temperature were 10 mmHG and 765°F, respectively. The crude oil design basis was a 40-API-gravity West Texas Intermediate crude oil. There was no published data available on operating vacuum columns at this severity. The 1000+ °F portion of the crude oil TBP distillation curve was extrapolated. Although the extrapolation was poor, this example highlights the limitations of a standard crude distillation by ASTM D2892.

This column started up and operated at HVGO TBP cutpoints as high as 1150°F. However, the column operated for only six months, and it began to coke up. During the initial operation the metered overflash was only about 600 bpd. There were attempts made to increase the overflash by increasing the wash oil rate; however, the metered flow from the slop wax tray never increased much above 600 bpd. The wash oil rate was increased by 50% during this period with no appreciable change in metered flow rate. The unit metering was later confirmed by the addition of an orifice plate in series with a vortex meter. The operating problem was the inability to generate overflash. The wash oil spray header was operated between 4,500 and 7,000 bpd, and the metered overflash increased by only 200 bpd. (Flow control valve pressure drop, valve position, and spray header pressure drop change confirmed the flow rate increase.) The spray header pressure drop was measured at 25 psi at 7,000 bpd.

Attempts were made to model the column operation using the design crude oil data. The model indicated the HVGO yields were low based on the observed flash zone temperature and pressure. The design basis calculated overflash, assuming 4,500 bpd of wash oil, was 2,250 bpd. The observed column performance data did not match the computer model. The column eventually had to be shut down to replace coked wash oil packing. The cause of the coking was not poor spray header design (nozzle overlap 200%) or nozzle plugging. The coking of the wash packing was cross-sectionally uniform in the middle of the packed bed. There was no coke on the bottom of the bed and almost no coke on the top. Later contaminant analysis of the 600 bpd of metered flow²¹ showed it was essentially all entrainment. The wash zone coked because there was no overflash.

The original design computer model used an ASTM D2892 TBP distillation of the crude oil. The refiner's laboratory was limited to ASTM D1160 distillations of the heavy oil streams. The actual vacuum bottoms produced from this column contained essentially no distillable oil under the D1160 laboratory test conditions. Additional HTSD testing of the vacuum column products by an outside laboratory revealed a feed distillation much different from the original crude TBP distillation. Figure 9 shows the design

crude vacuum column feed and the synthesized vacuum column feed TBP distillations (analyses by HTSD).

**CASE 2 - IMPROVED DESIGN METHODS
FEED CHARACTERIZATION BY ASTM D2887
AND HTSD**

A hypothetical deepcut vacuum column design is presented. The feed to the column has been synthesized by backblending the product streams from an actual lube vacuum column operation. The resulting synthesized atmospheric residue (Figure 10) is used as feed to the proposed fuels vacuum column design. The feed and the products from the lube operation were analyzed by ASTM D2887 and HTSD. The unit material balance was within 1%. The flow sheet modeling for this example uses the nontraditional method presented earlier.

The feed to this vacuum column was a 23.0 API Light Louisiana Sweet (LLS) atmospheric residue. The operating column from which the feed TBP distillation was synthesized had several side products. This improved the synthesized vacuum column feed characterization because the narrow boiling range lube cuts allowed better pseudocomponent property predictions.²² A crude vacuum column fuels operation usually produces only three wide boiling range cuts (LVGO, HVGO, and Vacuum Residue) and there is generally only an average API gravity of each stream. A lube column produces narrower boiling range cuts; therefore, the pseudocomponent gravity estimations are improved. The pseudocomponent NBP and specific gravity are used to calculate molecular weight, acentric factor, and critical temperature and pressure. The calculated equilibrium K-values are improved because the parameters used in the calculation have been generated from an accurate NBP and specific gravity.

In addition, the simulation results of the operating data from the lube column show very good agreement with plant data.²³ The conclusion was that the feed synthesis was accurate. The hypothetical design and revamp of the deepcut fuels vacuum column using the atmospheric residue from B. Fleming, et al.²³ feed characterization will present some interesting observations. The calculated wash zone dry-out rate is 9/1 (volume of wash oil to volume of overflash).

Table 4 - Deepcut Vacuum Column

	Using Simulated Distillations
Wash Oil Rate, bpd	8,700
Overflash Rate, bpd	950 ⁽¹⁾
(1) No Entrainment	

The feed characterization of the vacuum column feed is always best accomplished by blending the products. In this example, the operating lube column produces seven (7) products that were analyzed using ASTM D2887 and HTSD. The plant operating data was simulated and the computer

model results closely matched the observed plant data. The products from this column have a relatively narrow boiling range; therefore, the estimating techniques of constant Watson K-value for the cuts gives a good breakdown of the pseudocomponent specific gravity. The molecular weights are estimated from the specific gravity and the normal boiling point. The molecular weights of heavy hydrocarbon stream are best estimated by specific gravity and kinematic viscosity.²⁴ The calculated stream viscosity from the model can be used as check of the stream molecular weights. The model's calculated stream viscosities were reasonable when compared to laboratory values.

The heaviest lube distillate cut and the vacuum residue distillation were generated from an HTSD. The distillation allowed characterization of the feed to 1380°F. Under the flash zone conditions of a deepcut vacuum column there is almost no volatilized material heavier than 1380°F.

The calculated wash rate and overflash of a vacuum column operating at a flash zone temperature and pressure of 765°F and 15 mmHG, respectively, is presented in Table 4. Some deepcut vacuum columns have had very short run length because of wash zone coking, and the coking always results in black gas oil. Black oil causes shut-downs.

Wash zone dry-out directly affects unit run length. If the bed is not sufficiently wetted in the middle it will coke. Deepcutting a high metals feedstock is a special design case. The deepcut operation volatilizes a significant amount of metals. A high-efficiency wash section is required.

These high-efficiency wash sections require significantly more wash oil than a low-cutpoint or low-efficiency wash zone. Proper simulation and feed characterization improves the predicted wash oil rate (on some deepcut units the required wash oil is 2 to 3 times the design) so that the equipment can be designed correctly and shut-downs avoided.

CONCLUSIONS

Deepcut vacuum column revamps are more common in the refinery industry today. The design of deepcut vacuum unit revamps is not a trivial matter. The operating history of many units has been poor and there are fundamental issues such as feed characterization and modeling techniques that need to be considered. Proper feed characterization by ASTM D2887 and HTSD and modified simulation methods allow for a correct gas oil yield, overflash, and wash oil rates to be calculated.^{25, 26} The deepcut vacuum column economic benefits to the refiner can be more accurately estimated and the unit's reliability improved. ■

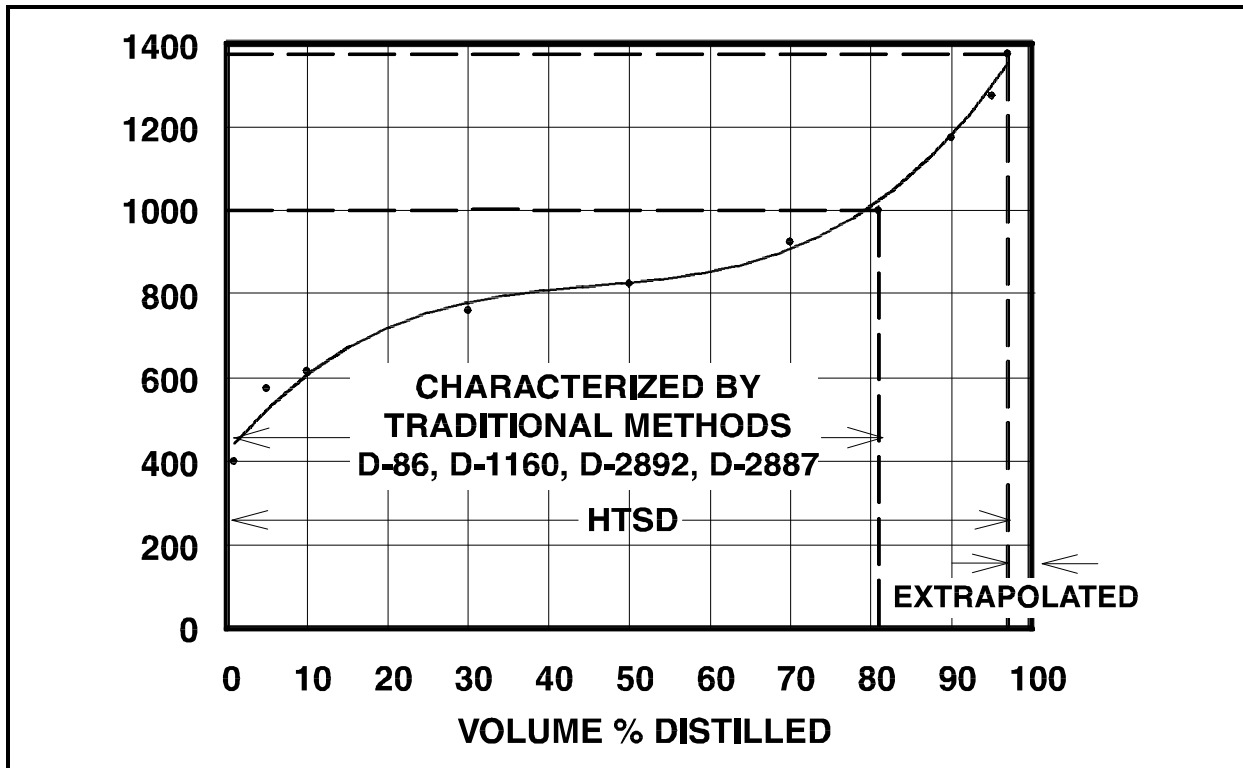


Figure 1 - Vacuum Column Feed Distillation

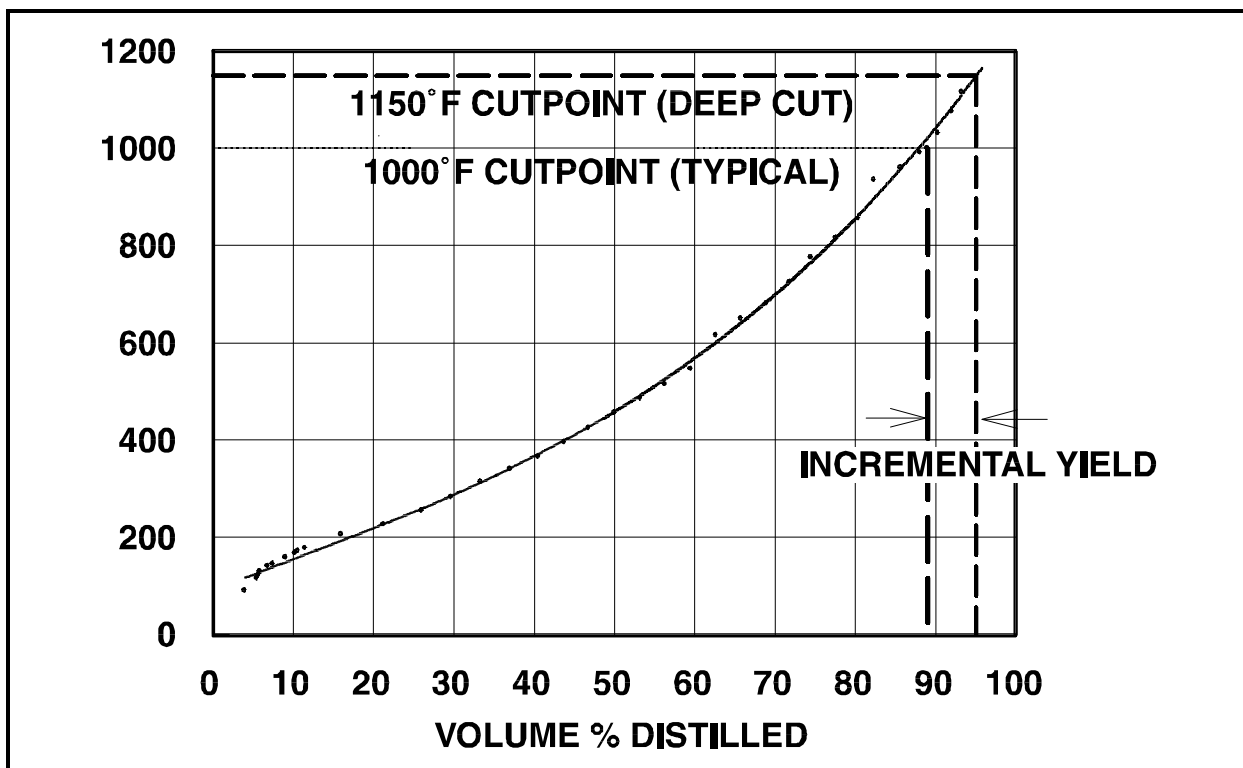


Figure 2 - Crude Oil TBP - HVGO Cutpoint

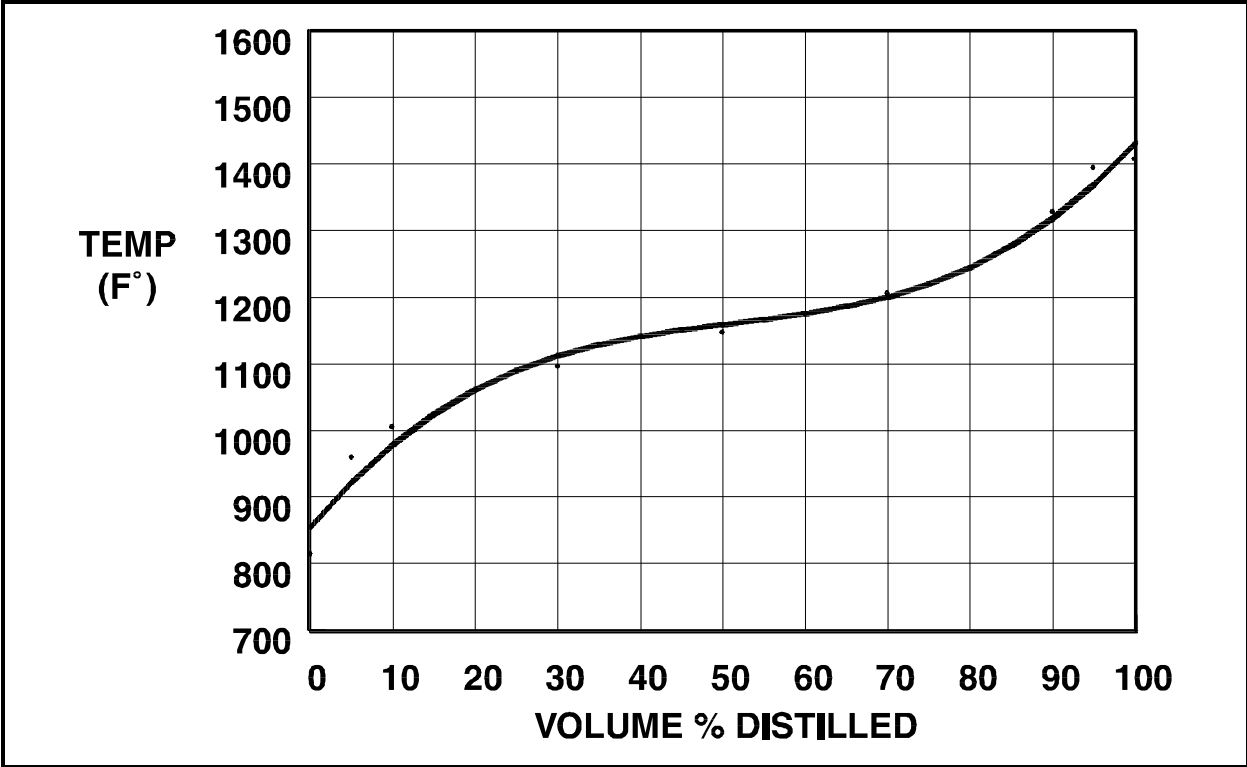


Figure 3 - Overflash TBP Curve - Maya Crude Oil

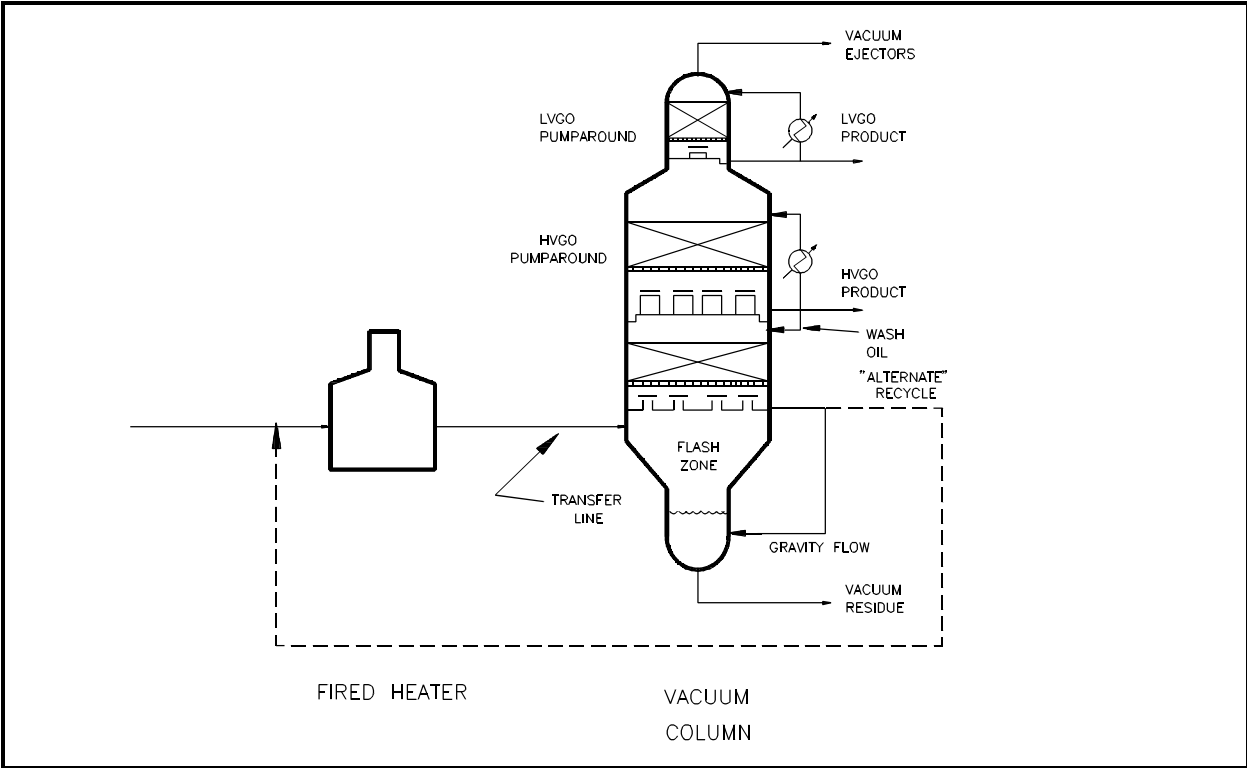


Figure 4 - Vacuum Unit Process Flow Diagram

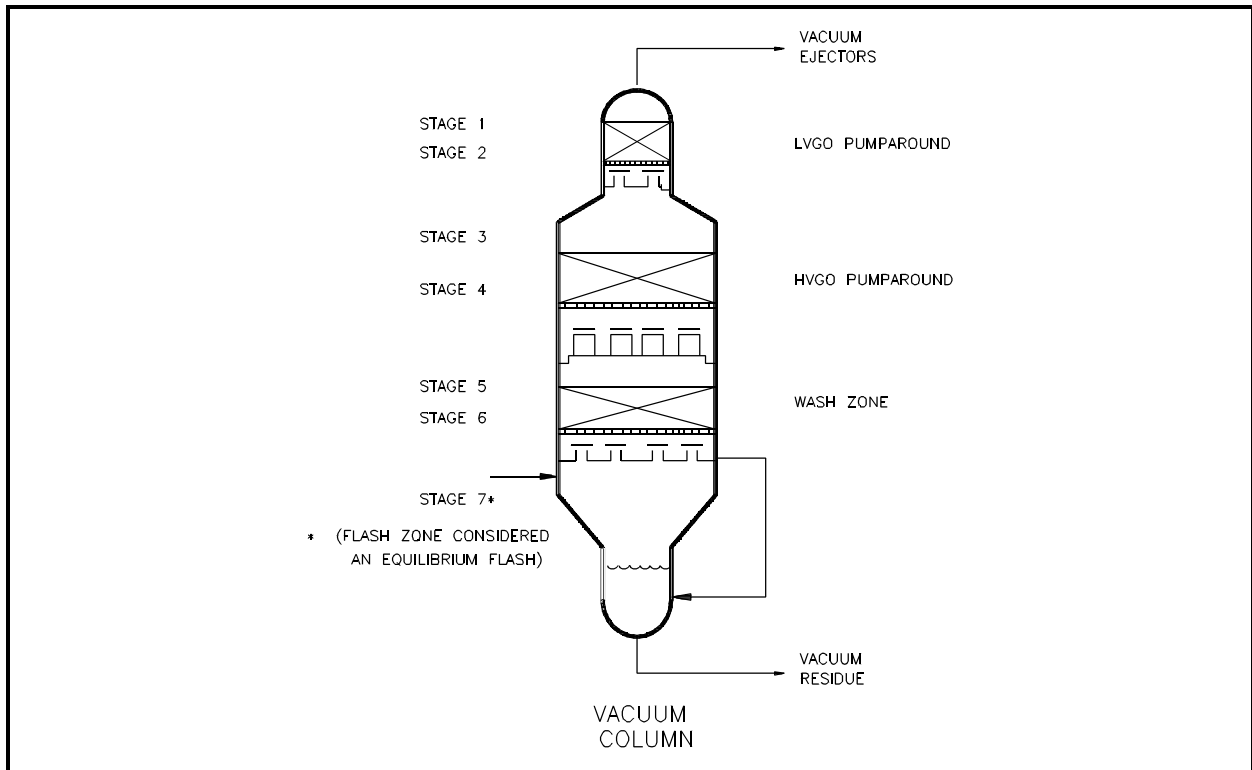


Figure 5 - Vacuum Column Computer Model - Conventional Flowsheet

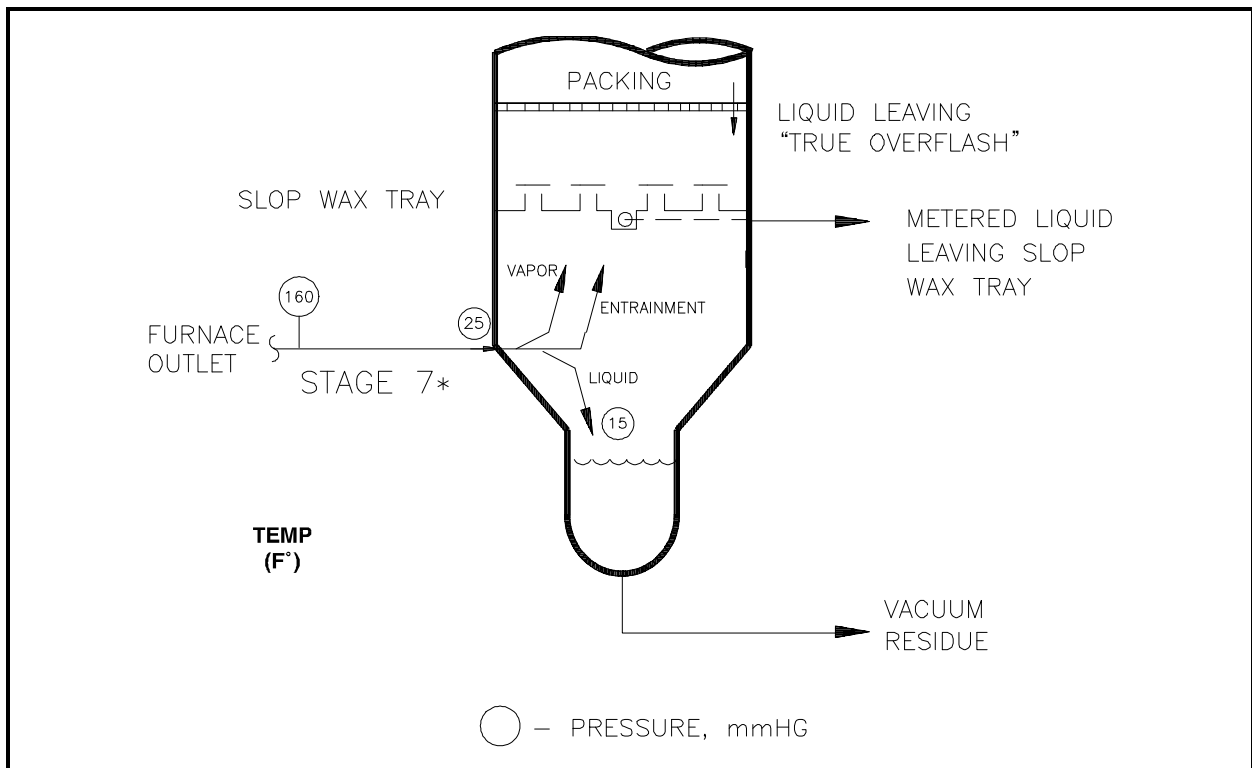


Figure 6 - Flash Zone Schematic

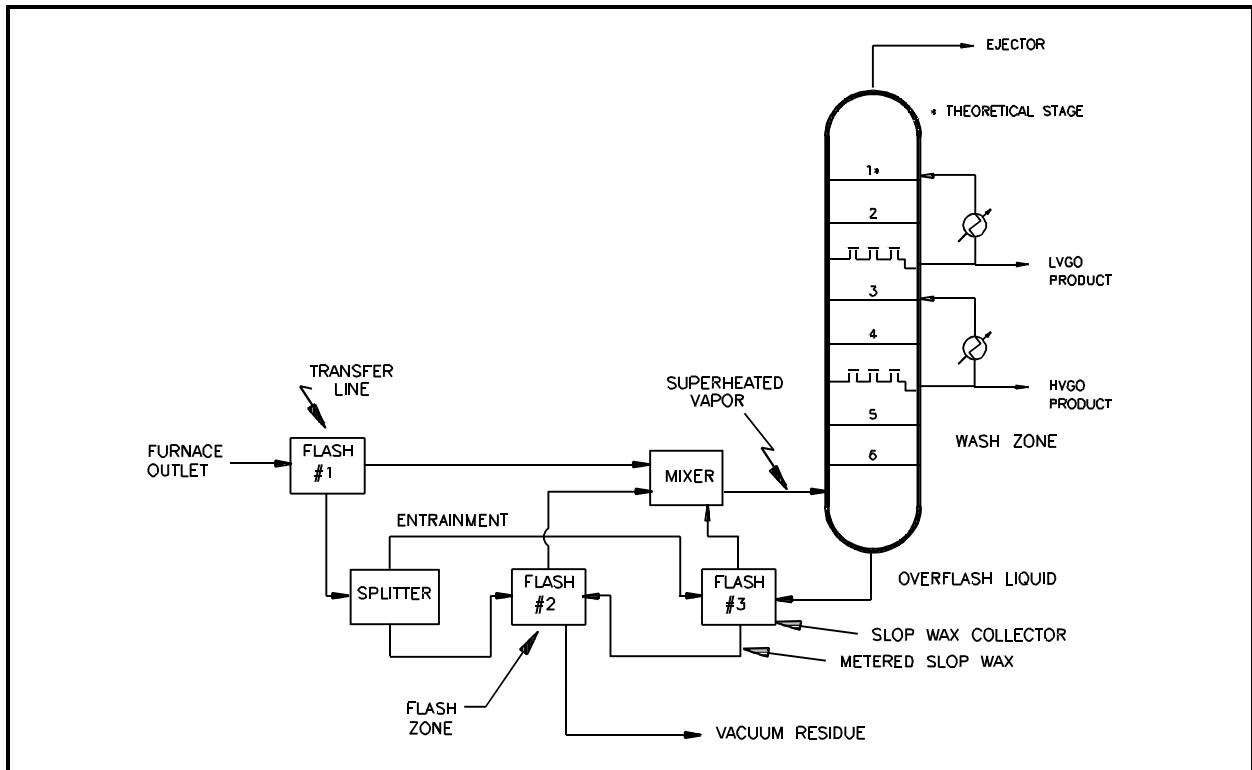


Figure 7 - Alternate Computer Model

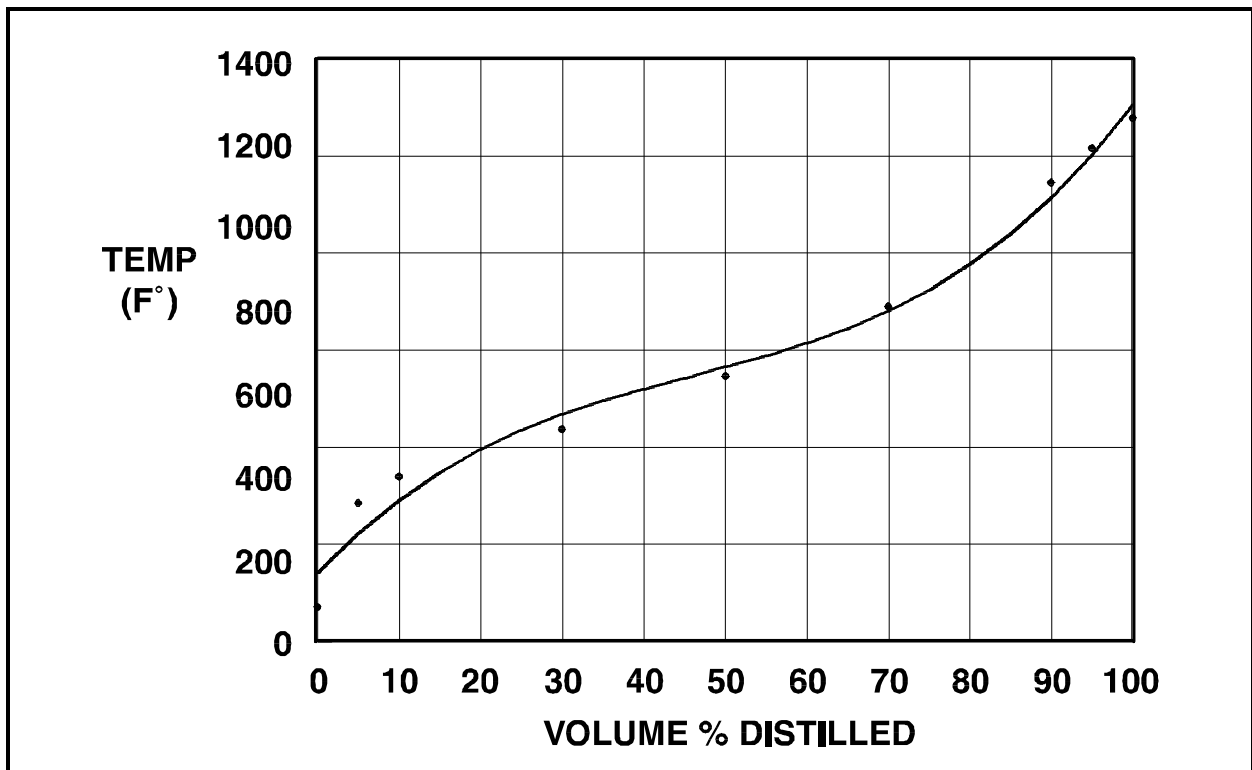


Figure 8 - Case 1 - Design Atmospheric Residue TBP Distillation

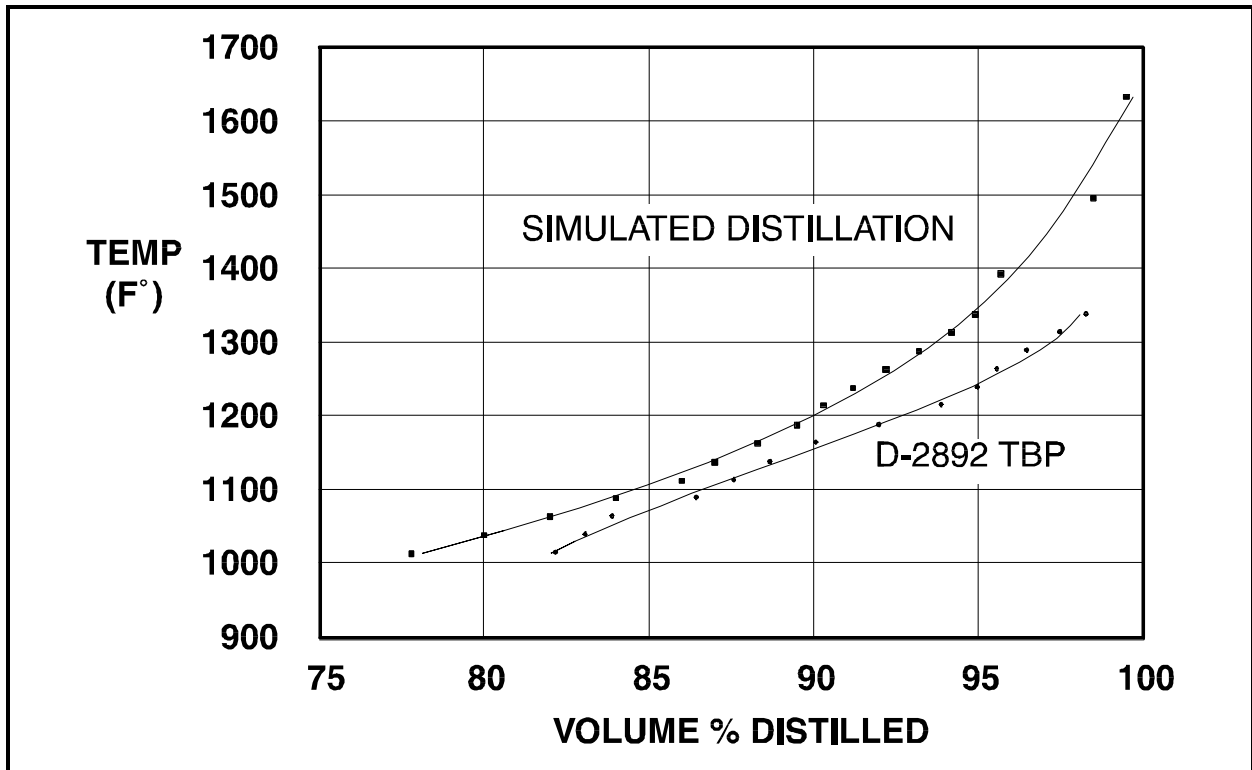


Figure 9 - Case 1 - Design vs. Synthesized TBP Curve (HTSD)

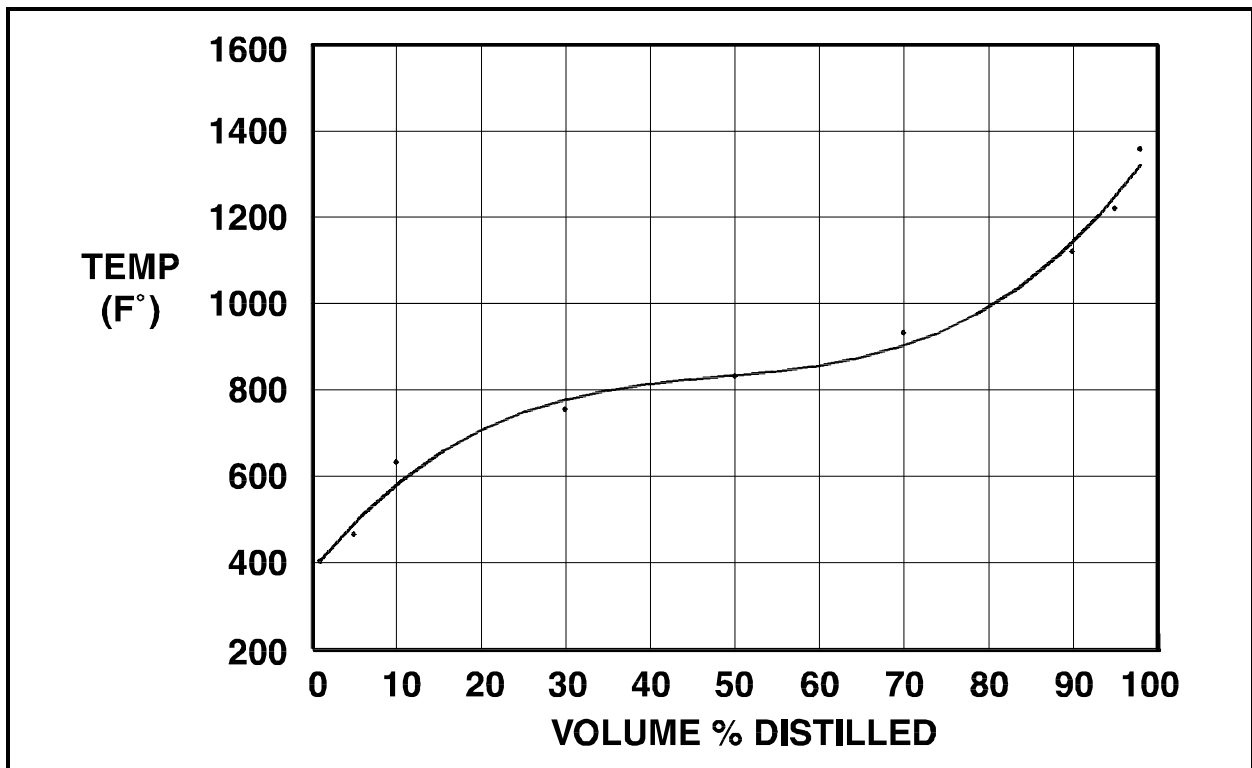


Figure 10 - Case 2 - Synthesized Atmospheric Residue TBP

REFERENCES

1. Roberts, D.A., Janosfia, A.S., van der Piepen, R., "Recover additional distillate from vacuum residue," *Hydrocarbon Processing*, Vol. 72, No. 7, July 1993, pp. 75-78.
2. American Society of Testing Materials, D1160 "Test Method for Distillation at Reduced Pressures," Annual Book of ASTM Standards, Petroleum Products, Lubricants, and Fossil Fuels, Section 5, Volume 05.02, 1990
3. American Society of Testing Materials, D2892 "Test Method for Distillation of Crude Petroleum (15- Theoretical Plate Column)," Annual Book of ASTM Standards, Petroleum Products, Lubricants, and Fossil Fuels, Section 5, Volume 05.02, 1990.
4. Peterson, J.L., Cannon, H.G., "Crude Oil Assays," *Petroleum Processing*, Oct. 1946, pp. 113-119.
5. American Society of Testing Materials, D2887 "Test Method for Boiling Range Distribution of Petroleum Fractions by Gas Chromatography," Annual Book of ASTM Standards, Petroleum Products, Lubricants, and Fossil Fuels, Section 5, Volume 05.02, 1990.
6. Lieberman, N.P., Process Improvements Engineering, Delayed Coker-Vacuum Tower Technology, New Orleans, Louisiana, May 1993.
7. Van Winkle, M., "Distillation Curve Correlations," *Petroleum Processing*, Nov. 1954, pp. 1738-1741.
8. Van Winkle, M., *Distillation*, McGraw Hill, New York, 1967, pp. 127-157.
9. Golden, S.W., Martin, G.R., "Revamping Vacuum Units from HVGO Quality and Cutpoint," AM-91-45, NPRA Annual Meeting, San Antonio, Texas, March 17-19, 1991.
10. Miguel, J., Castells, F., "Easy Characterization of Petroleum Fractions," Part 1, *Hydrocarbon Processing*, Vol. 72, No. 12, Dec. 1993, pp. 101-105.
11. Riazi, M.R., Daubert, T.E., "Characterization Parameters for Petroleum Fractions," *Ind. Eng. Chem. Res.*, Vol. 26, 1987, pp. 755-759.
12. Golden, S.W., Martin, G.R., "Improve HVGO Quality and Cutpoint," *Hydrocarbon Processing*, Vol. 70, No. 11, Nov. 1991, pp. 69-74.
13. Golden, S.W., Martin, G.R., "Revamping Vacuum Columns from HVGO Quality and Cutpoint," *Erdol & Kohl Erdgas Petrochemie*, August 1992, pp. 295-300.
14. Benedict, Q.E., "The Technique of Vacuum Still Operation," *Petroleum Refiner*, January 1952, pp. 103-10.
15. Lieberman, N.P., Lieberman, E.T., "Design, Installation Pitfalls Appear in Vac Tower Revamp," *Oil and Gas Journal*, Aug. 26, 1991, pg. 57.
16. Lieberman, N.P., Lieberman, E.T., "Inadequate Inspection Cause of Flawed Vac Tower Revamp," *Oil and Gas Journal*, Dec. 14, 1992, pp. 33-35.
17. Golden, S.W., Sloley, A.W., "Simple Methods Solve Vacuum Column Problems Using Plant Data," *Oil and Gas Journal*, Sept. 12, 1992, pp. 74-79.
18. Watkins, R.N., *Petroleum Refinery Distillation*, 2nd Edition, Gulf Publishing Company, Houston, Texas, 1973, pp. 4-8.
19. Golden, S.W., Lieberman, N.P., Liberman, E.T., "Troubleshooting Vacuum Columns with Low-Capital Methods," *Hydrocarbon Processing*, Vol. 72, No.7, Nov.1993, pp. 81-89.
20. Negin, K.M., "Design Considerations for Crude and Vacuum Revamps," Foster Wheeler Heavy Oils Conference, Orlando, Fl., June 7-9, 1993.
21. Golden, S.W., Sloley, A.W., Fleming, B., "Refinery Vacuum Columns Troubleshooting," Session 24A, AIChE Spring Meeting, Houston, TX., March 31, 1993.
22. Van Winkle, M., *Distillation*, McGraw-Hill, New York, 1967, pp. 336-339.
23. Fleming, B., Sloley, A.W., Golden, S.W., "Lube Vacuum Column Revamps," Foster Wheeler Heavy Oil Conference, Orlando, Fl., June 7-9, 1993.
24. Riazi, Mohammad, R., Daubert, Thomas E., "Molecular Weight of Heavy-Oil Fractions from Viscosity," *Oil and Gas Journal*, Dec. 1987 pp. 110-112.
25. Edmister, W.C., Pollack, D.H., "Phase Relations for Petroleum Fractions," *Chemical Engineering Progress*, Vol. 44, No. 12, pp. 905-926.
26. The American Petroleum Institute, *Technical Data Book-Petroleum Refining*, Washington, D.C. 1983.