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Simulation model of a vacuum heater transfer line

The vacuum tower is a critical part of many crude distillation units, and the vacuum heater transfer line is a critical part of vacuum tower operation. The vacuum tower's vacuum heater, heater transfer line and flash zone operate in concert with one another, so they must be designed as an integrated whole rather than as individual pieces. In a grassroots design, it is important to minimize the distance between the vacuum charge heater and vacuum tower to shorten the length of the vacuum heater transfer line. However, in a revamp of an existing unit, this distance and the transfer line pipe routing are already in place, so the new design must deal with constraints imposed by the existing layout.

The feed portion of a vacuum tower is a very complex, non-ideal system. Obtaining a complete picture of the high-temperature, extremely low-pressure, high-velocity, two-phase feed stream to use in design work requires two steps using two distinct modeling methods. Step 1 addresses the impact of the transfer line on the lower portion of the vacuum tower, and will provide design information for heater duty, the inlet separation device, wash zone internals and stripping section internals. Step 2 covers transfer line and heater hydraulics, and will provide the sizing basis for the transfer line and heater tubes. The output of these two steps will allow the entire system, from the heater through the lower section of the vacuum tower, to be designed as an integrated unit.

A recent crude/vacuum unit revamp project successfully applied this two-step process with commercially available simulation tools and calculation methods to predict transfer line performance and propose modifications to meet project objectives.

The objectives of the revamp were to increase the refinery's crude slate flexibility, specifically toward running heavier opportunity crudes, as well as provide a 14% increase in crude rate (38.5 Mbpd–44 Mbpd), while continuing to produce paving-grade asphalt.

Step 1: Transfer line and lower portion of vacuum tower. Vacuum tower operation, product cut points and product conditions (e.g., asphalt viscosity and gasoil asphaltene content) are controlled by flash zone temperature and pressure. The vacuum charge heater and vacuum tower can be modeled as a heater feeding directly to a column, if the model will only be used for unit monitoring or for modifications in the upper sections of the tower. However, if the purpose of the model is focused around the transfer line, flash zone and wash oil sections of the vacuum tower, a more complex approach is required.

Previous work has shown that the liquid and vapor portions of the vacuum tower charge stream are likely not at equilibrium as they exit the transfer line.[1] Modeling the exit of the transfer line and flash zone of the vacuum tower must account for the nature of this non-equilibrium stream in specifying flash zone conditions, designing the wash oil section, and designing the inlet separation device.

A process flow diagram (PFD) of the vacuum unit is shown in **FIG. 1.** The existing vacuum tower had a vacuum diesel draw, a heavy vacuum gasoil (HVGO) draw, a wash oil draw and a bottoms asphalt product. In this tower, a wash oil draw is required to meet asphalt viscosity and penetration specifications while maintaining HVGO quality that is adequate for a hydrocracker. The vacuum tower modifications included the replacement of

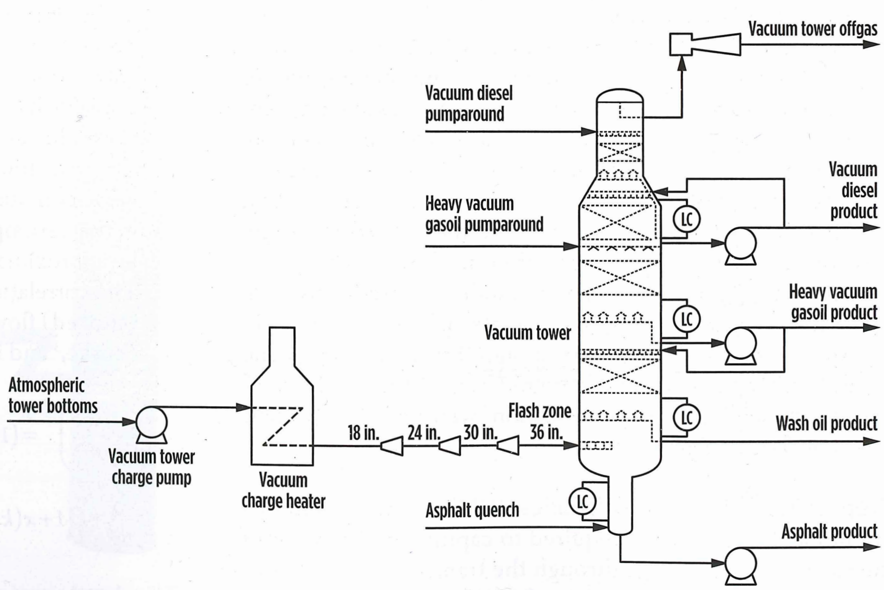

FIG. 1. PFD of the vacuum tower and heater.

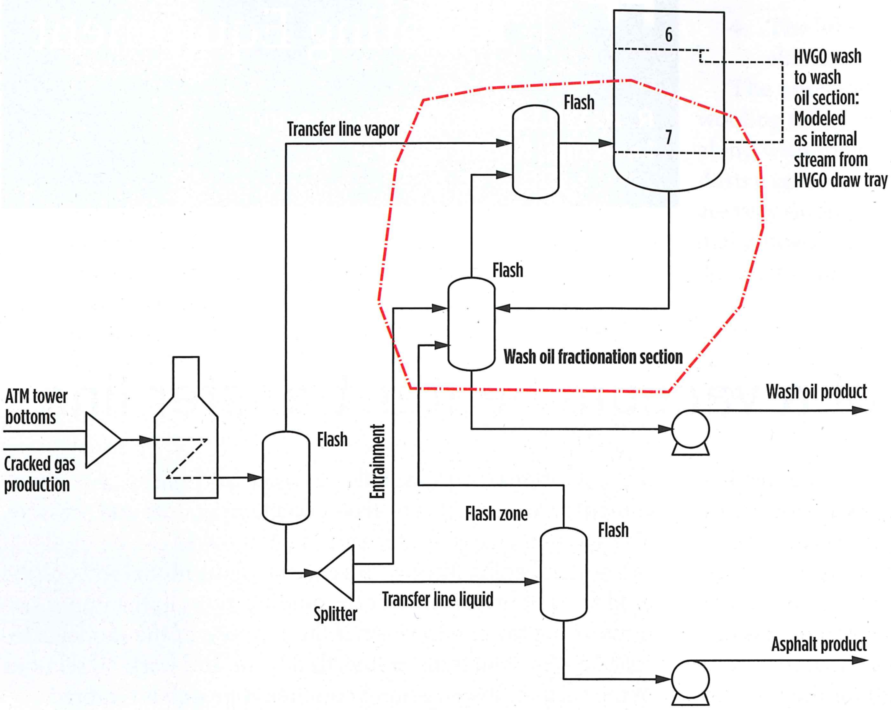

FIG. 2. Simulation model block flow diagram of the lower portion of the vacuum tower.

some trayed sections with packing, the addition of new packing in the vacuum diesel pumparound section, the replacement of a wash oil grid with a packed section, and the replacement of the wash oil recycle with an HVGO recycle.

To model the modified system, the project used flash and splitter unit operations, as shown in **FIG. 2.** The first flash is set at a pressure between the heater outlet and the flash zone pressure, and allows the model to behave in a manner consistent with the theory that vapor and liquid in the transfer line are not truly in equilibrium. Liquid from this flash is split into a fraction that represents entrainment going up to the wash oil section and a fraction that proceeds into the flash zone, where it is flashed at flash zone pressure.

The wash oil section of the vacuum tower is represented by two flashes external to the vacuum tower and one tray within the vacuum tower. The combination of the flashes and tray represents between two and three theoretical stages of separation. HVGO wash oil to the wash oil section of the tower is modeled as an internal stream from the HVGO draw tray. In actuality, the HVGO tray is a total draw tray, and the hot recycle to the wash oil section is pumped back before any heat exchange.

The non-equilibrium simulation model was used to provide vapor and liquid tray loadings to the internals vendor for packing, distributor and vapor horn design. Streams entering the various unit operations at the boundaries of the "flash zone" and the "wash oil fractionation section" were used to represent theoretical tray loadings.

Step 2: Transfer line hydraulics. While the non-equilibrium model from Step 1 is required to capture the behavior of the vacuum tower charge through the transfer line (thus providing heater duty and the sizing basis for the vacuum tower and its internals), this methodology does not provide hydraulic information about the transfer line itself. Therefore, the non-equilibrium model is not useful in determining transfer line diameter, pressure drop or velocities. For that design information, the project created a hydraulic model within the simulation to evaluate the pipe routing and line diameters necessary to meet the required flash zone conditions. One caveat to the hydraulic model is that the two-phase flow correlations will assume that the vapor and liquid are in equilibrium. From the non-equilibrium discussion above, this assumption is invalid along the entire length of the transfer line; however, the two-phase correlations include a correction for liquid slip, where appropriate. While the exact compositions of the vapor and liquid stream may not be rigorously accurate in the hydraulic calculations, the pressure drops and velocities derived are adequate for use in design.

It is important to differentiate between the following two terms as they relate to this study:

- **Sonic velocity** is the speed of sound in the vapor phase. The velocity of the vapor portion of the stream cannot exceed sonic velocity without pressure drop becoming prohibitive—sonic flow velocity is considered an absolute constraint. Typically, vapor flows will be designed to be 50%–80% of sonic to provide some design margin. Calculations of sonic flow are well known and readily available. For this revamp project, sonic velocity of the vapor phase in the transfer line ranged between 420 ft/sec. and 480 ft/sec.
- **Critical (or choked) velocity** is the maximum attainable velocity for two-phase flow, taking both phases into account. Significant theoretical and experimental work has been completed in developing correlations for two-phase critical velocity. The methods available have sufficient uncertainty, and two-phase flow hydraulics are complex enough that multiple locations along the transfer line are frequently calculated at critical velocity in deep-cut vacuum units.[2] For the transfer line in this revamp project, critical velocity was calculated to be approximately 200 ft/sec. total stream velocity. The correlation used by the simulator for critical (choked) flow is based on the work of Henry and Fauske,[3] and is presented in Eq. 1:

$$-\left(\frac{G^2}{k}\right)^{-1} = (1+x(k-1))x\frac{dv_g}{dp} + (v_g\left(\frac{1+2x(k-1)+kv_l^2}{(x-1)+k(1-2x)}\right) \tag{1}$$
$$\frac{dx}{dp} + k\left(1+x(k-2)-x^2(k-1)\right)\frac{dv_l}{dp} + x(1-x)\left(kv_l - \frac{v_g}{k}\right)\frac{dk}{dp}$$

where:

k = slip ratio = V_g/V_l

x = quality (gas mass fraction)

v_g/v_l = specific volumes of the gas and liquid (1/density).

Design of the transfer line balances capital investment against hydraulic constraints. As part of that balance, two or three sections of the transfer line are frequently allowed to reach critical velocity. Operating at critical velocity is undesirable, as it can lead to liquid entrainment and high pressure drop. However, experimentation in the hydraulic model shows that elimination of critical velocity in one location (by increasing line size) introduces critical velocity in another section, so it is difficult to completely eliminate in a revamp. This phenomenon, combined with the large line sizes required to mitigate critical velocity at very low pressures, pushes designers to accept critical velocity at a few locations. Critical velocity in the heater tubes should be avoided, but critical velocity in the outlet tubes just prior to connection into the transfer line is not uncommon. Critical velocity is also often accepted at the tower inlet, the largest section of the transfer line.

For the hydraulic model of the transfer line, piping should be broken into separate segments, so no single segment's pressure drop represents greater than 10% of the inlet pressure of that segment. In addition, fittings (elbows, expanders, etc.) should be represented with a separate segment. 3D model printouts of the existing transfer line, the originally proposed transfer line (developed in an early design phase without rigorous hydraulics) and the final design transfer line for this revamp project are illustrated in **FIGS. 3A, 3B** and **3C**, respectively. The pipe segments chosen for the model are illustrated in **FIG. 4.** A piping equivalent length for the pipe or fitting, as determined in literature,[4] was used as the line length for the segment.

A simplified heater hydraulic model was included to evaluate velocities and pressure drops through the heater tubes. This simplified model does not replace a full heater evaluation, but can reasonably evaluate hydraulics. For this portion of the model, the heater inlet tubes, heater tubes and heater outlet tubes were modeled as separate pipe segments. Heater firing was modeled as a duty applied to the heater tubes. The heater duty was set to match the required duty determined by the Step 1 vacuum tower model to meet project specifications.

For this project, the hydraulic model was created in a simulation program with the ability to reverse-calculate pipe segments. Reverse-calculating pipe hydraulics allowed the project to specify the known flash zone pressure and temperature, and easily determine conditions backward through the transfer line sections to the heater. For a simulator that cannot calculate bi-directionally, adjust blocks can be used to force reverse calculation. Reverse calculation of the transfer line is required for this iteration because the vacuum tower flash zone is where the target pressure/temperature condition is located. The heater outlet and transfer line hydraulics must be designed to meet these flash zone conditions. Attempting to iterate line size and routing calculations forward from the heater

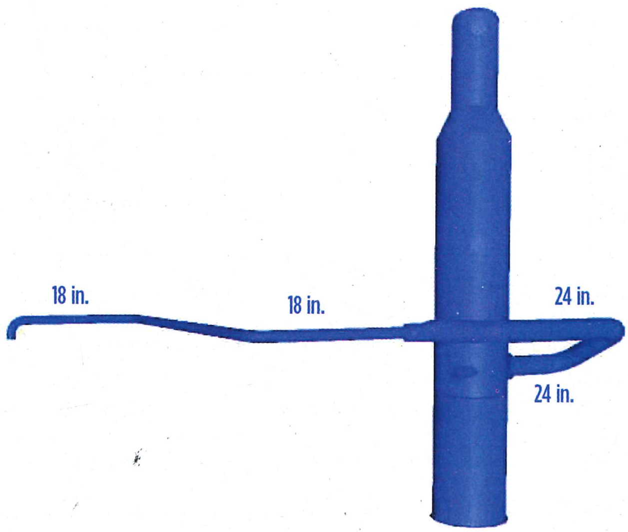

FIG. 3B. 3D model printout of the initial vacuum tower transfer line routing proposal.

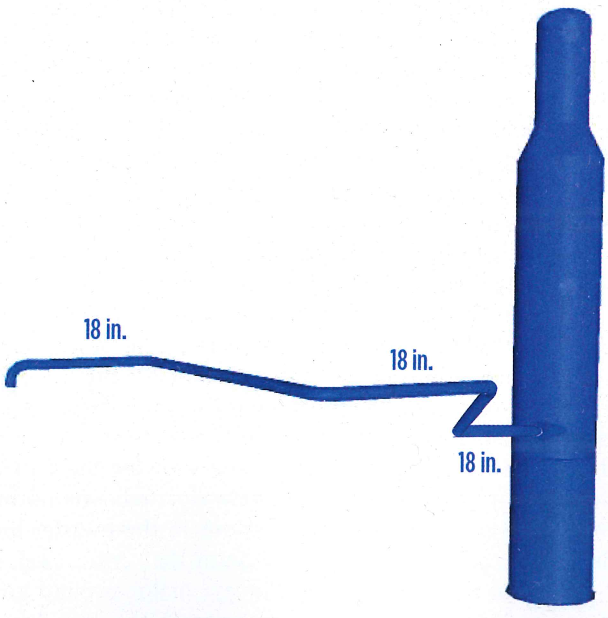

FIG. 3A. 3D model printout of the original vacuum tower transfer line routing.

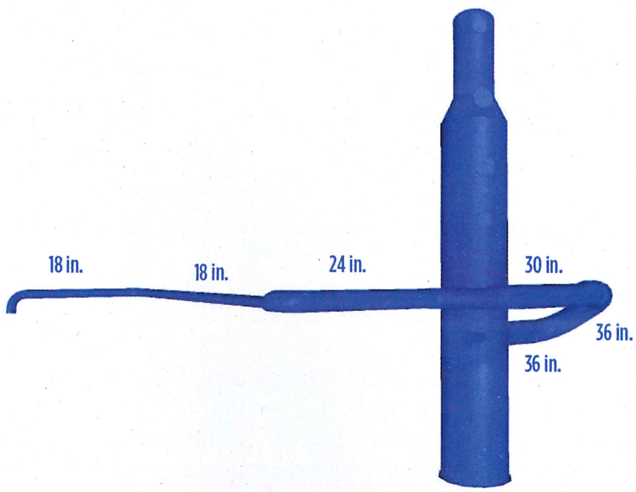

FIG. 3C. 3D model printout of the chosen vacuum tower transfer line routing.

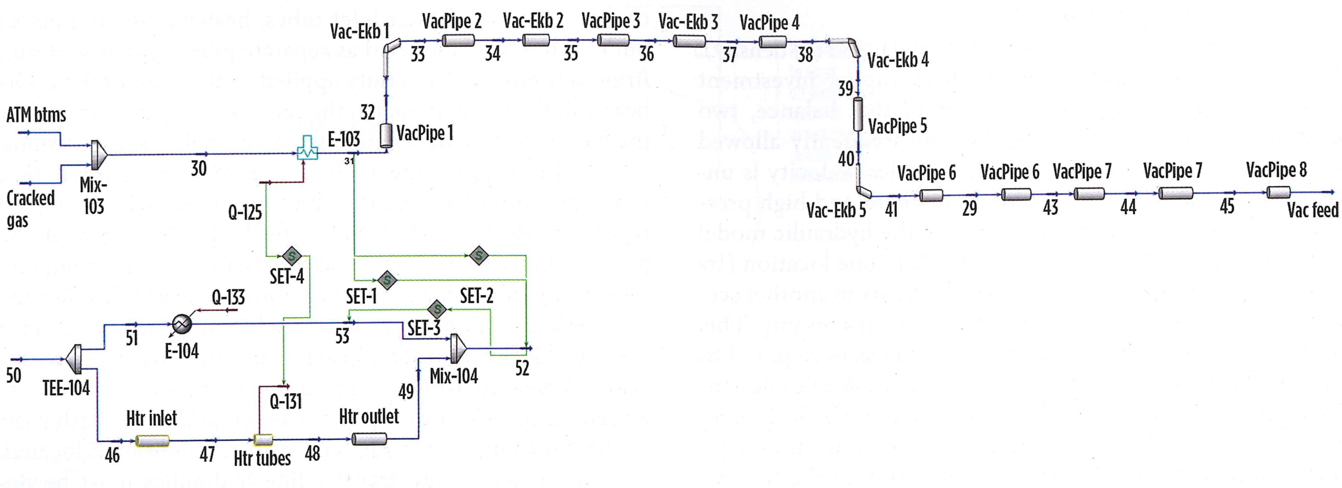

FIG. 4. Hydraulic model line segments in the transfer line simulation.

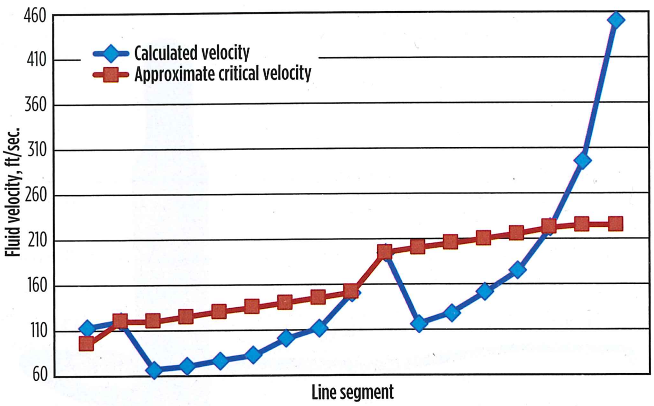

FIG. 5A. Velocity profile of the initial vacuum tower transfer line routing proposal.

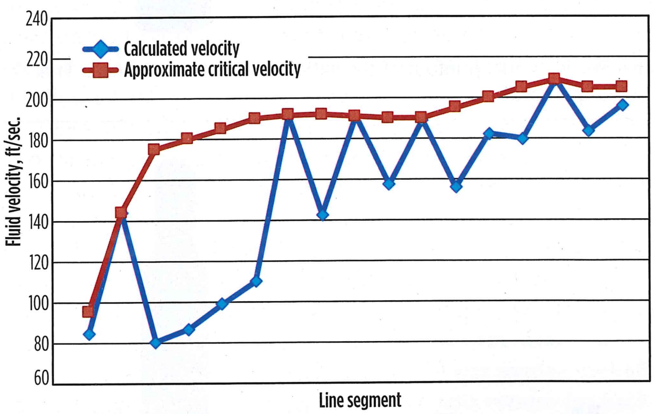

FIG. 5B. Velocity profile of the optimum transfer line routing for process.

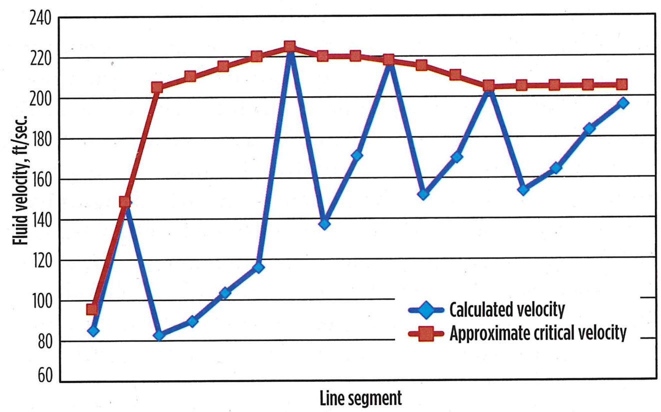

FIG. 5C. Velocity profile for the chosen vacuum tower transfer line routing.

becomes a frustrating process because the transfer line exit, typically along with several other sections of the transfer line, are at critical velocity. As such, a very small change in pressure at the inlet of the transfer line can cause the calculations to fail due to critical or sonic velocity. Reverse calculation simplifies the iterative process by making the highest-velocity zone a "known" point, rather than a calculated point.

Once the model was set up, the iterative process of defining transfer line sizes and routing began. The first iteration was based on the originally proposed transfer line size and arrangement with the design flowrate and crude slate. **FIG. 5A** shows the results of this iteration, including a comparison of the calculated velocity to the critical velocity for each segment. For these line sizes, the transfer line outlet is above sonic velocity, and six sections of the transfer line, along with the heater tubes, are at or above critical velocity. This result confirms that the originally proposed transfer line design is inadequate to meet project requirements.

To eliminate the sonic velocity condition and improve the near-critical velocity conditions in the transfer line, pipe diameters were adjusted and optimized, beginning with the last section of piping (at the vacuum tower inlet), targeting vapor velocity in all sections of the transfer line to be well below 80% of sonic velocity while allowing the critical (choked) flow calculation to be rarely violated. Attempting to eliminate all critical velocity sections in the transfer line reduced line pressure drop to the point that critical velocity existed in the heater tubes. Since a major revamp goal was to maximize flexibility and rate within the capacity of the existing heaters and tower shells, increasing heater tube size was unacceptable. To avoid heater modifications, the project targeted operating at or close to critical velocity in the transfer line, where possible, followed by step changes in line size when velocity increased above critical velocity. A greenfield design would have had the option of minimizing pressure drop in the transfer line (ideal), and then designing the heater to avoid critical velocity at that lower pressure. For this revamp, the heater, tower and distance between the two were fixed constraints.

After multiple iterations, the project proposed a feasible solution by stepping the transfer line size up in the smallest increments possible with commercially available pipe sizes. The results of this case are shown in **FIG. 5B,** including a comparison of the calculated velocity to critical velocity. From a process standpoint, this case represented the optimum solution available with the existing heater and line routing between the heater and vacuum tower. However, this case had constructability and cost concerns related to the large number of welds and the cost of purchasing relatively short sections of large, high-alloy, unusually sized piping.

The project team suggested limiting pipe sizes to more standard 24-in., 30-in. and 36-in. nominal diameters. Results from the final iteration, using these more readily available pipe sizes, are listed in **FIG. 5C,** including a comparison of the calculated velocity to critical velocity. This option has four sections of the transfer line calculated at critical flow, avoids critical flow in the heater and was chosen as a reasonable balance between velocities and anticipated installed costs.

Takeaways. The crude and vacuum unit revamp, including the transfer line and vacuum tower, was completed in 1Q 2017. Actual heater outlet temperatures, flash zone pressure and temperature, and product specifications match very closely with design values. The unit started up on a crude slate similar to the pre-revamp slate, and has shifted to the planned heavier crude slate. The crude charge rate has been between 45 Mbpd and 45.5 Mbpd, above the project target of 44 Mbpd. With all crude slates and rates that have run since startup, the unit has met asphalt property specifications, produced high-quality gasoils and been within the operating range of all new equipment. These results show that designing the vacuum tower transfer line and flash zone using this two-step methodology will provide a successful project with an appropriate level of conservatism at a reasonable cost. HP

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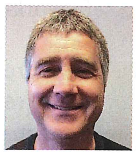

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