

TITLE

High Throughput Surfactant Synthesis, Characterization and Formulation (Chris Tucker, Carol Mohler, Keith Harris)

ABSTRACT

The drive towards more sustainable surfactants has increased the demand for the synthesis, characterization and formulation of new surfactants. We have developed an automated high throughput workflow for the synthesis, characterization and formulation of new surfactants derived from sustainable raw materials. Our approach to developing these new surfactants for potential commercial introduction involves first the synthesis of libraries of surfactant structures with a diversity of hydrophobe and hydrophile structures. These surfactants are then characterized for solubility, surface tension reduction, critical micelle concentration, pour point, foam stability, wetting, gel regions etc. Select surfactants from these screens are then further characterized for oil solubilization and interactions with other materials in solution such as water soluble polymers, other surfactants and solvents. The results from these second order screens are then used to select surfactants for further high throughput formulation studies for applications such as hard surface cleaning, laundry products, water borne paints and agricultural product delivery systems. In addition to the above screens we have developed informatics to track, visualize and model the large volume of results obtained to aid in our decision making process. High throughput techniques allow for the synthesis of large libraries of surfactant structures with a great deal of variability in both the hydrophobe (size, branching, etc.) and hydrophile structure. We have correlated structural characteristics to key performance properties such as oil solubilization, wetting, foam generation and stability, gelation and interaction with water soluble polymers. Based on these results we can develop structure property correlations to aid in decisions on structures of interest for further development

INTRODUCTION

The increasing drive towards more sustainable surfactants and formulations has increased the need for techniques to rapidly screen the physical and solution properties of new surfactants and the need to develop efficacious formulations based on green components. We have developed automated workflows to synthesize and characterize new surfactants and rapidly formulate them into final products and optimize for performance. This paper will detail some of the methods developed utilizing both vendor supplied and custom built tools and the software needed to store and model the results obtained. The overall goal of this work is to increase the speed at which one can characterize and formulate new surfactants into products by at least 10 fold.

EXPERIMENTAL

Experimental Design.

The software application Library Studio (Symyx, CA) was used to design the high throughput surfactant characterization experiments, and convert the design into a template that can be used by the robotic liquid handlers. The experiments were typically done using small scale samples (~1 mL vials) in a 96 well format, arranged in an 8 row x

12 column array. For the surface tension and CMC experiments, a typical experimental design is shown in Figure 1. In this design, each row corresponded to a different surfactant. The concentration of the surfactant varied across the row from approximately 5×10^{-4} to 1 weight percent. Two stock solutions of each surfactant were needed to make the range of surfactant concentrations used in the study, and water was added to each sample to keep the total weight constant at 800 mg.

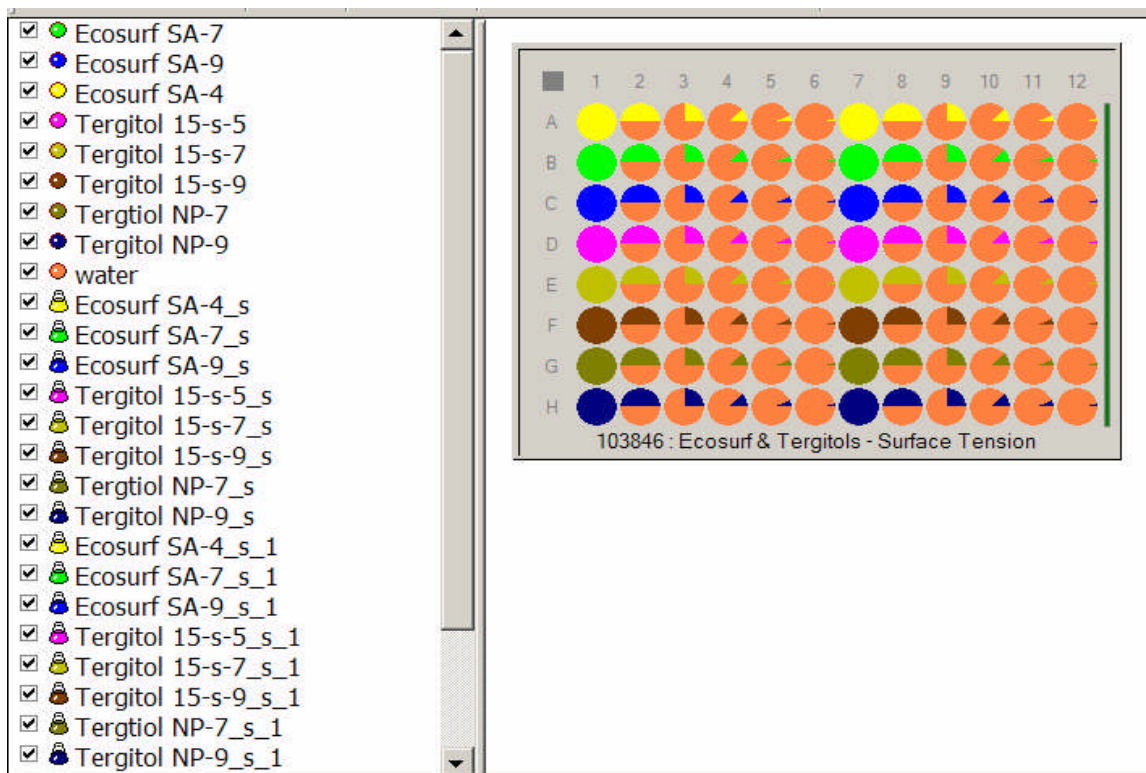


Figure 1. Typical experimental design for high throughput surfactant surface tension studies. Each row is reserved for a different surfactant, and the surfactant concentration is varied from high to low across the row. In this design the surfactant concentration varied from 5×10^{-4} to 1 weight percent, and water was added to ensure the sample weight was constant at 800 mg.

Liquid Handling.

Stock solutions of the surfactants in water were made at the concentrations needed for the robotic liquid handlers to make the plates described above. For the surfactant surface tension measurements, stock solutions were made at surfactant concentrations of 1 and 0.0156 weight percent. These stock solutions were then diluted to the appropriate level for each sample using either a TECAN 200 or a Hamilton Microlab Star liquid handling robot.

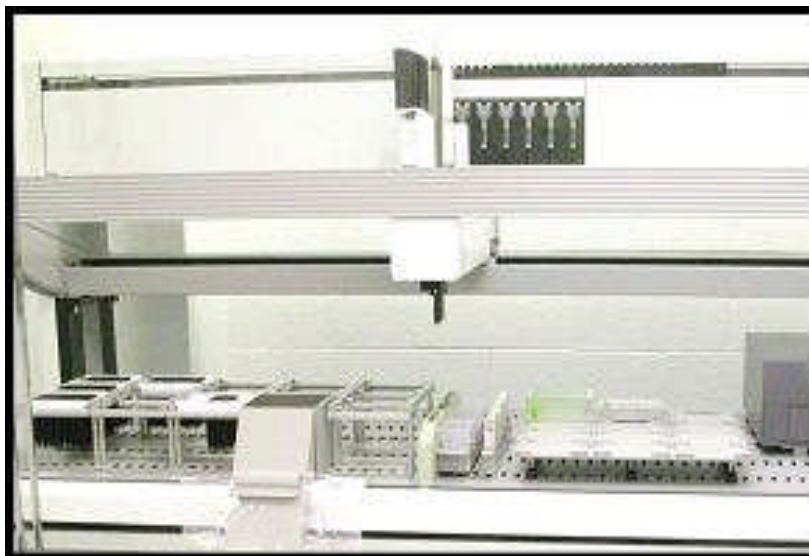


Figure 2. TECAN 200 liquid handling robot.

For either robot, calibrations correlating the amount of each volume dispensed with the desired mass for each liquid were made for each material to be dispensed. To accomplish the calibration, empty 1 mL vials (8x43 mm) were tared, a known volume of the material was dispensed into the vials, and the vials were reweighed. Three replicate sets of dispensed volumes were made for each material to estimate the error of the calibration. For the materials used in these studies the relationship between target volume and actual weight was linear over the range of the dispense amounts used (25 – 800 μ L).

Both robots are equipped with heating capabilities. Source reservoirs are placed into specially designed heating units with a temperature range from 25 to 120° C, although the disposable tips are not suitable for use above 90° C. These reservoirs allow the liquid handler to transfer materials that might normally be solids at room temperature. For example, in the oil solubilization work previously described, some of the surfactants are waxy solids. However, once melted, these materials may be handled in the same manner as any liquid source.

Again a calibration step is required to determine the operational parameters necessary for accurate volume transfer and one aspect that needs to be considered in this situation is cooling rate. It is imperative that the material not cool and solidify during transfer. To this end, the materials were heated to at least 20° C above their respective melting point, ensuring that they retain sufficient heat to remain liquid throughout the transfer step.

Surface Tension Measurements.

For surface tension measurements, samples were dispensed into the individual wells of a specially designed black polypropylene 96-well plate (Kibron, Inc, Finland) with conically-shaped wells. Accurate dispensing of 50 μ L of each of the samples into each individual well was accomplished using a SerialMate liquid handling robot. The filled plate was then loaded into the entrance port of a Delta-8 Multitensiometer (Kibron, Inc.,

Finland) to perform surface tension measurements (see Figure 3). Eight mini-probes, hanging on microbalances, are immersed into the first column of the plate (one probe per well), and the maximum pull force exerted on each probe as the probe is slowly withdrawn from the liquid is monitored. The surface tension of the liquid is extracted from the maximum pull force exerted on the probe just as it exits the liquid.^{i-v} This method is very rapid, and the Delta-8 is capable of determining the surface tension of 96 samples in a very short time (2-10 minutes).

The instrument was calibrated before each use by using de-ionized water as a reference material. A value of 72.8 ± 0.2 mN/m was obtained at 23°C, in good agreement with the literature value of 72.3 ± 0.1 mN/m at 23°C.^{vi} The wet and dry probe stability bounds were set at 0.20 mN/m. The plate vertical up- and down-speeds were set at 100% of their maximum value. The probes were subjected to a thermal cleaning cycle after each 96-well plate was measured to minimize any cross-contamination between plates.



Figure 3. The Kibron Delta-8 multichannel tensiometer (left) and close-up view of the eight measurement probes (right). A 96-well plate is loaded on the left-hand side of the unit, and is automatically moved under the probes during a measurement.

Oil Solubilization

Studies may also be conducted to assess the impact of any component in a formulation on the formulation properties and performance. These mixtures generally contain surfactants and may, or may not, contain additional materials such as solvents, chelants, stabilizers, defoamers or a host of other components. Components typically vary in concentration and ratio relative to other components. Formulation stability is usually a prerequisite for commercialization and can significantly impact system performance. For preparation of a cleaning formulation, enhanced oil solubility is a desired feature of the cleaner. The more oil the formulation can solubilize, the greater the efficiency at removing it from the desired surface.

To evaluate the relative solubilization efficiencies of some common surfactants an experimental template was prepared. In the following example, samples of increasing surfactant concentration were combined with a single hydrophobe to determine

hydrophobe solubility. For this solubilization study 1000 mg formulations were prepared using the surfactants of interest at two concentration levels, 5 and 10 wt %. To these formulations, 5 wt % of a hydrophobic material was added. The exact nature of the hydrophobe is irrelevant so long as it can be transferred by the liquid handler. In the plate shown in Figure 4, a range of 16 different non-ionic surfactants are combined with four oils of increasing hydrophobicity. Once the desired formulation was prepared, a fixed amount of the hydrophobe was added, the mixture was agitated and allowed to equilibrate for a minimum of 24 hours at room temperature. Next the solution was examined to determine the number of phases present. The hydrophobe is assumed to be soluble until a separate, excess oil phase is detected. Comparisons can then be made as to the efficiency of the surfactant to solubilize a given hydrophobe.

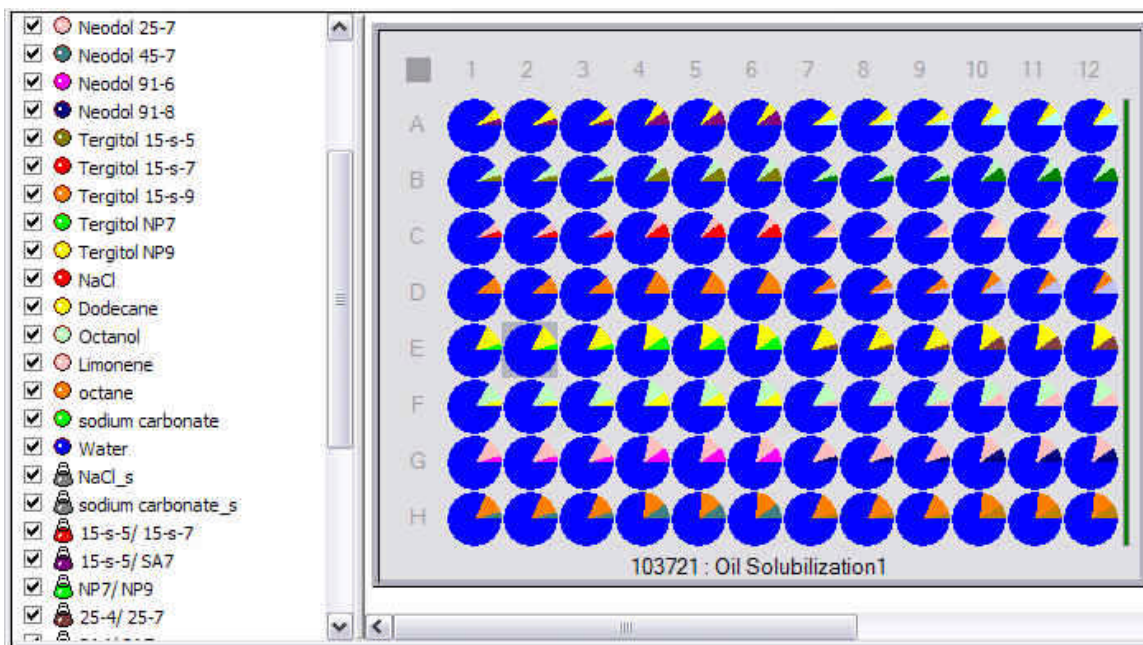


Figure 4. Oil solubility in a given surfactant solution. The aqueous solution is prepared with increasing levels of surfactant, then the oil is added.

As with all designs created in Library Studio, substitution of a new surfactant for an existing one is simply a matter of adding the new compound to the list of possible materials. The original design is then copied and the new material replaces the existing surfactant. Similarly additional components may be added to an existing formulation so that phenomena like the effects of surfactant blending can be studied. Again the original design is copied and a new compound is then added to the original formulation. For example, this plate “Oil Solubilization1” was copied and a mono-valent salt was also added to create a new and different set of formulations. In this manner the user can evaluate the effect of a particular salt on the oil solubilization of a specific surfactant. It becomes obvious that a wide range of compositional variations and their effects can be studied rapidly using these tools.

RESULTS AND DISCUSSION

Surfactant CMC and Surface Tension Reduction.

The ability of the Delta-8 multiteniometer to rapidly measure surface tensions enables the surfactancy properties of many diverse molecules to be screened in a short period of time. For example, the Delta-8 was used to measured the concentration dependence of the surface tension of several aqueous formulations of bis-propan-2-ols shown in Figure 5. This data allows a direct comparison of the relative utility of these molecules in reducing the surface tension of water. For these molecules the surface tension ranges from approximately 45 mN/m to less than 30 mN/m at 1 weight percent surfactant, which is a substantial variation in the ability to reduce the surface tension of water. In addition, the CMC of the molecules is dramatically different, ranging from as low as 0.002 weight percent for molecules with 8 or 9 carbons, to as high as 0.1 weight percent or more, for longer alkyl chains. It was possible to collect this entire data set in three 96 well plates, which corresponds to as little as 20 minutes of data collection time.

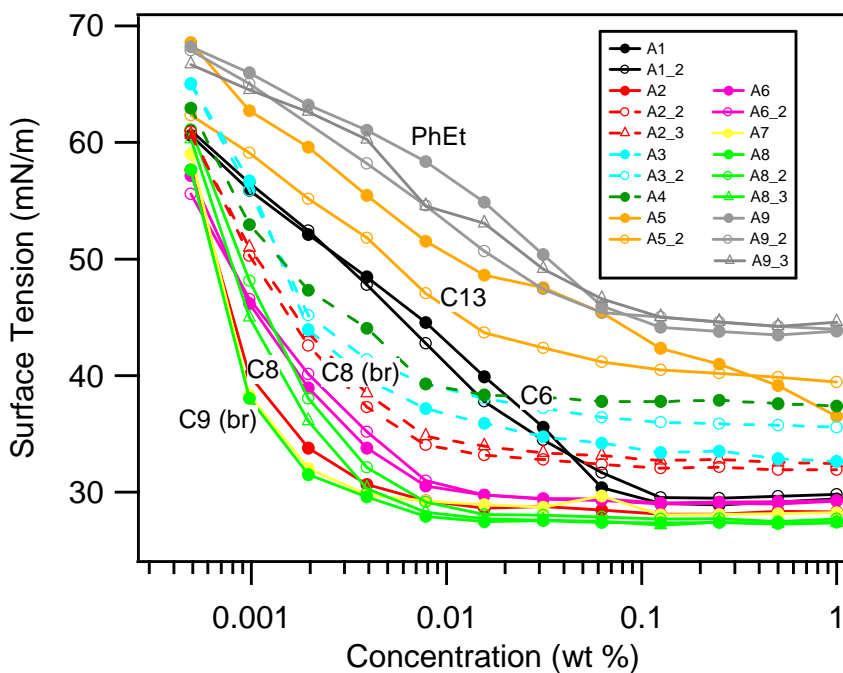


Figure 5. The concentration dependence of the surface tension of several bis-propan-2-ols

The high throughput surface tensiometer was also used to study the surfactant properties of several new EcoSurf surfactants, which were developed by Dow Chemical as effective alternatives to the nonylphenol based surfactants. Formulations containing EcoSurf SA-7 have been shown to consistently deliver good cleaning efficiency for CSPA DCC-17 soil.^{vii} The concentration dependence of the surface tension of aqueous solutions of three EcoSurf surfactants is shown in Figure 6. All three surfactants (EcoSurf SA-4, SA-7 and SA-9) were able to substantially reduce the surface tension of water even at very low concentrations (surface tensions near 35 mN/m for concentrations as low as 0.05% by weight surfactant). The critical micelle concentrations (CMC) of all three surfactants range were roughly similar, but appeared to increase in the order SA-4 (0.008 wt%) < SA-7 (0.015 wt%) < SA-9 (0.020 wt%). This follows the trend in cloud point and solubility for these surfactants. The CMC values measured using the Delta-8 were

somewhat larger than those measured by conventional techniques, nevertheless clear trends in surfactant activity with concentration and molecular structure were observed.

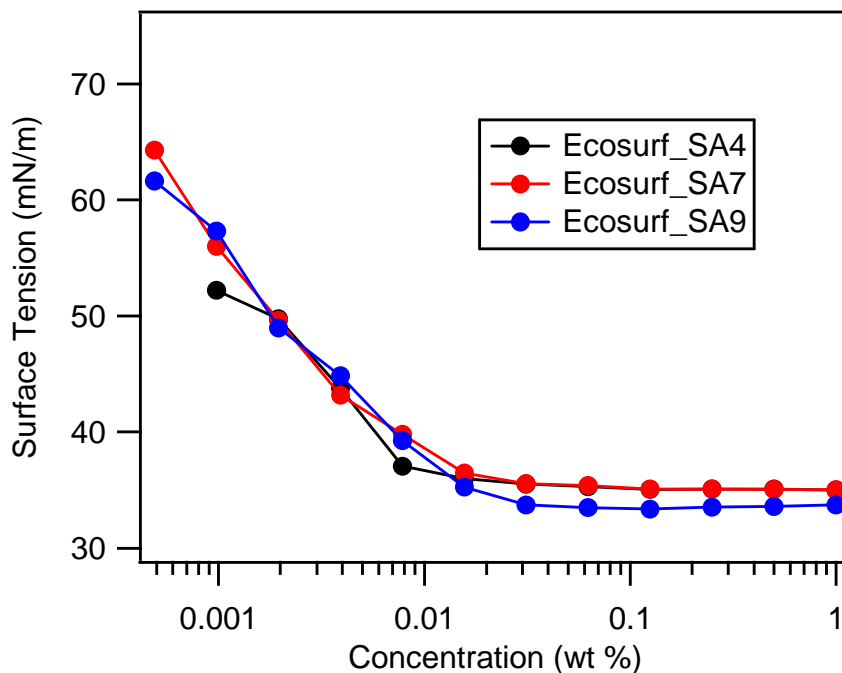


Figure 6. Surface tension as a function of concentration for aqueous solutions of EcoSurf SA-4, SA-7 and SA-9.

Oil Solubilization

Oil Solubility as a Function of Surfactant Type and Concentration

When determining the efficiency of a surfactant at solubilizing a given oil, identifying the maximum hydrophobe uptake is critical. This point is most readily identifiable by the formation of a second excess phase in the sample. Therefore the ability to detect separate phases is key to determining the solubilization of one component in another and visual inspection is the most common means of doing so.

The images shown in Figure 7 are representative of the typical type of data collected with a specially designed high throughput instrument called the PICAI. Here we can see a series of formulations of various surfactant concentrations with two different levels of the hydrophobe octanol. The series produces the formulations in triplicate to demonstrate the reproducibility of the system. The figure also shows the impact of temperature on the ability of the surfactant to completely solubilize the oil. Here the data is collected at 5°, 20° and 50° C.

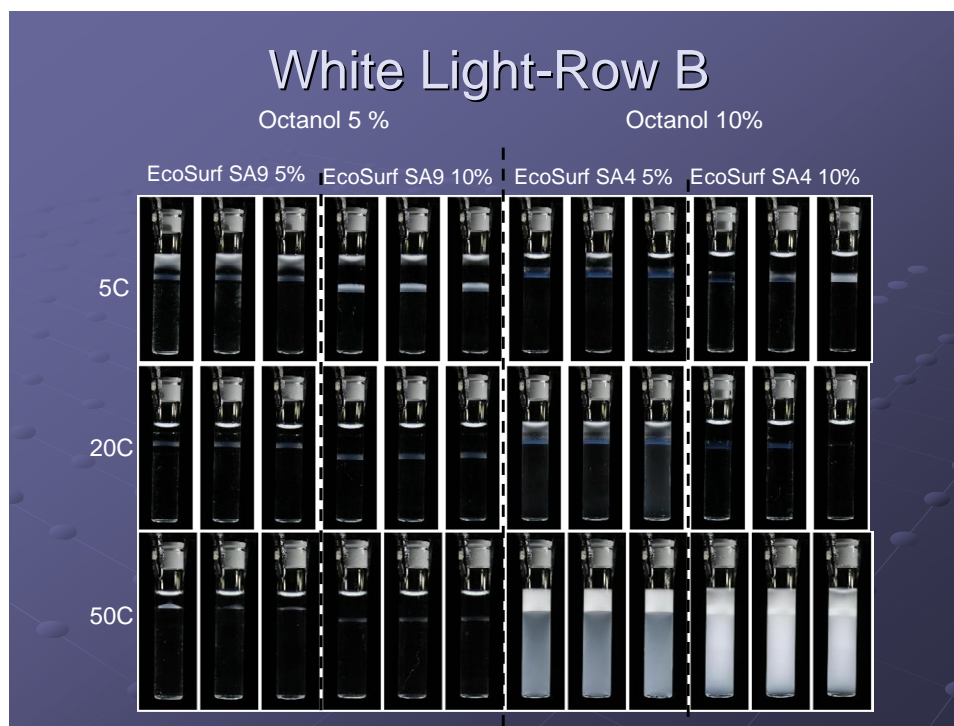


Figure 7. Example of the images collected from the PICA II and useful for evaluation of sample phase behavior

Hard Surface Cleaner Formulation

Hard surface cleaners are a large and diverse market. Preparation of a formulation typically focuses on a specific surface and specific soil. The flow chart in Figure 8 shows the general high throughput approach to developing these formulations. Two criteria must be met for any potential commercial formulation; stability and performance. In studies of hard surface cleaners, thermal stability is of critical importance. Once again the PICA II is chosen for this evaluation. Candidate formulations that demonstrated this attribute move into a second experimental design where evaluation of cleaning performance is conducted. From this testing a predictive model is generated that not only helps optimize the formulation, but also assists in understanding the chemistry involved in meeting this cleaning challenge.

For evaluation of the cleaner performance we once again turn to miniaturization and parallelization to create a new test protocol. In this process, 24 formulations, each one unique or as many replicates as desired, are tested simultaneously on a single substrate. The substrate is soiled and aged in the same manner as with the conventional test procedure. The substrate is then loaded in the testing apparatus, mechanical agitators are placed above each test area, the formulations are added simultaneously and the solutions are agitated. After a specific interval, agitation is suspended, and the agitators and test formulations are removed. The substrate is removed, rinsed and allowed to dry. Visual inspection ranks the cleaning efficiency of each formulation. Figure 9 shows a typical substrate coated with a conventional black, oily soil, then cleaned using 16 different cleaning formulations. (Columns 5 & 6 were not exposed to cleaning fluids in this example.) Here the performance differences are obvious between several of the

formulations. The superior formulation appears to be the solution used in well D1 (lower left-hand side).

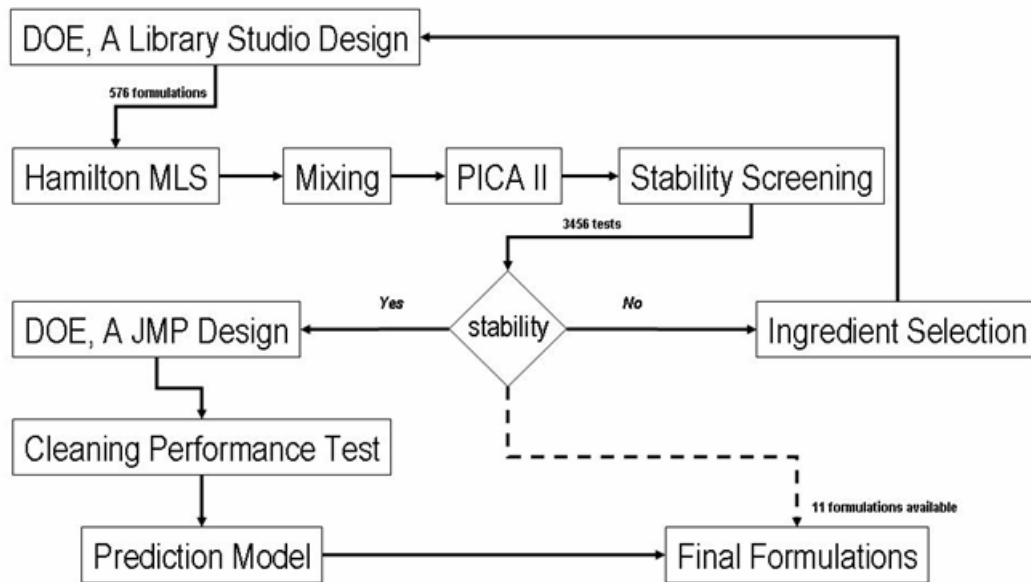


Figure 8. Flow chart of the typical high throughput Hard Surface Cleaner development

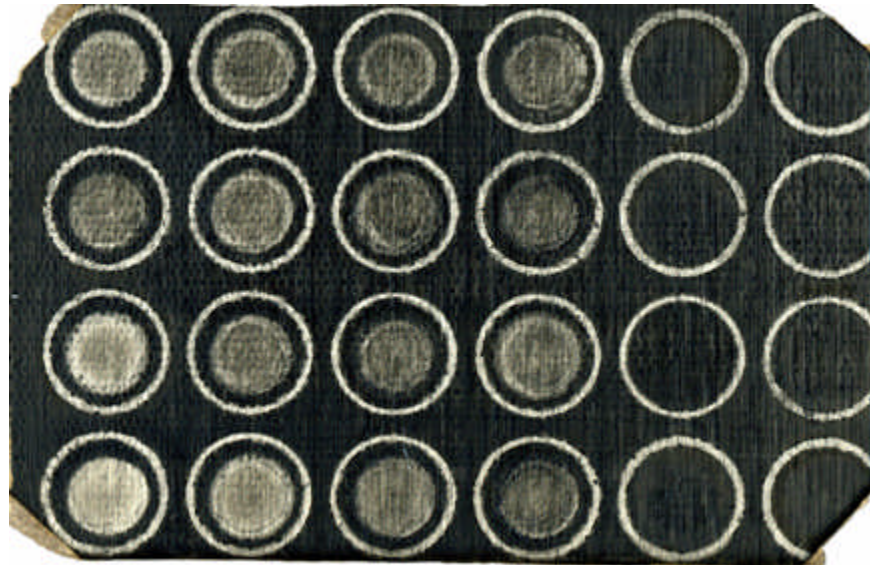


Figure 9. Sample of soiled substrate after cleaning with 16 different candidate cleaner formulations.

Using the above workflow it is possible to generate a model to predict cleaning performance vs. formulation composition using standard statistical analysis software such as JMP. An analysis of the data generated for the example above is shown in Figure 10 below.

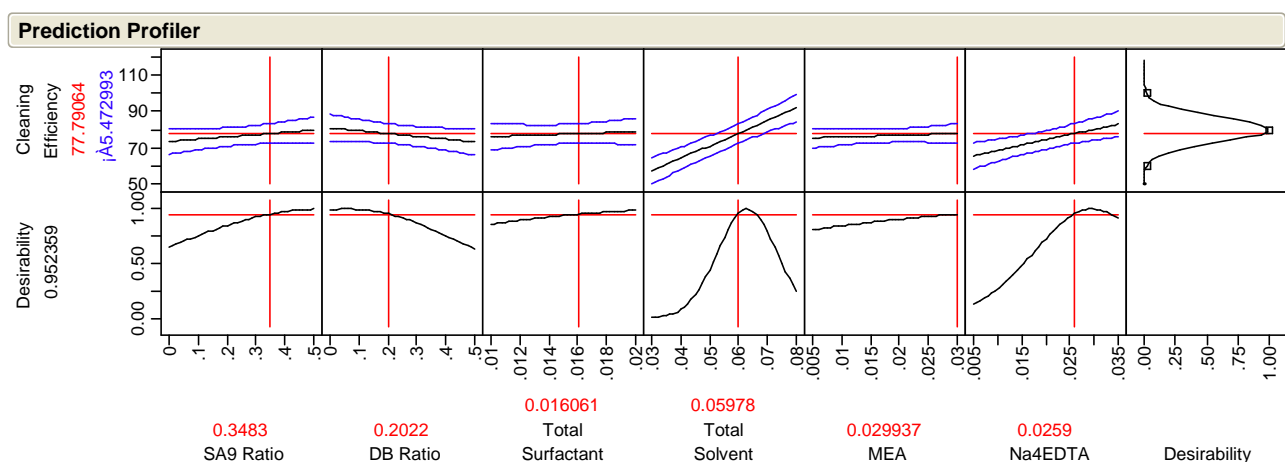


Figure 10. Statistical model of cleaning performance vs. composition

CONCLUSIONS

The need for greener surfactants and cleaning products is well known. While most consumers and manufacturers recognize the importance of green products there is still the requirement that products deliver on performance expectations. The methods described in this paper are useful both in the design and characterization of new, greener surfactants but also in generating and evaluating of new consumer cleaning formulations which minimize the impact of cleaners on the environment while maintaining customer expectations for performance.

REFERENCES

- ⁱ C. Johans, I. Palonen, P. Suomalainen, P.K.J Kinnunen, *American Laboratory*, (37)25, 14 (2005).
- ⁱⁱ S.D. Christian, A.R. Slagle, E. E. Tucker, *Langmuir*, 14(11), 3126 (1998).
- ⁱⁱⁱ W.D. Harkins, H.F. Jordan, *J. Am. Chem. Soc.*, 52(5), 1751 (1930).
- ^{iv} B.B. Freud, H.Z. Freud, *J. Am. Chem. Soc.*, 52(5), 1772 (1930).
- ^v J. F. Padday, A.R. Pitt, R. M. Pashley, *J. Chem. Soc., Far. Trans I*, 71(10), 1919 (1974).
- ^{vi} T.F. Young, W. D. Harkins, *International Critical Tables of Numerical Data, Physics, Chemistry and Technology*, ed. E.W. Washburn, Volume 4, 447 (1926-1930).
- ^{vii} M.I. Busby, J.J Michalowski, A.B. Argenton, Submitted to CESIO 2008 Conference.