AC 2009-830: ENGAGING HIGH-SCHOOL STUDENTS IN ENGINEERING, SCIENCE, AND TECHNOLOGY USING VIRTUAL LABORATORIES

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Adam Kirsch teaches physics, chemistry, engineering, and physical science at Crescent Valley High School. Mr. Kirsch’s eight years as a licensed professional mechanical engineer within the pulp and paper industry prior to entering the teaching profession strongly influences the emphasis within his classrooms. He feels that true learning is achieved when the learner is confronted with meaningful experiences. Traditional textbook instruction falls short of providing the engagement and open-endedness necessary to enable the learner to permanently integrate new understanding, particularly associated with math and science, within their cognitive framework. In his eight years as a high school teacher, Mr. Kirsch has often utilized the context of engineering and its focus upon problem solving to engage students in community-based projects.

Engaging High School Students in Engineering, Science and Technology using Virtual Laboratories

Abstract

The Virtual Chemical Vapor Deposition (CVD) Laboratory was originally developed for capstone projects in experimental design to be used by seniors and graduate students in engineering at the university level. The objective of this study is to explore the use of the Virtual CVD Laboratory as a learning platform at the high school level. While the simulation can be transferred intact, level-appropriate curriculum and assignments were developed for 9th and 10th grade high school students. In 2007-08, the Virtual CVD Laboratory was used by 263 students in *Introduction to Engineering* and in seven sections of *Chemistry* at Crescent Valley High School (CVHS). The most prevalent theme in examining student work was the wide variety of responses elicited by this ill-structured project and the clever ways in which statistical methods were synthesized and integrated into student understanding. Based on this successful experience, two workshops have been delivered, a two day workshop for high school teachers, community college instructors, and university professors in Summer 2008 and a one day workshop exclusively for high school teachers in Fall 2008. This interaction between CVHS and Oregon State University can be considered as a model to promote engineering and systems thinking at the high school level.

Introduction

With funding from the NSF CCLI and the Intel Faculty Fellows Programs, we have developed two virtual process laboratories, the Virtual Chemical Vapor Deposition (CVD) Laboratory and the Virtual BioReactor (BioR) Laboratory.[1,2] In a virtual laboratory, simulations based on mathematical models implemented on a computer can replace the physical laboratory. Since real systems do not deterministically adhere to fundamental models, random and systematic process and measurement variation can be added to the output. There are reports of successful integration of this modality to improve content specific domain knowledge at the high school level, such as in biology,[3] chemistry,[4] and physics.[5,6] Rather than being content specific, the virtual laboratories we have developed use the cognitive apprenticeship model of an engineering problem. They employ computer-aided technology to simulate complex industrial processes that are not accessible to students in a conventional university laboratory and allow future engineers to practice the skills they will need in industry, in much the same way a flight simulator is used for training pilots. The objective of the study presented in this paper is to develop and promote the use of one of these types of virtual laboratories, the Virtual CVD Laboratory, as a learning platform at the high school level. In order to construct and convey a meaningful project that high school teachers could reasonably implement, two major activities were used. First, a level-appropriate curriculum was developed and beta-tested in the introductory engineering and chemistry classes at Crescent Valley High School (CVHS). Second, that experience was used to develop and present workshops to high school teachers on how this tool can enhance student learning and, specifically, how they can implement the Virtual CVD laboratory into their curriculum.

Research suggests that student learning increases when activities undertaken for the purpose of learning are themselves meaningful to the learner.[7] Additionally, informed by research centered on student learning and understanding, the American Association for the Advancement of Science, in its *Benchmarks for Science Literacy – Project 2061*, speaks to the need for fundamental shifts away from rote learning and content knowledge, and the necessity for transitioning to pedagogical approaches emphasizing process, critical thinking, and problem solving within multiple contexts.[8] This group also emphasized the need for all students to obtain scientific literacy. Sixteen years later the ideals communicated in *Benchmarks* continue to drive curricular reform. For example, the new version of the Science Education Standards for the State of Oregon[9] advocates for less emphasis on content and increasing emphasis upon process as embodied in two contexts: *Engineering Design* and *Scientific Inquiry*. Not only is the word "engineering" a part of Oregon's Science Standards, but suddenly it comprises a quarter of the curricular emphasis identified for all K-12 classrooms in the state. There is no doubt that the discipline of engineering offers a particular powerful context for the integration of math, science and technology education coupled with the development of problem solving and design skills. This type of student engagement is viewed as a national need; legislators have passed the America COMPETES Act,[10] part of which mandates the development of instructional programs designed to integrate laboratory experience with classroom instruction.

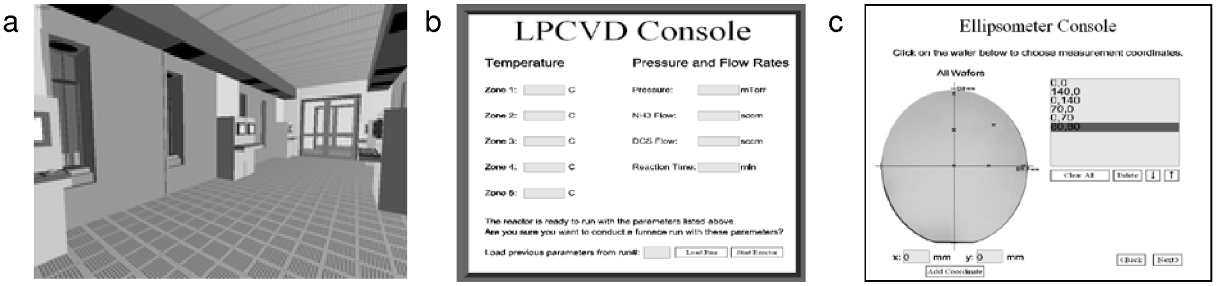
To provide a meaningful learning environment and acknowledge the ideals echoed in Education Standards for years, students must be given the opportunity to engage in problems, to develop and provide solutions that are perceived as authentic. Students must be given the opportunity to tackle ill-structured problems (as opposed to typical text-book problems); these types of problems compel learners to seek knowledge and understanding for themselves. Often they learn the most through failure and mistakes, intrinsic pieces of the engineering process. Only by forcing students to perceive such problems and failures as opportunities instead of things to be feared, will we truly prepare our students to make meaning of engineering and science in the real world. This work is based on the premise that one of our students' greatest values to our future society will be their ability to contend with open-endedness and ambiguity to provide solutions to the problems they themselves identify.

Although a substantial case can be made as to the values of a curricular approach with this emphasis, all pedagogical decisions within today's classroom must still account for the realities of limited budgets and resources. The idea of using virtual laboratories to facilitate project based learning is compelling since, once the software has been developed, the cost to transfer it is relatively small, consisting mostly of developing teaching materials and teacher expertise. The software design allows the application itself to be used without modification. No matter the course employing the Virtual CVD Laboratory, students run the reactor, take thickness measurements, and analyze their data. At the high school level, the Virtual CVD Laboratory can be used to make instruction more meaningful for students by making it more authentic and realistic. Through project based learning and the excitement of hands-on activities, students are engaged and encouraged to use higher cognitive skills. This authentic culture couples the ability to learn with the ability to use knowledge in a practical context. Through this activity, they are also presented with the opportunity to consider engineering as a future career. They often become more motivated as they feel the work they do makes a difference or has applicability in the real world. These aspects are especially effective for students with non-conventional learning styles.

Virtual CVD Laboratory

The instructional design of the Virtual CVD Laboratory is based on a cognitive apprenticeship model where students are provided a problem in the similar context to an engineer in industry. Specifically, student teams attempt to optimize the performance of an industrial process by investigating the effect of the input variables. The deposition of silicon nitride, Si_3N_4, films by chemical vapor deposition was chosen as a model system. CVD is an important unit process used to grow thin films in the manufacture of integrated circuits and other devices. This process has sufficient complexity to warrant a methodological design approach, but also can be qualitatively considered in terms of engineering science fundamentals such as mass transport and reaction kinetics. In contrast to a physical laboratory experience, data collection is performed virtually by the simulation, and therefore, consumes a relatively small amount of the student's cognitive load. Thus, student effort can be expended on problem scoping (including information gathering) and developing an experimental strategy to explore the design space and solve the problem. In other words, students can invest cognitive load on the analysis and interpretation of the data and on applying this analysis to make decisions and iterate on the experimental .[1]

The software is designed as a number of independent components. The three main components are the 3D student client, the web instructor interface, and the data server. The Virtual CVD Laboratory student client is a *three-dimensional (3D) graphical interface* that provides the look-and-feel of a typical semiconductor manufacturing environment. From here the students can make reactor runs, take measurements that they specify, get output data and determine the cost of their experiments. Figure 1 displays screen-shots of this interface. This student user interface goes beyond simply providing a method for students to access the simulation. It also allows students to become familiar with the appearance of a cleanroom. The similarity of the 3D interface to popular video games allows this learning platform to feel familiar and non-threatening to the student. To grow Si_3N_4 thin films using the Virtual CVD reactor, the student must typically specify 9 operating parameters. The reactor input screen is shown in Figure 1b. The different temperature zones in the reactor (5 zones by default) can be independently controlled. In addition, the flow rates of ammonia and dichlorosilane feed gases, the reactor pressure and the reaction time must be chosen by the student. After the student has run a batch of wafers through the virtual reactor with a given set of input values, they have access to a virtual ellipsometer, similar to the tools engineers use, to measure the film thicknesses. They need to select the wafers they will measure and the measurement locations on those wafers. Figure 1c displays a view of the virtual ellipsometer console for a specific wafer. From these data, students can estimate the overall film uniformity. The students are charged virtual money for each run and for each measurement. This feature applies a realistic cost constraint resembling that which an engineer would experience in industry. After the students determine their final optimized reactor settings, they can submit the process recipe via the 3D Student Client.



The reactor is ready to run with the parameters listed above.
Are you sure you want to conduct a furnace run with these parameters?

Load previous parameters from run#:

Click on the wafer below to choose measurement coordinates.

0,0
140,0
0,140
70,0
0,70
80,80

x: 0 mm y: 0 mm

Figure 1. Screen shots of the *Virtual CVD* 3D graphical user interface a. CVD reactor bay in the virtual fab, b. *Virtual CVD* reactor parameter inputs: these parameters must be input by the student to run the reactor c. selection of measurement points on a wafer.

The *Instructor Web Interface* has been designed to allow transportability of the learning tool and to provide instructors an easy way to administer the project, change reactor parameters (if desired) and assess the students' performance. To implement in a course, an instructor can set-up an instructor account.[11] After establishing an instructor account, the application can be personalized for use in a specific course and student accounts can be established. Through this web interface the instructor has access to the students' interactions with the Virtual CVD Laboratory. All of the students' virtual experimental activity, including the data for student runs and measurements, is captured in a database and can be utilized as an assessment tool. The instructor's web interface contains an overview page which shows the total number of furnace runs, measurement sets and total cost. By clicking on a student's account name the instructor can view the student's chosen reactor parameters for each run, and the student's measurement points and resulting measured values for each measurement set. The time at which the run or measurement set was made is also shown. These data can be exported to a Microsoft Excel spreadsheet. Furthermore , using the web interface the instructor can customize the reactor behavior. Instructors who do not wish this level of specificity can simply use the default values.

High School β-Implementation

The Virtual CVD Laboratory was used in two classes during the 2007-2008 academic year at Crescent Valley High School in Corvallis, Oregon. CVHS has a student population of approximately 1000 students. A summary of the experimental activity is shown in Table 1. In total, 123 teams completed over 1,500 runs and made over 60,000 measurements. The first class was *Introduction to Engineering*, comprised of 53 students most of whom were 9th-graders. The second course was 1st-year *Chemistry*, which involved 210 students within seven sections (taught by three different instructors). The curriculum was developed as a collaborative effort between CVHS and OSU, leveraging the materials available from OSU, but modifying the instruction to be level appropriate. A key element in the success of this cross fertilization is that a graduate student (one of the authors) participated in the high school curricular development and the initial classroom delivery. An overview of the curriculum and the outcomes from the initial deployment are presented in this section.

Table 1. Average responses of post worksheet Likert survey

Class	Teams	Runs	Measurements	Cost
ITE08	31	424	10899	$ 2,937,425
Total Engineering	**31**	**424**	**10899**	**$ 2,937,425**
CH108	16	158	3772	$ 1,072,900
CH208	23	323	33686	$ 4,141,450
CH308	10	140	4819	$ 1,061,425
CH408	15	131	3544	$ 920,800
CH508	8	102	2369	$ 687,675
CH708	11	153	3659	$ 1,039,425
CH808	9	93	2122	$ 624,150
Total Chemistry	**92**	**1100**	**53971**	**$ 9,547,825**
Total	**123**	**1524**	**64870**	**$ 12,485,250**

Introduction to Engineering – Curriculum

This class was team taught by one science and one applied technology teacher. Student learning objectives targeted through use of the Virtual CVD Laboratory were the development of critical thinking and problem solving skills. Additionally, the use of the Virtual CVD Laboratory was expected to reinforced concepts of engineering design as embodied using the class IDEAL model (**I**dentify, **D**evelop, **E**valuate, **A**ct, **L**ook back). Finally, the Virtual CVD Laboratory was expected to provide a context for an introduction to the discipline of chemical engineering. The implementation of the Virtual CVD Laboratory required 780 minutes of class time. The primary components of this implementation are shown in the flow sheet in Figure 2.

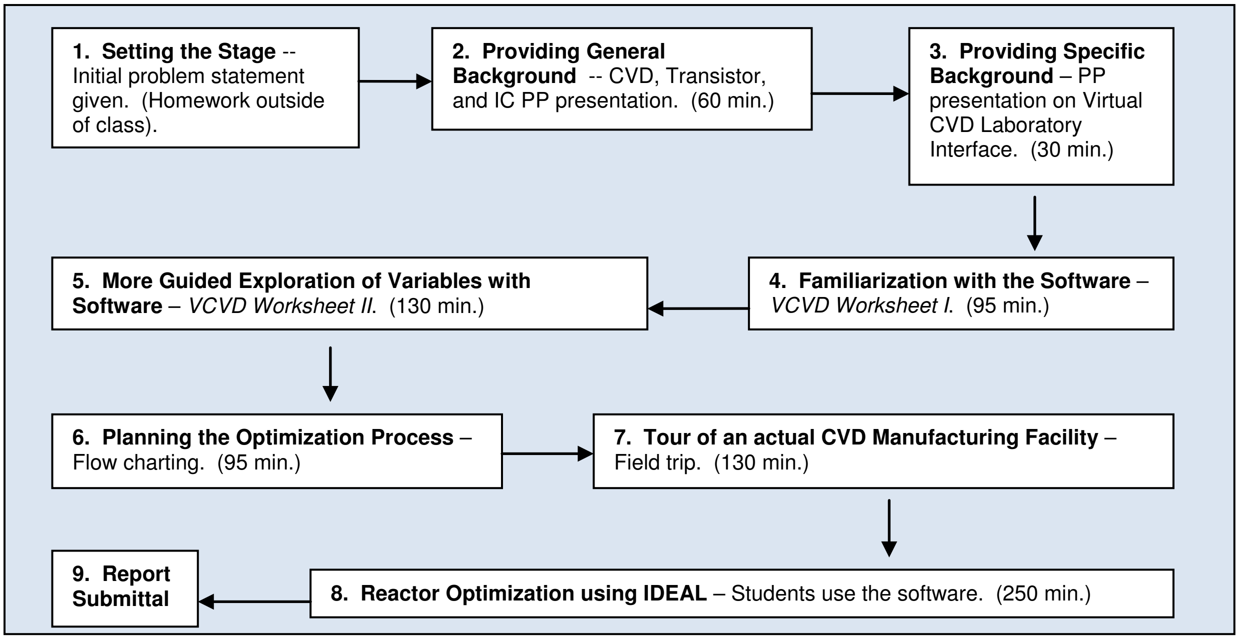


Figure 2. Activities for the Virtual CVD project in the *Introduction to Engineering* class.

Initially students were given a preliminary handout that emphasized the situated nature of the project where class instructors represented owners of a manufacturing company utilizing the CVD process, and pairs of students were asked to imagine themselves as process engineers tasked with determining the combination of operating parameters necessary to achieve a uniform silicon nitride deposition upon each wafer. Simultaneously, as each reactor run and thickness measurement costs money, students were also challenged to minimize the cost of their optimization process. Optimum parameters resulting in successful deposition were determined and controlled by program parameters established by the classroom instructors. Two deliverables were required: (1) a formal report listing optimized reactor parameters coupled with evidence in the form of deposition measurements intended to support their claim for optimization; and (2) a laboratory journal documenting each action the group made and the reasoning they utilized to reach their decisions during reactor optimization.

The initial handout presented for Step #1 was read by students outside of class prior to the initial PowerPoint presentation listed in Step #2. Step #2 was the first use of dedicated class time for this project. In this second step, students received instruction via a PowerPoint presentation intended to introduce the process of chemical vapor deposition used to manufacture transistors, transistors themselves, and integrated circuits (the primary application for transistors). Introduction of the actual Virtual CVD Laboratory did not occur until Step #3 at which time the interface of the Virtual CVD Laboratory was introduced. Although preceded by the PowerPoint lesson in Step #3, Step #4, with its hands-on aspect, was expected to be the most effective means of introducing students to the Virtual CVD Laboratory software. The process was guided by a step-by-step worksheet. Initially, it was believed that following the completion of this worksheet, students would be ready for project work. However, given that the class consisted primarily of 9th graders having limited experience addressing open-ended problems with numerous variables, an additional level of scaffolding was provided. In Step #5 students were given a second worksheet to complete. On this second worksheet, students were instructed to sequentially alter specific variables (all furnace zone temperatures simultaneously by the same amount, the increase in temperature of a single furnace zone, chemical flow rates, and reaction time), one at a time, to gain initial insights regarding variable impact upon silicon nitride deposition. Step #5 was a purposeful attempt to provide scaffolding to compensate for basic chemical and scientific principles missing from participant backgrounds. The 9th grade participants typically receive such instruction in the 10th grade.

Once acquainted with some of the reactor parameters impacting wafer deposition, Step #6 asked students to develop a plan outlining their approach for reactor optimization. Specifically, students were asked to identify a strategy to employ when they used the Virtual CVD Laboratory. What parameters would be optimized first? Which ones later? What decision point would initiate advancement to the next stage of their plan? To facilitate this process, students were asked to illustrate their plan with a flow chart. Prior to pursuing reactor optimization within Step #8, class participants toured a CVD facility operated by a local community business partner during Step #7. In addition to the facility tour (limited to viewing the lab from observation windows), actual CVD process engineers responsible for various portions of the company's CVD process at the manufacturing facility were made available to respond to student questions. In this way students were permitted to obtain additional insights related to their optimization plans. Moreover , this field trip experience increased the sense of authenticity for this activity. Following the visit to the local manufacturing facility, students were given class time to work toward reactor optimization in a self-directed fashion.

Introduction to Engineering - Outcomes

Figure 3 presents the summative performance of the student teams in the *Introduction to Engineering* class. Students spent between $17,000 and almost $200,000 on experimentation and achieved uniformities between 85% and 99%. This project forced students to evaluate the trade-off between these two performance metrics.

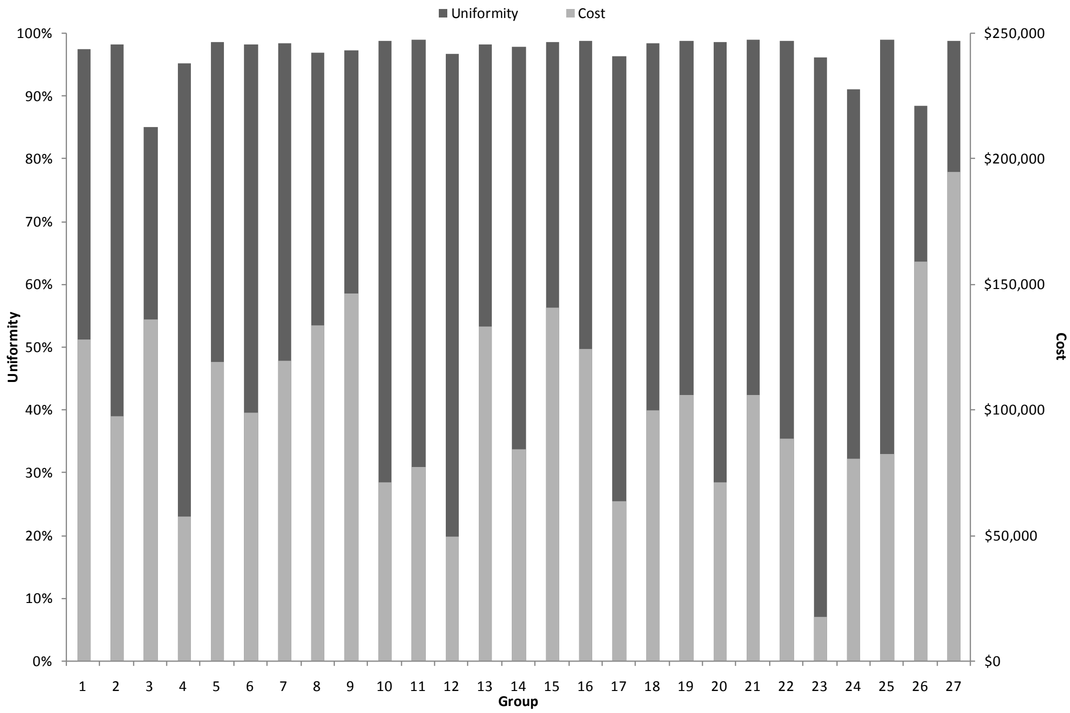
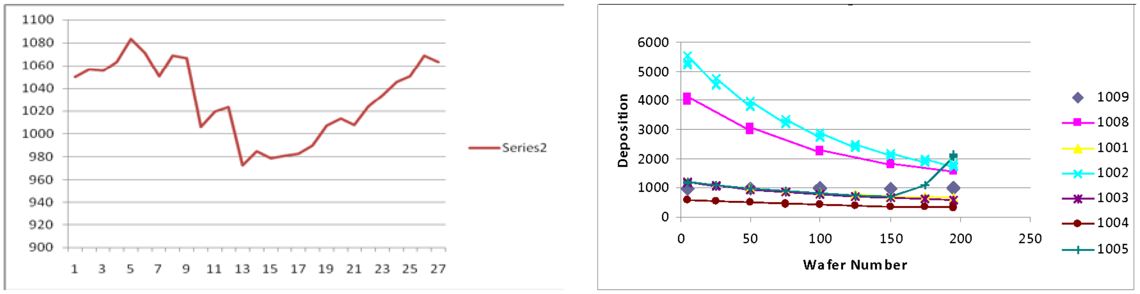


Figure 3. Summative performance of students in the *Introduction to Engineering* class. Students had to balance improved uniformity and cost.

The assessment of the Virtual CVD Laboratory for this high school pilot was evaluated in a holistic manner towards the effectiveness in meeting the learning objectives. A number of noteworthy outcomes, both anticipated and unanticipated, resulted from the implementation of the Virtual CVD Laboratory within the *Introduction to Engineering* class. It was anticipated, for instance, that these students would have difficulty with the development of an optimization strategy and corresponding flow chart. Step #6 (Figure 2) was intended to assist students. As anticipated several groups struggled to complete their flow charts. More importantly, and perhaps more telling as to the difficulty students in general have when asked to methodically plan an approach as opposed to randomly experimenting, of the twenty-seven student groups, only two groups were observed to actually utilize their flow charts to guide their initial optimization process. Most groups, when entering the self-directed phase, proceeded with optimization in a random fashion despite their previous planning. Future delivery will provide structure to make it necessary to refer back to the flow charts.

Figure 4 shows summary graphs taken directly from three groups' final reports. This sample is representative of the wide variation in output that is a reflection of the open-endedness of the project work. The tasks presented to the students utilizing the Virtual CVD Laboratory compelled groups to not only determine an optimization scheme, but to also creatively communicate their results. Some groups gave little or no evidence to justify their results, either simply stating their conclusion unsupported or presenting graphs of their measured thicknesses that failed to support their conclusions. For example, Group 1 (Figure 4) fails to demonstrate even the basic difference between deposition uniformity throughout the reactor and uniformity upon each individual wafer. Here the group simply plotted the twenty-seven thickness readings recorded from a batch of produced wafers, three readings each from nine different wafers throughout the batch, without delineating location of each reading within the reactor or upon an individual wafer. This group's explanation of this unlabelled graph was simply "Our graph is not as good as some peoples, but we did fewer trials." On the other hand, the nature of the task caused many groups to carefully consider the formats of their presentations. The graph presented by Group 2 illustrates uniformity throughout their reactor for a number of trials. Within the text of their report they distinguish the uniformity displayed here from single-wafer uniformity. Group 3 integrates statistical methods into the analysis reporting two graphs, one for average thickness on a given wafer (central tendency) and one for the range (dispersion). This integration of mathematics content into their work is a positive outcome from the situated nature of this authentic activity. Both Groups 2 and 3 presented these graphs as evidence that they had successfully optimized reactor parameters. These results indicate that students were encouraged to use higher cognitive skills as they contended with the open-ended optimization challenge.


a. Group 1

b. Group 2

c. Group 3

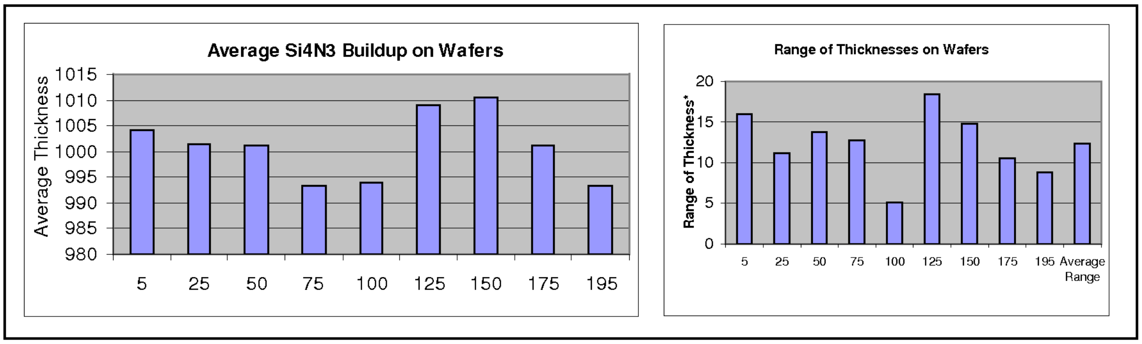


Figure 4. Graphical results reported by three different groups in *Introduction to Engineering*. a. Group 1 fails to acknowledge a difference between uniformity throughout the reactor vs. uniformity upon each individual wafer b. Group 2 illustrates deposition uniformity throughout the reactor for various runs c. Group 3 reports both measurements of central tendency and measurements of dispersion.

The contextual and creative integration of statistical methods at a surprisingly high level for this 9th grade cohort was a positive outcome. In addition to the example cited by Group 3 above, a particularly notable performance is as follows. Within the Virtual CVD Laboratory, as many as eight different wafer reactors can be set up to perform deposition, and as many as eight different ellipsometers can be operated with which to measure wafer deposition. While the instructor has the ability to alter process and measurement characteristics, none of the ellipsometers were actually modified for use with this class. Nevertheless, some students perceived differences between readings when different ellipsometers were used to measure deposition thicknesses. In fact, one group made sure to repeat all measurements with the same ellipsometer to reduce measurement variation. Thus, the nature of the tasks presented to the student when using the Virtual CVD Laboratory seems to create a heightened awareness of possible complicating factors and an appropriate response to these factors – a desired outcome.

The integration of statistics in a meaningful way was also demonstrated in the groups' experimental strategies. For example, one group wrote:

> *"We did not decide to change the temperature zone without thinking about the other parameters and their possibilities first. There were two other choices of parameters that we could have changed: flow rate (keeping the 10:1 ratio) and reaction time. We had learned in our preparation that both flow rate and reaction time had their own effects, both positive and negative, on the wafer deposition. We also noticed, however, that these effects were a little weaker than when we changed the temperature zones. Changes could be made concerning wafer deposition with both the flow rate and the reaction time. These were relatively minor changes, for us, compared to changes that we were able to make by adjusting the temperatures of individual zones 1 through 5. Changing temperature was a factor that we could change with much variability. With the zones, we were able to pinpoint exactly what wafer numbers needed to be thicker or thinner. We decided that we would choose to change the zone temperatures basically to maintain control of our runs and our trials."*

In this description, we see students doing a couple of things. First, these students noticed differences in the relative magnitudes of the impacts some variables had on deposition. Upon discovering these differences, they opted to work with the more significant variables first (temperatures). In essence they had performed a *Screening Experiment* covered in courses of Design of Experiments. In addition when considering this aspect of the problem, these young engineers realized and discovered something else – that while all variables could impact deposition, some variables (zonal temperatures) could be used to affect changes on specific wafers while other variables were better suited to affect changes upon all wafers. This realization lead to a very specific optimization strategy.

Finally, a remarkable synthesis of statistical methods in the manufacturing context of this situated project was demonstrated in the following excerpt:

> *"Using Microsoft excel, we also calculated that the average wafer deposition is about 999.2 angstroms with a standard deviation of about 6.74. What this means is that 68% of all wafers are between 992.5 and 1005.9 angstroms in deposition, and 98% of all wafers are between 985.7 and 1012.7 angstroms in deposition. Assuming that all wafers produced must be within 15 of 1000 angstroms, only about 1% of all wafers produced would have to be discarded due to defects."*

This strategy aligns with concepts of Statistical Process Control taught in Industrial Engineering.

As presented above, the most prevalent theme in examining student work was the wide variety and clever ways in which statistical methods were synthesized and integrated into student understanding. Given that these students did not have the engineering science background to understand this process from first principles, it is not surprising to see the common use of statistical methods. What did surprise the authors, were the cases in which statistics was applied at a quite sophisticated level.

Chemistry – Curriculum

Although implementation within the seven chemistry classes mirrored implementation within the *Introduction to Engineering* class in some aspects, there were notable differences. As with the *Introduction to Engineering* class, objectives best obtained through use of the Virtual CVD Laboratory were the development of critical thinking and problem solving skills. But where the use of the Virtual CVD Laboratory was expected to reinforced concepts of engineering design for the engineering student, the Virtual CVD Laboratory was expected to help the chemistry student develop the ability to identify and quantify relationships between variables and reinforce chemical concepts of stoichiometry and reaction dynamics. The differences in the learning objectives illustrate the versatility of a virtual laboratory in addressing differing curricular goals. The implementation of the Virtual CVD Laboratory within chemistry required 420 minutes of class time. The primary components of this implementation are shown in Figure 5.

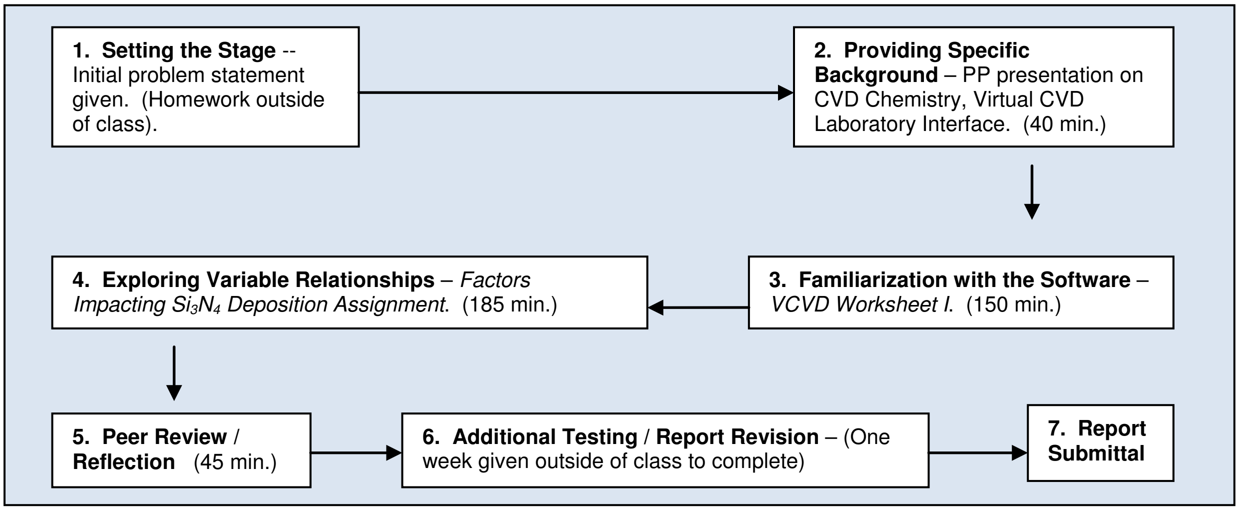


Figure 5. Activities for the Virtual CVD project in the *Chemistry* classes.

Within the *Chemistry* classes, the utilization of the Virtual CVD Laboratory was more directed, although, once again, tasks were framed within the situated context of the project. Instructors remained owners of a company utilizing the CVD process, however this time student groups represented consultants hired by the owners to characterize the operating characteristics of their wafer reactor. As such, students needed to decide what information to obtain, how much information to obtain in order to convince the owners of the relationship of the parameter in question to wafer deposition, and how to display the results to convince the owners. Although accrued costs were to be minimized, chemistry students were not asked to optimize wafer reactors for a targeted thickness. Instead, students were asked to couple chemical principles of stoichiometry, reaction dynamics, and limiting reagents to their understanding of the process of science. Specifically, students were asked to determine how the *ratio* of ammonia to DCS flow, temperature and reaction time impact the deposition of Si_3N_4. As before with the engineering students, the goal of minimized research cost was pitted against a second goal – in this case that goal was fully supporting the relationship that exists between the three parameters and wafer deposition throughout the reactor with sufficient evidence. Students were left with some uncomfortable questions. What trials should be run? How many data points are sufficient when drawing conclusions about relationships? What graphs should be produced to illustrate the desired relationship?

As with the *Introduction to Engineering* class, the instruction in *Chemistry* was deliberately scaffolded as shown in Figure 5. A few notable differences are discussed below. Step #1 was a brief homework assignment describing the chemical reactions involved with the CVD process modeled in the Virtual CVD Laboratory. This assignment was tied to the stoichiometry unit and was given to students several weeks prior to their first hands-on experience with the software. In this way, the classroom lesson was integrated into the project-based learning experience. Students were given approximately 185 minutes of class time to develop a deliverable consisting of a brief report describing the steps taken to determine the relationship between deposition and each targeted variable, evidence in the form of a graph complete with a regression displaying the strength of each correlation, specific connections to chemistry concepts, and a justification stating why the data presented was sufficient to fully describe the relationship between deposition and each of the three factors.

Chemistry – Outcomes

Originally this projected only included Steps #1-#4 in Figure 5. However, when the reports first were turned in, it was evident that many students fell far short of properly conveying the desired relationships. As a result, Step #5 was added. At this time, a brief period of instructor-led discussion sought to identify shortcomings in graphs and relationships between variables. Students were asked to exchange reports with one another and were asked simply “would you be convinced by the evidence presented if you were the owner receiving this report?” “Do you even understand what the graphs are representing?” Students were asked to respond in writing to the group whose paper they were reviewing, and to provide a list of questions about the results that were presented intended to focus the authors upon shortcomings in their data. Once papers were returned to their original owners, students were given a week to address identified shortcoming and resubmit their final deliverable.

Figure 6 presents representative graphical results that student groups reported. The first three graphs (Groups 4-6) show three different approaches to investigate the relationship between the reaction time and deposition while the fourth graph (Group 7) shows the effect of gas flow ratio. The rich nature of this open-ended project forced students to clearly define how to approach the task. For example, students had to first recognize the need to differentiate between deposition throughout the reactor across all wafers and deposition upon a single wafer. For instance, Group 4 (Figure 6) showed results in which the relation between reaction time and deposition is displayed for a single wafer, clearly revealing a linear trend (as it should be). Alternatively, Group 5 opted to make batches at only two reaction times, but measured across the entire boat instead of focusing upon a single wafer at a single location. Testing at only two different reaction times is not sufficient to verify the linear nature of the relationship. Finally Group 6 ran five batches of wafers at five different reaction times and plotted the average deposition of all wafers versus reaction time; this method enabled them to confidently discover a linear relationship. While this approach contained many more measurements than needed, it was remarkable in that this group not only used the same parameters each time but also measured the same point on the same wafer a number of times in an attempt to quantify both reactor and ellipsometer variability. As in the *Introduction to Engineering* class, we see creative and sophisticated application of statistical methods. The relation of flow ratio and deposition thickness, depicted by Group 7, is clearly more complex.

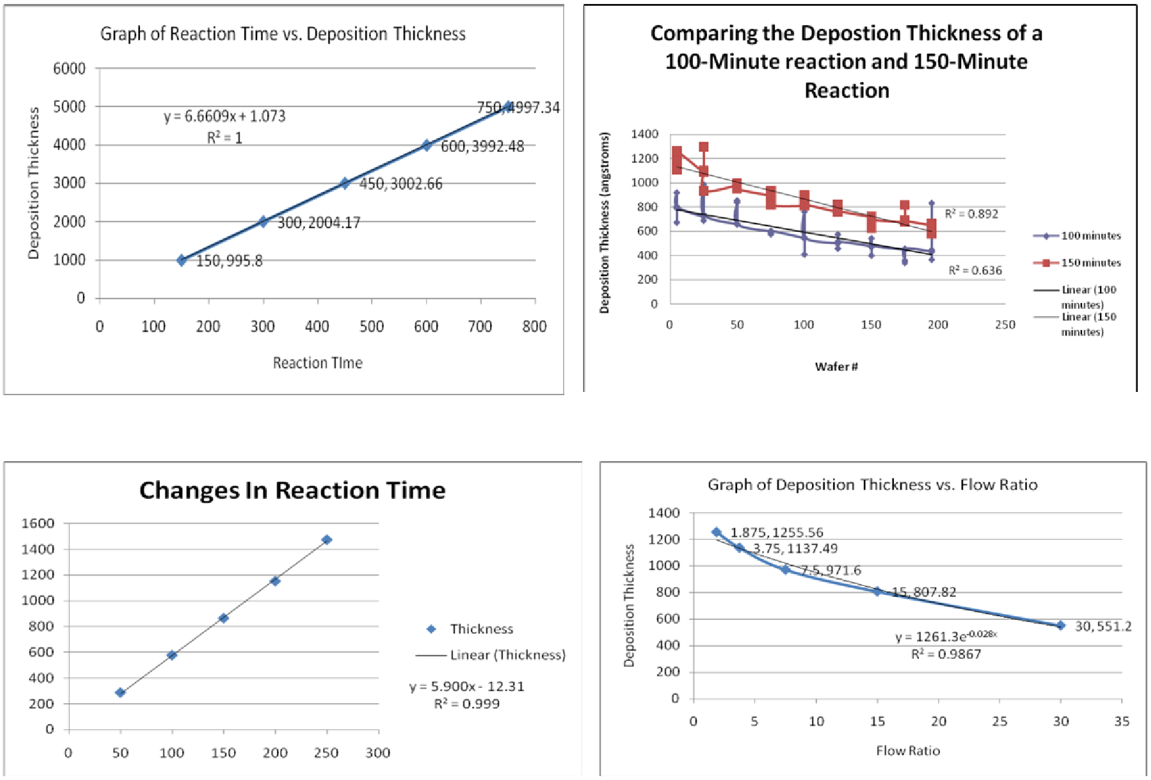


Figure 6. Graphical results reported by four different groups in *Chemistry*. a. Group 4, b. Group 5, and c. Group 6 show alternative methods for determining the effect of reaction time on thickness. d. Group 7 explores the effect of feed gas flow ratio.

In the justifications of their approaches, groups often demonstrated higher level cognition, often corresponding to *Evaluation*, the deepest level in Bloom's taxonomy. For example, although students were instructed to use regressions to quantify the correlation present between their variables, Group 4 (Figure 6a) extended their interpretation of their regression to justify the use of only five data points to sufficiently illustrate the relationship between deposition and reaction time.

> *"We believe that we have collected sufficient data because of the consistency and the number of points we had. If we were only to test 2 or 3 points, we still wouldn't be able to say much about the deposition thickness, because we don't have enough data points. However, we have five total data points (excluding the point (0,0)), which we believe is enough to come up with a rough sketch of*

> *the graph. In addition, the data points have an amazing correlation. They are almost perfectly linear. On the graph, it can be seen that the thin, black line matches almost perfectly with the thick, blue line (the one that corresponds to the data points)."*

This assignment tasks students to make key decisions before proceeding with their experimentation. To minimize the cost of their experimentation, students needed to carefully construct exactly what data they needed to plot. Surprisingly, formulating what to plot was very difficult for many students. When given a textbook problem with a given x and a given y, they were proficient. However, with the Virtual CVD Laboratory they had multiple columns of data from which to choose, and often lacked the clarity to define which of these columns to select. This aspect became a teachable moment during the project. After struggling and frustration, students became willing to listen to suggestions and began to realize the importance of identifying independent and dependent parameters. This identification further enabled careful consideration of the data that needed to be collected.

One challenge for the instructor is that the very richness of this activity makes student assessment problematic. The great number of creative approaches for accomplishing the same objectives seemingly demands one to rank the various approaches. Certainly a large number of batches might be enough to justify a conclusion regarding the nature of the relationship between one of the reaction parameters and deposition thickness. As the examples above illustrate, the use of creative methods and techniques, often employing tools from other disciplines (i.e. mathematics and statistics), coupled with the freedom to select their own approach to the problem, empowered the majority of these chemistry students to take the realistic problem-solving techniques far beyond the techniques required in solving textbook problems within more traditional educational frameworks.

Workshops for High School and University Instructors

Based on the experiences at CVHS discussed above, two workshops were presented on the Virtual CVD Laboratory to introduce this tool to high school and university level instructors. During Summer 2008, 12 participants attended the first Virtual CVD Laboratory workshop. The second workshop was held in Fall 2008 and served 7 participants. Both workshops were held on the campus of Oregon State University in Corvallis, Oregon and participants came from a wide variety of geographical locations, both local to the Pacific Northwest and as far away as New York, South Dakota, Montana and Arizona. In total there were 19 participants including 11 high school teachers, 5 community college teachers and 3 4-year university teachers.

These workshops were designed to give participants an introduction to the Virtual CVD Laboratory and inspire participants to use it in their classes. In order to accomplish these goals, the completion of the workshop needed to provide participants with sufficient information to achieve the following objectives:

- Operate the Virtual CVD Laboratory including performing runs and making measurements
- Utilize spreadsheet software to analyze data and report results
- Use the features of the Instructor Interface

- Design and instructional unit that uses the Virtual CVD Laboratory
- Reflect on the usability and feasibility of using the Virtual CVD Laboratory

A flow diagram of the workshop activities is presented in Figure 7 with block height proportional to the amount of time spent on each topic.

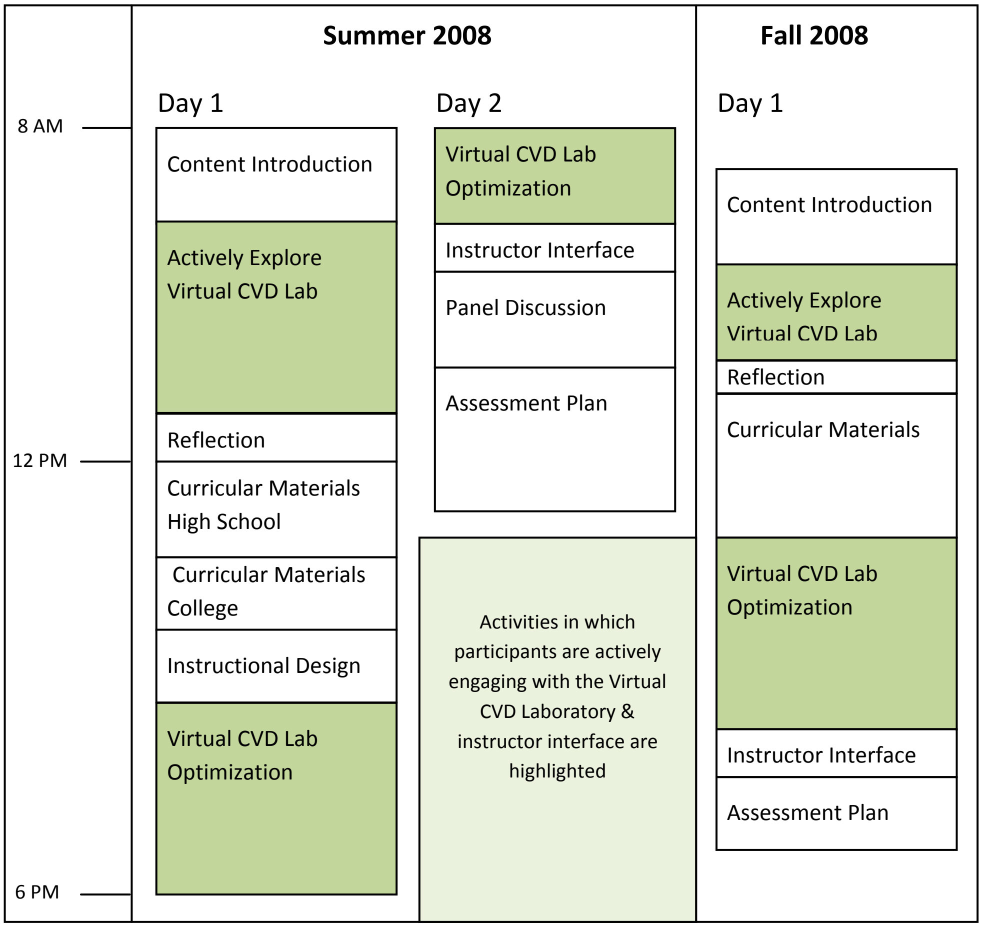


Figure 7. Activities in the Summer 2008 and Fall 2008 Virtual CVD Workshops

The workshop flow started with general introductions. As the virtual CVD lab is based on one of the many steps in semiconductor processing, it was necessary to provide the workshop participants with a brief overview of microprocessors, transistors and the integrated circuit manufacturing process. A more detailed description of the process modeled by the Virtual CVD Laboratory followed that provided participants with relevant technical information. Participants were then given the opportunity to directly interact with the program and experience it from a student perspective, walking through an orientation worksheet very similar to the one previously used in high school classes. After working with the program curricular materials and curricular development were discussed. Students that had taken classes in which the Virtual CVD Laboratory was used contributed with panel discussion and their perspective of the program. Participants were encouraged via discussion and surveys to consider and formulate when appropriate how the program could be used in classes they teach and what benefit the Virtual CVD Laboratory offers as an addition to traditional teaching methods. With classroom integration in mind participants were further offered the opportunity to test the Virtual CVD Laboratory in an optimization exercise. The workshops rounded out with additional discussion, active walk-through of the instructor interface and resources available to instructors and overview of assessment.

Pedagogy

In preparing and delivering the workshop, the author's structured it in such a way that participants would have access to a variety of resources both at the workshop and as a reference in the future while preparing to present material in class. One such resource was the workshop binder that had materials from each presentation given throughout the workshop. This allowed participants to easily follow along with presenters and make notes as necessary. The binder also contained, interactive worksheets, technical references on the Virtual CVD Laboratory program operation as well as CVD processing information covering mass transfer and reaction processes in more detail. Further, the binders included sample curricular material that could be used as a template for implementation of the Virtual CVD Laboratory in their classes and contact information for all presenters and assessment information. The curricular materials, including implementation schedule, worksheets, assignment sheets and presentations were also made available on the Virtual CVD Laboratory website. After being assigned instructor login information, participants could download soft copies of these resources for easy modification, reproduction and use in their classes. Participants commented positively on the availability of these resources. Some comments include the following statements:

> *"Excellent resources. Having the PowerPoint will make my use feasible."*
>
> *"My students need context! So I will definitely use these resources to provide that for that & educate myself on the process as well."*
>
> *"The instructor resources on the webpage will aide greatly in giving the students an overview of the process."*
>
> *"The background information supplied will help me prepare the lectures and labs, and will help the students to prepare the pre-lab materials."*
>
> *"Terrific, fantastic! I will use the PowerPoint slides as they are; I have read most of the background information and will finish doing so before implementing so I can be more helpful for students at making the simulation more realistic."*

The author's also attempted to balance knowledge conveyance via PowerPoint slides with active learning via hands on experimentation with the Virtual CVD Laboratory and associated tools. Participants at the first and second workshops spent approximately 50% of the workshop time actively engaging with the Virtual CVD Laboratory and instructional tools. This allowed workshop participants to not only hear about and see how the program operates and how this tool might be implemented and managed in a classroom setting, but also experience it on a smaller scale.

Assessment

At the end of each workshop participants were asked to rate the workshop and workshop material on a Likert scale. A summary of the questions asked and statements posed as well as the average score for each question is given in Table 2.

Table 2. Average responses of post worksheet Likert survey

	On a scale of 1 (not likely, disagree) to 5 (likely, agree), rate the following:	*Average*
1	How likely you are to use the Virtual CVD Laboratory in a class next year.	4.47
2	The Virtual CVD Laboratory Workshop was well prepared.	4.74
3	The Virtual CVD Laboratory Workshop was useful to me.	4.84
4	I am able to navigate, perform runs and make measurements using the Virtual Chemical Deposition (CVD) Laboratory.	4.63
5	I am able to use Excel to analyze data and report summary results.	4.56
6	I am able to use the features of the Instructor Interface.	4.61
7	I am able to design an instructional unit that uses the Virtual CVD Laboratory.	4.13

The questions were rated on a scale of 1 to 5 with 1 corresponding to not likely, disagree and 5 corresponding to likely, agree. The statement "I am able to design an instructional unit that uses the Virtual CVD Laboratory" scored lowest with an average score of 4.13. In comments relating to this statement, some participants noted the following:

> *"It'll take time & work."*
>
> *"I would've liked a little more depth in explanation of the general process of CVD."*
>
> *"I wish we could have developed a whole instructional unit."*
>
> *"I am now much more prepared to develop my course material for the semiconductor fabrication course."*

The statement "The Virtual CVD Workshop was useful to me" received the highest score, 4.84. The positive response was echoed in the comments, with most participants noting in their comments that the workshop was helpful, useful, or informative. Additional encouraging comments about the workshop from the Likert survey include the following statements:

> *"It was an eye-opening experience to meet instructors so attuned to chemical engineering and nanotechnology. I am very much inspired to continue in this direction in my own classes at home."*
>
> *"I am excited to use this with my students!"*
>
> *"The virtual lab is a wonderful tool & the amount of resources made available to the participants is truly amazing & very appreciated! Thank you!!!"*

In general, all Likert scores were very high and participants were quite satisfied with the overall experience.

In addition to the end of workshop Likert survey, two other surveys were given to participants throughout the workshop. These surveys were targeted at gaining further information about potential implementation of the Virtual CVD Laboratory participant classes. The first survey was given at the beginning of discussion on curricular materials. It asked questions regarding potential classes in which to use the Virtual CVD Laboratory, technology available for use, applicability, and value the Virtual CVD Laboratory offers and can add to classes and instruction. The most common classes cited by participants in which to use the Virtual CVD Laboratory were semiconductor manufacturing and microelectronics courses (lumped together as one category). These courses, generally with an engineering focus, were cited by 9 teachers.

The second most common class cited was chemistry, closely followed by physics. Other classes noted include introduction to engineering, principles of engineering and math. Participants were able to see many ways that utilization of the Virtual CVD Laboratory could enhance their classrooms. They gave examples of specific principles that the Virtual CVD Laboratory could help address, such as stoichiometry, gas law and reaction kinetics. Participants also gave examples of more broad concepts such as design of experiments, scientific inquiry, critical thinking, problem solving skills and connecting the classroom to a real life application. Participants had many positive comments on the value-added in the use of the virtual laboratory. Some representative comments include the following statements:

> *"Low cost, low maintenance with high equipment uptime."*
>
> *"Less time spent on mechanics (equipment set up/clean up etc.) and more time spent on experimentation"*
>
> *"Exposure to processes not physically available."*
>
> *"Applied real-world. I think the hardest thing for high school students when trying to comprehend chemistry concepts is the abstractness of the content, so I'm always looking for tangible applications, and this one is more than just an example."*
>
> *"It will provide a better real-world connection btw (*between*) students and complex problem solving than I can generally provide in class."*

The second survey given to participants was after using both the student interface and instructor interface of the Virtual CVD Laboratory as well as being introduced to curricular materials that had been utilized in previous courses. This survey asked questions regarding outline of instruction, implementation plans, adaption of the Virtual CVD Laboratory for students that struggle and for students that progress quickly, as well as implementation barriers. All surveys indicated that participants planned to follow the outline of instruction that had been developed, at least initially. More than half of the participants planned to develop their own implementation plan or modify the previously developed implementation plan significantly for use in their classes. To adapt the plan to students that struggle, the most common answers from participants were to provide more scaffolding and more guided instruction and restrict the number of parameters to explore or add exploration parameters one at a time, sequentially. Other plans included setting up runs with no noise, putting students in groups, and offering help via help sessions and help from more advanced students. Adapting for students that progress quickly was planned to be accomplished through having them explore more variables simultaneously, changing error settings in the instructor interface and making the process less guided and more open-ended. Finally, participants noted some barriers to implementation such as software and hardware problems, student inexperience with excel and lack of knowledge on the background of CVD and the underlying principles. Even with these potential barriers, the Likert survey indicated that the majority of participants intended to use the Virtual CVD Laboratory in their classrooms.

Conclusion

The objective of this study is to explore the use of virtual laboratories as a learning platform at the high school level. Level-appropriate curriculum and assignments were developed for 9th and 10th grade high school students and used by 263 students in *Introduction to Engineering* and in seven sections of *Chemistry* at Crescent Valley High School. The most prevalent theme in examining student work was the wide variety of responses elicited by this ill-structured project and the clever ways in which statistical methods were synthesized and integrated into student understanding. Based on this successful experience, a workshop for teachers has been developed and delivered twice. The response was very positive. As one of the workshop participants summarized:

> *"As a "new" instructor, I am motivated to bring high tech to my students, but I run out of time and money. This lab/workshop has delivered tangible content that is classroom ready. I also has the perk of engaging, thought-provoking activities. A winner for me and I will be using it in a number of classes!"*

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