AC 2007-257: A WEB-BASED COMPLEMENT TO TEACHING CONSERVATION OF MASS IN A CHEMICAL ENGINEERING CURRICULUM

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A Web-based Complement to Teaching Conservation of Mass in a Chemical Engineering Curriculum

Abstract

Web-based instructional modules have been widely used to teach engineering topics. In many cases, the modules are developed for a chosen topic at a specific point in the curriculum. A different approach is being pursued to develop interlinked curriculum components (ICCs), which can be used by students at many different points in the four-year curriculum. As envisioned during their development, faculty members might use an ICC to introduce students to a set of concepts or use an ICC to provide a review of a set of concepts when they will be used in a more advanced course. The initial ICC prototype focuses on conservation of mass (CoM). A description of the CoM ICC is provided together with preliminary results.

Introduction

A chemical engineering department, with NSF support, is renewing its entire four-year curriculum to achieve four additional student learning outcomes:

1. Apply fundamental ideas over an expanded range of time and length scales
2. Apply ChE fundamental ideas to emerging application areas
3. Construct solutions for more complex, more open-ended synthesis tasks
4. Transfer fundamentals and knowledge to unforeseen future challenges[1].

To achieve this comprehensive result, the project has adopted three strategic approaches:

1. *Curriculum content renewal and development*: Extend an existing unifying framework to incorporate expanded time and length scales, encompass emerging and traditional application areas, and increase emphasis on design and synthesis.
2. *Student assessment*: Develop assessment strategies for the additional learning outcomes.
3. *Faculty development*: Support faculty members as they assimilate new research on assessment, learning and teaching.

Interlinked curriculum components, or ICCs, are a major part of the curriculum renewal process. An ICC is a Web-based resource for teaching and learning as well as a 'chunk' of material that is significantly smaller than a typical semester course. Some ICCs focus on 'narrow and deep' ideas, e.g., specific application areas or skills; while many ICCs focus on common concepts (e.g. conservation laws) that span courses and application areas. The project team developed the concept and format of ICCs to increase unity, coherence, and efficiency and maintain effectiveness of the new curriculum.

This paper focuses on one ICC, which is built around conservation of mass, which appears throughout a ChE curriculum and can be summarized in a deceptively simple statement (where each term applies to the same specific time period):

$$\begin{pmatrix}\text{Accumulation of}\\ \text{Mass within a System}\end{pmatrix}=\begin{pmatrix}\text{Input of Mass}\\ \text{to the System}\end{pmatrix}-\begin{pmatrix}\text{Output of Mass}\\ \text{from the System}\end{pmatrix}$$

Student learning assessment indicates that ChE students are challenged to apply conservation of mass to a wide variety of settings. The goal of the conservation of mass ICC (CoM ICC) is to create a web-based tool that can be used and reused in multiple courses throughout a ChE curriculum. CoM ICC will help students to improve their conceptual understanding of conservation of mass and apply it across the ChE curriculum.

Conservation of mass was selected as the focus of the ICC for various reasons:

- Conservation of mass is one of the cornerstones in chemical engineering. It is a core concept that serves as the basis for many courses (e.g., material balances, mass transfer, reaction engineering, process dynamics, and process design). Failure to grasp it at an early stage of chemical engineering education compromises the learning process throughout the whole chemical engineering curriculum
- Mass is the easiest extensive property for students to use as they learn about the process of applying conservation laws to process model development. All are familiar with mass, can see it and visualize it, and simple problems abound that can be used to teach the general concepts of writing a conservation law equation. Energy, as a property, is complicated by existing in several forms that cannot be seen, easily visualized, or directly measured, and momentum is a vector, with its own mathematical challenges. If conservation concepts are learned well, then learning the more difficult laws becomes a matter of learning more about the specifics of dealing with those properties, rather than general conservation methodology issues.
- Mass conservation concepts span a wide spectrum of applications with various scales of time and space. Examples include the determination of how much feedstocks are needed to operate an industrial facility, how much products can be obtained, product quality and content, inventory tracking in storage operations, concentration and amount of streams resulting from purification and separation processes, product distribution of chemical reactions, transport and fate of pollutants into the atmosphere and water, and life cycle analysis of natural resources and industrial products.
- Because of the various facets of mass conservation, it is typically taught from different perspectives over different courses. There is a need to present the concept and its basic computational aspects in a consistent, consolidated, and comprehensive manner.

To achieve this goal, the CoM ICC includes several elements to help students solve problems that deal with both:

- Steady-state and unsteady-state problems
- Non-reactive and reactive systems
- Single and multiple unit processes

To help students deal with the wide variety of settings described above, faculty members have constructed the CoM ICC around the following problem solving framework that will provide the foundation for coherence and continuity throughout the curriculum as it is applied to other ICCs:

1. Start with a problem
2. Define the system boundaries and the problem objectives

3. Create a graphical representation of the process (flow charts)
4. Perform a degree of freedom analysis: apply the concept of conservation of mass to the defined system; use material properties and process constraints to obtain additional equations
5. Use a variety of analytical and numerical techniques to solve the equations, compare results, and evaluate the reasonableness of the solution

The paper presents the CoM ICC, describes the development process, describes applications in ChE courses, and presents responses from students, who have used the CoM ICC.

CoM ICC Description

Glover et al have described a systematic framework for application of conservation laws for developing mathematical models of physical systems and computing desired quantities[2–5]. The DLR project team recognized that chemical engineering students are expected to apply conversation of mass throughout the chemical engineering curriculum and decided that developing a CoM ICC that would introduce students to applications of CoM as well as provide review and practice in later courses would be a high priority for the project. In its current form, the ICC has eight learning outcomes. Upon completion of the ICC, students will be expected to:

- Define terms relevant to developing mathematical models of physical situations using conservation of mass: mass, accumulation, steady state…
- Create a concept map[6,7] involving concepts related to conservation of mass
- Explain the difference between conserved and non-conserved properties and the difference between steady state and unsteady state processes
- Select an appropriate system and time period for obtaining unknown mass related quantities of interest
- Organize a defined system and set of mass-related quantities and develop a set of mathematical equations that represent the appropriate mass balances
- Assess the number of degrees of freedom and the number of equations required to determine the unknown variables. If the system is under or over specified, make changes to the set of equations to obtain a well-posed problem
- Solve the set of mathematical equations to obtain the desired quantities using analytical and numerical tools
- Create challenging mass balance problems and evaluate students' performance in solving them.

To help students achieve the learning outcomes, the DLR project team designed the ICC with five principal parts:

- **Pre-test:** Students take a pre-test before entering the rest of the module to ascertain their current comprehension of conservation of mass and its applications
- **Topic notes:** This section contains the material students are expected to learn and apply. The material includes definitions and descriptions of using CoM to develop a mathematical model of a physical process. It also includes a section on chemical engineering equipment.
- **Examples:** Here, students can see how CoM can be applied to different chemical processes to obtain mathematical equations that are solved for the desired quantities.

- **Exercises:** This section gives students opportunities to try the process for themselves.
- **Post-test:** Students can evaluate their knowledge after working with the ICC.

The ICC is designed for a student to go through each of the principal areas while learning the ICC objectives. Readers interested in exploring the current version of the CoM ICC can try it at http://che.tamu.edu/orgs/NSFCR/01b/index.html.

Pre-test: Pretest currently consists of 11 multiple-choice concept questions. Students can self-evaluate their knowledge of the material. The pre-test might be especially valuable for students who are using the ICC for review. Students who are learning about applications of CoM for the first time may find the pre-test helpful in organizing their prior knowledge[8] about the topic. The web site also displays a score for the student who takes the test and provides a chance to improve this score after going through the topic notes, exercises, and examples in the ICC. Pre-test questions are being revised and updated continuously. A future plan is to ask the students taking the material and energy balances course in each semester to develop new concept questions and contribute to the concept inventory. This technique is especially useful as the students often identify a difficult concept and their answers to the questions may demonstrate the underlying difficulty in the comprehension of the material[9].

Topic Notes: The topic notes section is subdivided into three main topics: general balance equation, process classifications, stoichiometry, and chemical engineering equipment. The four main topics along with their subtopics are shown in Figure 1. The main topics and sub topics consist of text and equations that explain the topic. Also, short videos are used when needed. The purpose of this section is to teach the information covered under conservation of mass.

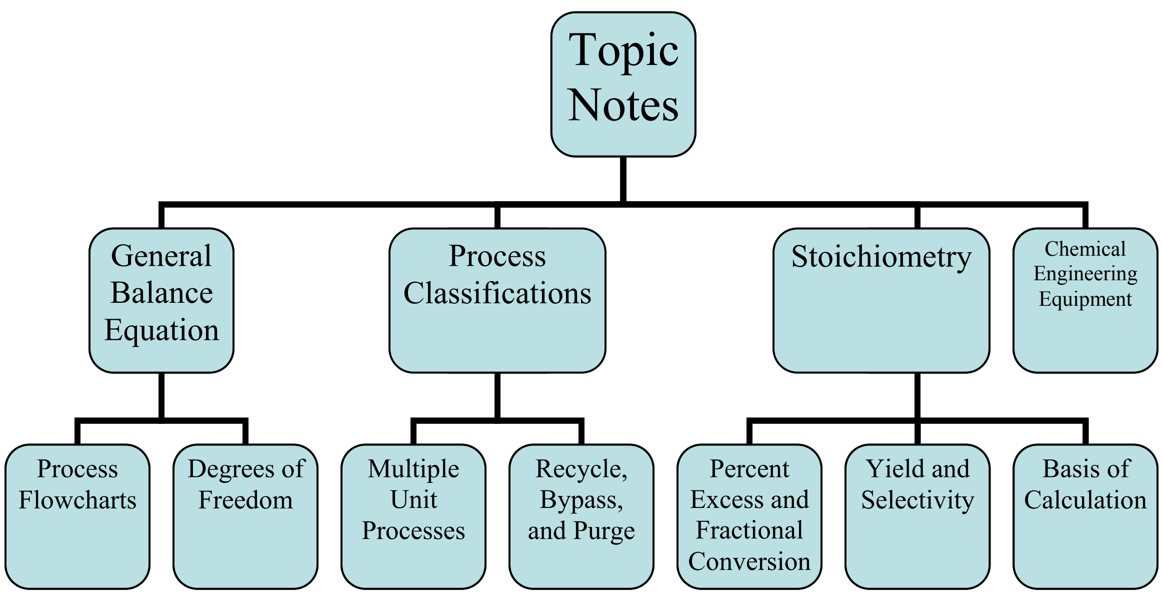


Figure 1. Organization of the Topical Material in the CoM ICC

Examples: This section is being constructed and updated continuously and currently involves several unsteady-state and steady-state examples. Each example takes the user through the five-step problem-solving framework. To enhance learning, active graphics and video features provide visual input to the user. Examples are presented using a consistent problem-solving framework so that student, when they encounter a new problem, will have a strategy and set of questions that they can ask themselves if they do not immediately formulate an approach for solving the problem. Use of the five-step problem-solving framework is reinforced through its consistent presence and appearance throughout each example.

Exercises: Presently, the exercises section contains a simple tank problem with one input and one output stream. In the first part, users are asked to create a specific schematic of the problem using a novel toolbar and pallet design (see Figure 2). The schematic is based on a word problem. In the second part of the exercise, the user is given the opportunity to select potential variables that could be used in the mass balance equation and construct a differential equation that would describe accumulation in the tank over time. This page has a feature that allows the user to check the correctness of the equation, once the user completes construction. The third part of the exercise is a tank simulation problem and allows the user to change the input and output flow rates and observe how the liquid level in the tank changes with time (see Figure 3). The general purpose of the three-part exercise is to teach and develop key engineering skills and concepts using a hands-on approach. In examples section, the user watches an instructor follow the five-step approach to solving the problem using a user interface that employs active graphics and video. On the other hand, the exercises utilize a hands-on interactive approach that allows the user to make mistakes and correct them.

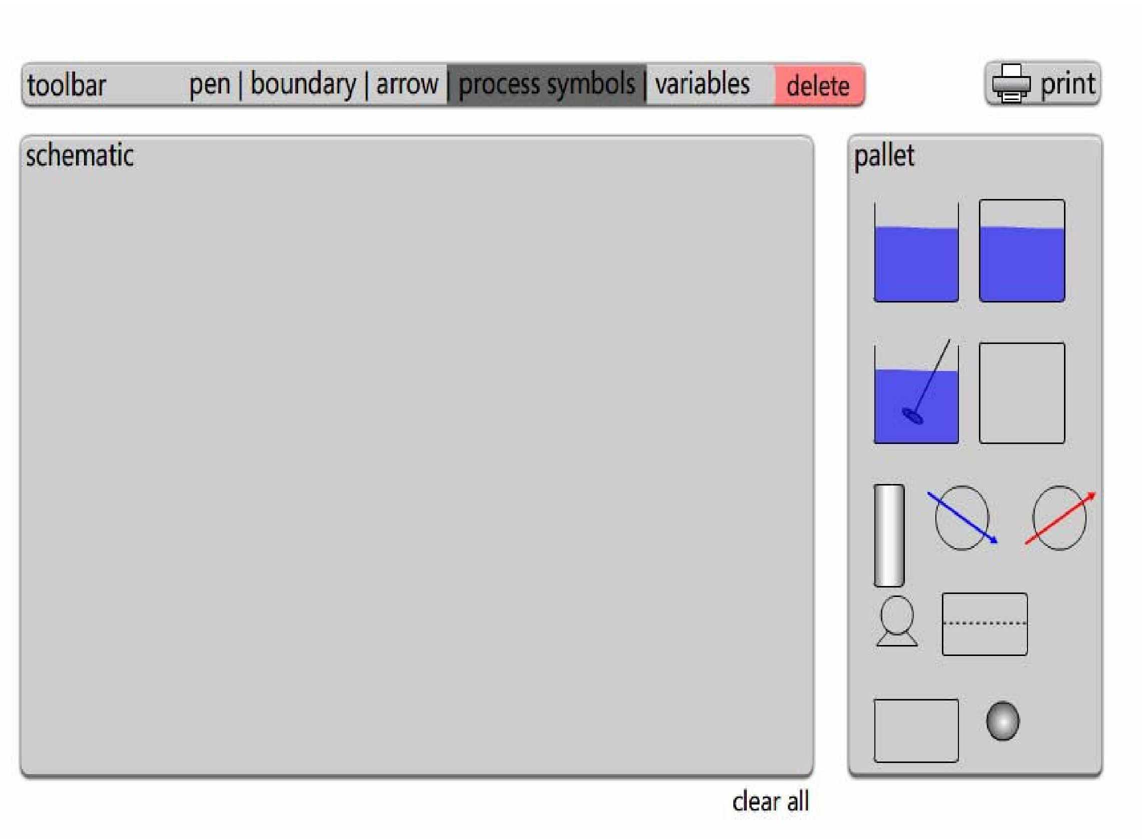
To assist visual learner, the ICC is equipped with an interactive animation tool. The user is given a pallet with a number of process units such as tanks, pumps, heaters, coolers, etc. Figure 2 is what the user sees before beginning to construct the schematic. The user can construct a process flow sheet and to define the system boundaries. The toolbar on the right shows components that may be used in constructing a system. A user can find the name of each component by hovering over its symbol. Components are an open tank, a closed tank, a stirred tank, a flash tank, a distillation column, a condenser cooler, a reboiler boiler, a heat exchanger, a generic process, and a mixer. A user constructs a process flow chart by dragging a desired component to the open flowchart window. Then, the user can designate a system by using the pen to draw a boundary around the system. Also, the user can label various process variables in the flow chart. In an exercise, a user will be presented with a textual description of the system and asked to construct a process flowchart. Interested readers can explore the process flow chart tool at http://che.tamu.edu/orgs/NSFCR/01b/exercises/02/02.html.

One of the easiest forms of a dynamic solution of mass conservation is the "tank-level" exercise (Figure 3). In this problem, the user changes the input and output flow rates. The dynamic solution of the system indicating the changes in liquid level is shown through a real-time animation to the left of the tank. The user can intervene in the middle of the simulation and change input and output data.

Post-test: The post-test is the same as the pre-test. The pre-test tests the students to see what information they already know. The post-test tests the student to see what information they learned from the ICC.

Usability Study

As work continued on the CoM ICC, the committee wanted student feedback to determine how the tool would be received by users. In spring 2006, the DLR team conducted a preliminary usability study on the CoM ICC. Three CHEN students who were members of the Student Advisory Board for the project participated. Each student met with a project team member working on faculty development and assessment and a project team graduate student. During the meeting, the student sat at a computer and worked through the CoM ICC. Student comments while reviewing the ICC were noted. At the conclusion of the session, each student completed a pencil and paper instrument requesting additional feedback on the ICC. Information from these



sessions was compiled into a report and feedback was considered during the CoM ICC revision process.

Figure 2. Process Flow Chart: Pallet and Animation Tool

The students who participated in the usability study were able to identify several things overlooked by the development team. Overlooked elements were the result of being too close to the process to notice problematic elements and also reflected the difference in viewing the material from the perspective of an expert attempting to teach and a novice attempting to learn. Students spotted inconsistencies in the way to which variables were referred throughout the ICC. They indicated that the graphic, while interesting, did not quite reflect the concept it was supposed to and suggested a redesign.

While working through the assessment portion of the ICC, the students identified places where either the questions themselves or the multiple-choice options were unclear and needed more complete information. They also suggested that being able to get immediate feedback on the assessment including analysis of their responses and other options would be very helpful for clarifying concepts on which they need to concentrate their efforts.

In addition to these elements, the students spotted incomplete areas of the ICC and “typos”. Overall, they thought the concept was a good one that would complement work done in their courses.

The major change that was made to the ICC as a result of the usability study was to completely redesign the tank simulation in the exercise section. The graph of the height of the liquid in the tank versus over time replaced other graphs to focus student attention on how the level responded to changes in the input and output variable. Student input had shown that the initial versions of questions on the pre-test needed revision to reduce confusion and changes were made in response to their feedback.

Figure 3. Tank-Level Animation Exercise

Conservation of Mass Concept Inventory Results

One of the objectives of ICCs is to aid students to improve their conceptual understanding. In order to collect some data on the current level of the understanding of students about conservation laws, in general, and conservation of mass, in particular, one of the faculty members on the DLR team agreed to use several assessment methods in a sophomore-level chemical engineering course on material and energy balances in which 100 students were enrolled in fall semester 2006. The assessment methods were: (1) concept inventory, (2) concept mapping, (3) daily questionnaires, and (4) faculty interviews.

The concept inventory, entitled Chemical Process Analysis Concept Inventory, was developed by Mike Haynak at Bucknell University. It contains 40 multiple-choice questions relevant to a material and energy balances course. The items are intended to examine student knowledge in the following areas:

- Types of systems
- Process classification
- Conservation of mass in simple systems
- Conservation of mass in reactive systems
- Conservation of mass in multi-component systems
- Phase equilibrium
- Atomic species balances
- Molecular species balances
- Heat of reaction
- Heat of solution
- Recycle/by-pass/Purge
- Ideal solution vs. non-ideal solutions
- Steady-state non-reactive systems
- Steady-state reactive systems
- Unsteady-state non-reactive systems
- Conservation of energy
- Analysis of experimental data

Students coming to this class have limited knowledge of conservation principles from earlier freshmen engineering courses. The inventory was given before the material balances were introduced. The results of collected data are summarized in Figure 4. Areas in which students at the beginning of course performed well (> 75% of the students provided correct answers) were:

- Steady-state non-reactive systems
- Analysis of experimental data
- Conservation of mass in simple systems

Areas in which students at the beginning of the course needed substantial improvement (< 40% of the students provided correct answers) were:

- Phase equilibrium
- Conservation of mass in reactive systems
- Atomic species balances
- Ideal solution vs. non-ideal solutions
- Conservation of mass in multi-component systems

- Molecular species balances
- Process classification
- Steady-state reactive systems
- Unsteady-state non-reactive systems

The team will continue to review these results to see if a smaller number of underlying concepts would help explain areas in which students need substantial improvement. Once the CoM ICC is used in the sophomore-level materials and energy balances course, use of the concept inventory will provide data on the extent to which students improve their conceptual understanding.

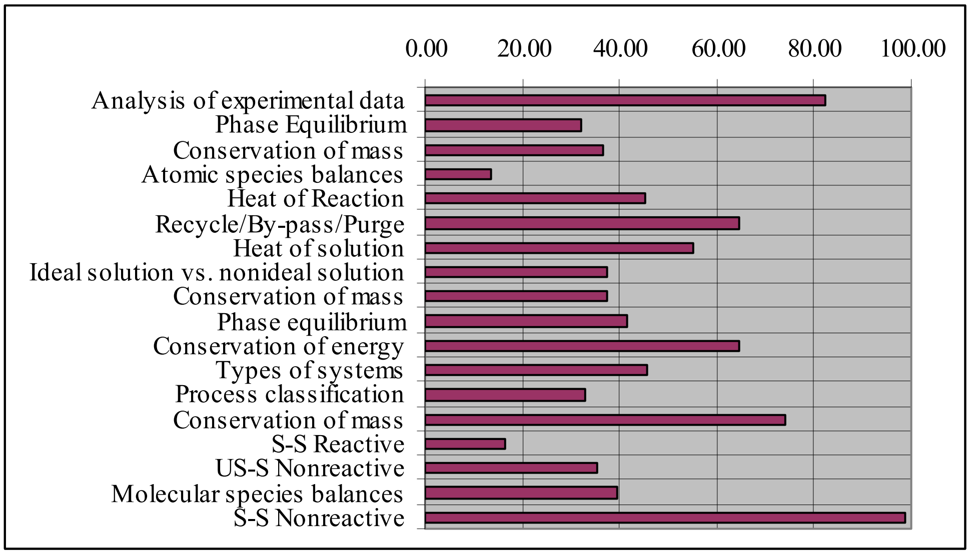


Figure 4. Results on the Conservation of Mass Concept Inventory Administered as a Pre-Test

Classroom Assessment Activities

In addition, students have participated in an in-class activity of concept mapping. Student teams of four were given 30 material balances concepts to be mapped together. Students enjoyed the activity and every team member participated enthusiastically. Concept mapping helped us to further diagnose student misconceptions in CoM. Rather than reproduce the concept maps that the students created, we have distilled their maps into more compact representations. In the compact representation, we show two concepts that a team of students has related and the verb that the students have chosen to describe the link between the two concepts. Some examples of misconceptions that appeared in the concept maps are shown below.

Process Specifications ➔Create ➔ Independent Equations
Temperature ➔Has ➔ Degree of Freedom
Basis of Calculation ➔ are ➔ Material Balance Equation
Process Flowchart ➔Basis of Calculation ➔ Independent Equations
Unsteady-state ➔ Creates a ➔ Semi-batch

The first example shows a student team's mistaken thought that process specifications create independent equations. The second example shows that a student team thought that temperature has a degree of freedom. The third example is vaguer; it appears that a student team thinks that the basis of calculations in chemical engineering is material balance equations. The fourth example shows that a student team thought that a process flowchart is the basis for calculation for a set of independent equations. In the last example, a student team thinks that an unsteady-state system implies a semi-batch process. Clearer pictures of the vague and incorrect conceptions of the students provide a basis for learning activities intended to clarify of repair conceptions of the students.

As a conclusion, the DLR team has found this activity to be very useful to both the students and the faculty and decided to incorporate the tool into the ICC. Although it seems to be more enjoyable and fun doing an in-class team activity with Post-it™ notes and paper, when the ICC is complete, the students will be able to check their own understanding of the concepts and plan their study time accordingly

Daily questionnaires were collected during each lecture throughout the semester. Students were asked to write one thing they did understand and one thing they did not understand from the lecture of the day. The results of the questionnaires have been compiled and used to clarify the concepts in follow-up recitation sessions by using additional examples and in-class discussions.

We will continue to use these tools to document student understanding and to guide the ICC development. Student comments from the daily questionnaires were mainly grouped around the use of degree of freedom in material balances, understanding the functions of chemical engineering equipment, steady state versus unsteady-state, especially how to set up unsteady-state problems. To perform the material balances, students need at least a qualitative understanding of how chemical engineering equipment works. Recognizing this need, we have decided to include topic notes on chemical engineering equipment in CoM ICC. Topic notes give a short description of each piece of equipment, include computer graphics and interactive animation to help the student to visualize how each works, as well as talk about driving forces, counter-current versus co-current flows.

Conclusions

The paper has presented results on development of a web-based supplement for conservation of mass that students may use through the undergraduate chemical engineering curriculum. The CoM ICC works on developing student learning from several different perspectives:

- Visual: Students construct a schematic of a system, e.g., tank, from a word description of the problem
- Analytical: Students construct a differential equation from a word description and a visual schematic
- Simulation: Students vary the inputs and outputs to the system and observe the changes in the behavior of the system.

A small group of students have used a preliminary version of the ICC and provided feedback that guided revisions. Finally, faculty members have used several assessment approaches to obtain more data on the conceptual understanding of the students relative to material and energy balances. This data will help us understand any changes brought about in student learning when they actively use the ICC.

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