Fundamental Research in Engineering Education

DEVELOPMENT OF CONCEPT QUESTIONS AND INQUIRY-BASED ACTIVITIES

in Thermodynamics and Heat Transfer: An Example for Equilibrium vs. Steady State

Margot Vigeant,+ Michael Prince,+ and Katharyn Nottis*
+ Bucknell University Department of Chemical Engineering • Lewisburg, PA 17837
** Bucknell University Department of Education • Lewisburg, PA 17837*

As a Chemical Engineering educator, you have perhaps experienced a situation in which a student who has done well on a numerical problem fails to grasp the underlying concept. For example, a student who correctly calculates that two objects that have come to thermal equilibrium in a room at 25 ºC must be at 25 ºC might also tell you (based on his or her perception walking barefoot across the floor) that a tile floor is cooler than a carpeted one, even if they are in the same room. These two situations describe the same problem, but the second situation highlights the student's failure to grasp the underlying concept in ways that the first situation does not. Understanding of basic concepts, rather than memorization of formulae, lays the groundwork for students' future study and their ability to apply principles to real problems as their careers progress.[1, 2]

A key barrier to conceptual understanding of important engineering concepts is that students arrive in our classrooms not as blank slates, but with existing conceptual frameworks describing how the world works.[1, 3, 4] In some cases, their earlier experience creates significant misconceptions that are not overcome by simply telling them the correct answer.[1, 5, 6] A key finding of the National Research Council's "How People Learn" was that faculty need to draw out and engage student preconceptions and help students understand ideas within the context of a conceptual framework.[3] As an example of the difficulty of instilling conceptual change, research

© Copyright ChE Division of ASEE 2011

Margot Vigeant *is an associate professor of chemical engineering and associate dean of engineering at Bucknell University. She has taught at Bucknell for 12 years, and is interested in innovative ways to improve conceptual understanding in undergraduate engineering courses, particularly thermodynamics.*

Michael Prince *is a professor of chemical engineering at Bucknell University. His current work in engineering education is in student motivation, conceptual learning, assessment, and "best practices" in undergraduate education. He is involved in the annual National Effective Teaching Institute workshop as well as numerous other workshops on active, collaborative, and problem-based learning.*

Katharyn Nottis *is a professor of education at Bucknell University. Her interests include educational assessment, statistics, and STEM education. Dr. Nottis has done leading work on teaching in diverse environments, successfully preparing students for work in a wide variety of school settings.*

with physics students demonstrated that traditional teaching methods produced only marginal improvement in students' conceptual understanding of basic physics concepts.[5, 6]

Fortunately for us and for our students, there are a number of instructional methods that have been shown to result in more significant conceptual gains than lecture. Hake showed that instruction that emphasizes student engagement significantly improved students' conceptual learning in physics.[5] Laws, et al.,[6] also working in physics, showed that inquiry-based laboratories were successful in improving conceptual understanding. Their implementation of inquiry-based activities, defined as instruction incorporating the elements in Table 1, resulted in more than 80% of students correctly understanding force, acceleration, and velocity while standard instruction had resulted in 20-50% of the students understanding those concepts.[6]

There are many definitions of "inquiry-based," but in general the approaches require that students pose and answer questions through direct experimentation, rather than lecture or in a plug-and-play style laboratory.[7]

The overall goal of the present work is to adapt the successful model of inquiry-based activities for conceptual change from physics to chemical engineering students in heat transfer and thermodynamics. The two components of this work have been to create reliable instruments to assess students' conceptual understanding in these areas and to develop and test inquiry-based activities. Ongoing work with the concept inventories has resulted in reliable assessments as well as documentation of student misconceptions that are altered little by traditional instruction.[8] We have also demonstrated some improvement of students' conceptual understanding as a result of a sub-set of the activities under development.[9] In this article, we present the development steps taken for a specific inquiry-based activity within our work. The particular activity and associated concept inventory question may be of interest to the readers, but we hope that the development process may be useful as well for engineering colleagues interested in adapting this educational approach. By adapting the demonstrated success of the physics model to chemical engineering concepts, we hope to enable similar growth in conceptual understanding in our own students.

TABLE 1
Elements of Inquiry-Based Activity Modules[6]

a) Use peer instruction and collaborative work
b) Use activity-based, guided-inquiry curricular materials
c) Use a learning cycle beginning with predictions
d) Emphasize conceptual understanding
e) Let the physical world be the authority
f) Evaluate student understanding
g) Make appropriate use of technology
h) Begin with the specific and move to the general

QUESTION DEVELOPMENT

The first step in developing an inquiry-based module is selecting the concept area to target. Equilibrium vs. Steady State was identified in a Delphi study by Streveler, et al., (2003) as a concept that was both important for students to understand and commonly misunderstood.[10] Our own classroom experience confirmed that this area can be a source of confusion for students. When two objects are at equilibrium, it implies the absence of net driving forces for change (for example, two metal blocks in thermal equilibrium are at the same temperature). "Steady state" describes a system where the measurable characteristics are invariant with respect to time. For example, water boiling in a pan on top of a gas flame may reach steady state, but the water is not in thermal equilibrium with either the flame or the surrounding environment. The prevalent student misconception about equilibrium and steady state is that they are simply two terms describing the same state. For example, a junior-level chemical engineering student defined "steady state" in the following way: "a steadily occurring process at equilibrium." It is important that practicing engineers be able to distinguish these two states; imagine the poor decisions that might be made by a plant engineer who believes a stream to be at the same temperature as its surroundings because someone told him or her it was at "steady state."

The next step is to create concept inventory questions that will assess whether students understood the concept correctly. To identify specific misconceptions, we want to create questions where the possible answers contain "distractors" or the most common misconceptions held by students. Therefore, the first version of a question is open-ended rather than multiple-choice in order to draw out students' specific preconceptions.

Examining student responses, we saw that misconceptions were often revealed more clearly in questions asking about an "everyday" setting rather than questions focusing on an "engineering" context. This makes sense as everyday situations readily draw upon students' prior knowledge and experience. While a number of excellent questions had been developed and tested for Equilibrium vs. Steady State by Miller, et al.,[11-13] each of these was in a plant or laboratory context. We therefore developed a question drawing on students' daily experience, the first draft of which is Q1 below:

> *[Q1] A cookware company makes cooking pans where both the pan and the pan's long handle are made of the same metal, joined in a continuous manner (no insulation between the handle and the body of the pan). Yet, they advertise that the handle is "cool touch." Can this be true when the pan is used to boil water on a conventional stovetop? Please explain.*

This question was included in a draft concept inventory given to 78 chemical engineering students at three universities. The students' answers were sorted into groups based upon common themes. Using this approach, four theme areas emerged, shown in Table 2. Eleven answers are omitted from Table 2, being either totally unique or left blank.

Student responses grouped in the first row in Table 2 assume thermal equilibrium between the boiling water and the metal of the handle. Students in the second grouping correctly answer that a handle may remain cool, but incorrectly answer that the only way for this to occur would be for the system not to be at steady state. The third row are correct in that the handle can remain cool, but claim the only way for this to happen is if the rate of conduction is low. While this is correct, it is not the only way for the handle to remain cool. The final group recognizes that it is possible to attain a steady state temperature that is lower than 100 ºC by balancing conduction and convection. While many students answered correctly, about half got the problem conceptually wrong.

Based upon the results in Table 2, a draft multiple-choice version of the question was constructed. This version contained an answer corresponding to each of the categories above, grouping the middle two answer themes into "b" as shown in Q2 below.

> *[Q2]. A cookware company makes cooking pans where both the pan and the pan's long handle are made of the same metal, joined in a continuous manner (no insulation between the handle and the body of the pan). Yet, they advertise that the handle is "cool touch." Can this be true when the pan is used to boil water for a long time at 100 ºC on a conventional stovetop?*
>
> *a) Yes, it is both possible and practical to create a continuously joined metal cool-touch handle.*
>
> *b) Maybe. Such a handle could be designed, but such a design would be unlikely to prove practical.*
>
> *c) No, it is not possible to create a continuously joined metal cool-touch handle.*

Q2 was piloted in a draft concept inventory taken in the first two weeks of class by 129 chemical and general engineering students at five institutions. A conventional item analysis was also conducted, guided by Classical Reliability theory.[14] According to this theory, information about identifiable factors of individual test questions is used to guide any changes in the inventory and increase the reliability of the total score. Two aspects of the individual test questions were examined: item discrimination and item difficulty. The Discrimination Index (D-Index), with a range from –1.00 to +1.00, was used to estimate discrimination of test items.[14] Participants were divided into the upper and lower third, based upon their overall scores. Students' scores on a specific item were then correlated with their overall score. The greater the positive value, the better the question discriminates. A positive value approaching 1.0 for discrimination index indicates that students who answered a given question correctly also scored well on the test as a whole, while those who answered incorrectly did not. A negative value for discrimination index would indicate that students who did poorly overall were able to answer a particular question correctly, while their better-scoring peers were not. A value of zero indicates a total lack of correlation between the score on the given item and the overall score. The "difficulty" of each question was measured by the percentage of students correctly answering a given question. According to Kaplan and Saccuzzo,[15] the ideal difficulty of a question is about 63% with questions on the total assessment ranging from 30% to 70% best able to distinguish among learners.

Evaluation of responses showed that the question had a difficulty of 15.3% and a discrimination index of 0.14. Looking more closely at responses, "a" was chosen by 15% of the students, "b" by 33%, and "c" by 52%. The target difficulty for the assessment is between 33% – 66% along with a discrimination index of at least 0.25. Faculty instructing the

TABLE 2
Grouped Short-Answer Responses for Q1

Answer Theme	Concept Interpretation	Example Student Response	# of students
Not possible; metal handle must be too hot if water is boiling	Equilibrium is being assumed between pot and handle	"No because heat will be transferred uniformly through the whole pan and all parts of the pan will heat up."	26
Possible; if rate of conduction is slow or handle is very long (nonsteady state)	Neither equilibrium nor steady state are assumed; the handle temperature rises continually, but so slowly as to not matter	"It is possible that the convection through the metal could take long enough that the water can boil before the handle gets hot enough to burn you. But it is dependent on the length of the handle and how much water it is heating."	9
Possible; if rate of conduction is slow (steady state)	Steady state heat transfer can be attained because the relatively small amount of energy to the handle can be released to the air	"Yes it can be true, as long as the rate of convection off the handle is greater than the rate of conduction through the handle."	5
Possible; if conduction through handle matches convection away from handle	Steady state heat transfer is assumed	"Yes. If the pan handle is long enough, the heat conducted through the metal handle may come to steady state with heat loss through convection, leaving the pot handle at a touchable temperature."	27

relevant courses were also asked to evaluate the question's relevance as an assessment of Equilibrium vs. Steady State. Feedback indicated that Q2 could be read as a "fin" design problem and as such, answered correctly without reference to the concept of equilibrium or steady state.

Accordingly, Q2 was reworded to improve clarity and emphasize the connection to the targeted concept. An additional option was also added in order to reduce the probability of students randomly guessing the correct answer. This version is shown in Q3.

> *[Q3] A cookware company makes cooking pans where both the pan and the pan's long handle are made of the same metal, joined in a continuous manner (no insulation between the handle and the body of the pan). Yet, they advertise that the handle is "cool touch," meaning that a person can safely hold the pot by its handle while the pot is in use without burning him- or herself. Can the handle remain cool when the pan is filled with water and brought to a boil at 100 ºC for a long time on a conventional stovetop?*
>
> *A) Yes, because with proper design of length and shape, a handle can maintain a steady state temperature significantly below 100 ºC.*
>
> *B) Yes, because the end of any handle must be in thermal equilibrium with the surrounding air.*
>
> *C) No, because the only place that the equilibrium temperature is below 100 ºC is at the end of an infinitely long handle.*
>
> *D) No, because the temperature of the metal handle must reach equilibrium with the temperature of the pan at 100 ºC after a long enough time.*

This question was used in a draft concept inventory taken by 150 chemical engineering students at four universities at both the start and end of their Thermodynamics course. Q3 had a difficulty of 37.2% at the start of the course and 40.4% at the end of the course, and a discrimination index of 0.32 (assessed at the end of the course only). These indicators fall within the target range for an acceptable concept inventory question. Of the student answers, 40% correctly answered "a," while 9%, 6%, and 45% answered "b," "c," and "d," respectively. The question achieved moderate difficulty and could discriminate between some high and low performers. The small change in responses from the beginning to the end of the course, for both this question and for the group of questions in this concept area, indicates that this is a relatively robust misconception area. Comments from a review panel of faculty who teach relevant engineering courses indicated that the wording on Q3 focuses attention appropriately on the Equilibrium vs. Steady State concept area. This question was accepted as part of the overall Thermodynamics concept inventory.[8]

Internal reliability, or a measure of the consistency of individual or subsets of questions across an instrument,[16] was determined for the draft version of the concept inventory. This was done using the Kuder-Richardson formula 20 (KR20) calculated for both the entire inventory and the concept sub-tests (*e.g.*, Equilibrium vs. Steady State). KR20 ranges from 0-1.0, and is a indicator of how well a set of questions are assessing the same idea. A score approaching 1.0 would indicate that students who do well on a given question tend to do well on all questions in that same content area, and students who do poorly on a given question will tend to do poorly in that entire concept area. This method of estimating reliability requires only one administration of the assessment and needs only the number of questions, the mean, and the standard deviation.[17] An internal reliability of 0.70 or higher is considered acceptable for research purposes.[17] The overall instrument has a post-course reliability of KR20 = 0.76, which is higher than 0.70 recommended for a research instrument.[17] The overall concept inventory has 35 questions, nine of which address the Equilibrium vs. Steady State concept area. Eight of the nine questions were developed by Miller, et al., for the Thermal and Transport Concept Inventory, and were reused with permission here. Note that although the reliability of those questions was assessed as part of the TTCI, reliability is context dependent and therefore was independently established for this concept inventory and its sub-tests. The post-course reliability of the Equilibrium vs. Steady State subset is KR20=0.72.

ACTIVITY DEVELOPMENT

Having established a reliable method for assessing students' conceptual understanding, the second part of our work is to develop inquiry-based activities to repair students' misconceptions. We are working to realize the specifications for inquiry activities of Laws, et al., (Table 1) with the following operational approach for any activity (letters refer to items in Table 1):

> *1. Students make and explain a prediction about the results of the activity <u>in writing</u> (c).*
>
> *2. Students conduct or observe the activity (b) making appropriate measurements (g). The activities are closely matched to the questions and designed to emphasize concepts over numerical calculations (d,e). It is important that they have some level of agency over the experiment.*
>
> *3. Students compare their experimental observations with what they had anticipated and explain any differences in writing (e, f). Students should consult with their peers (a) as they do this. Students are also asked post-activity written questions wherein they extend their understanding to new situations (h).*

The emphasis on prose explanations in the predictions, post-activity assessment, and extension questions helps maintain the focus on conceptual understanding rather than computation.

In general, activities were envisioned as physical realizations of concept questions. For the question discussed above, it was fairly straightforward to realize "Hot Pot" as an activity.

The activity apparatus consists of a metal cooking pot with a continuously joined metal handle placed on a hot plate and instrumented with thermocouples (or thermometers) on the pot and on the pot's handle as shown in Figure 1. To run the activity, students fill the pot with water and monitor the temperature of these locations as the water heats to boiling as well as while it boils. In addition to this "steady state" pot, an identical pot with the mass of water is left sitting on the laboratory bench in order to provide the "equilibrium" counterpoint. The current draft of the student handout for this activity is included in the appendix.

***Figure 1.** "Hot Pot" activity apparatus.*

While this seems simple, the activity allows students to participate in the construction of a situation where the most common distractors are obviously incorrect. The logging of temperatures at various locations on the pot (Figure 2) clearly shows that, while the water is boiling (after ~850s), the temperatures at these locations are approximately time-invariant (steady state). Figure 2 also demonstrates that these steady state values are different from each other as well as from the temperature of the boiling water (nonequilibrium). An additional interactive piece of this experiment is that students are invited to actually grasp the handle on the pot and experience for themselves that they can do so safely.

Context is important to the activities having their desired effect on conceptual understanding. In the three-step process outlined above, two of the steps involve student reflection and explanation. In order to create the potential for longer-term conceptual change, it is important that students go beyond observing the activities and be encouraged to take steps to internalize the lessons. Writing has been shown to be effective[19, 20] and has the benefit of being assignable as homework. As seen in the appendix, students are asked to

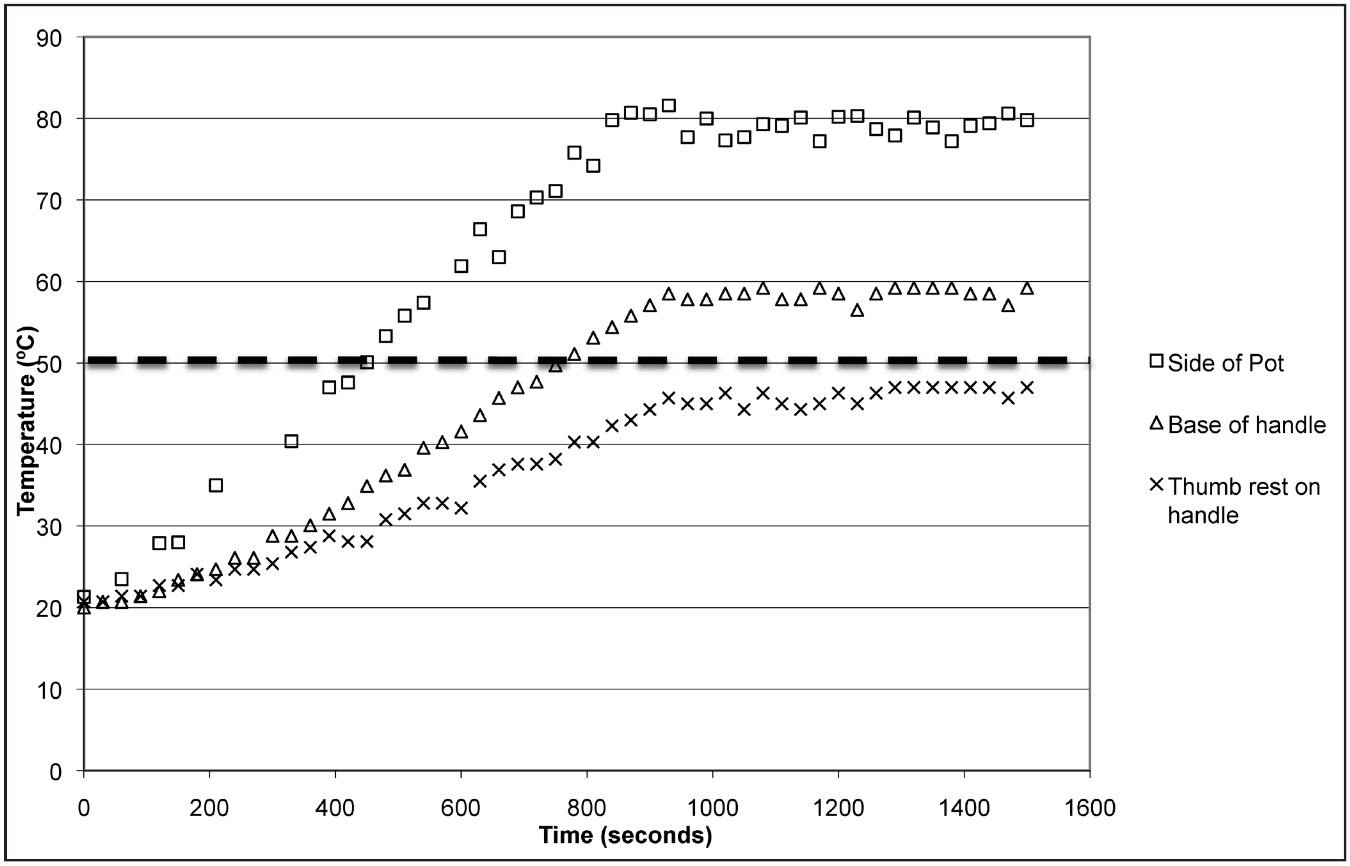

***Figure 2.** Sample data from "Hot Pot" activity. Dashed line indicates OSHA hot-surface personnel protection temperature, as assessed by ASTM Standard C 1055.[18]*

predict, in writing, what will happen. The overall goal of the post-experiment questions is to require students to compare their observations with the distractors from Q3. For example, in the experiment students observe that the pot handle remains touchable, but this could be due to Q3 answers a or b. In order to eliminate b, students measure the temperature of a pot that is at equilibrium with the room air and directly observe that the temperature is different for the "hot" pot.

An example of a student prediction (from a class in a small, private university), just prior to the activity, is "Yes [the handle could burn someone] because the metal will most likely be conductive and thus it should reach the same temperature as the boiling H_2O, which is hot enough to burn." As this student worked through the activity, she logged data similar to that shown in Figure 2. When asked in the analysis to predict what she would observe (question 7, Appendix) if the pot were in a) thermal equilibrium with the air, b) thermal equilibrium with the hot plate, or c) steady state with respect to energy transferred from the hot plate, she correctly predicts what would happen to the temperature of the handle and why: "a) No it would not burn you… it would be the same temperature as the air. b) Yes, it would burn you. If it's in equilibrium with the hot plate, then it would be the same temperature as the hot place, which is hot enough to cause a burn. c) No, it would not burn you. From the experiment, we learned that if the pot is at steady state with the hot plate, then the temperature of the handle will be cooler than the hot plate and thus safe to touch." In conclusion, she states "In this experiment, I learned that steady state and equilibrium are two completely different things. Just because a process has achieved steady state and is constant with time does not mean that everything is at the same temperature and in thermal equilibrium." All students in this class (n=25) were able to correctly address questions about the metal pot handle immediately after this experiment, with several specifically mentioning that it had helped clarify the difference between equilibrium and steady state.

Testing of our draft activities on a national scale is currently under way. While the small scale results noted above were promising, the sample size is too small (n=25) to draw overall conclusions. Larger-scale tests of activities show encouraging results. Overall, students from five diverse institutions (public, private, >20,000 students as well as <4,000) performing at least some activities score 66% (N=147) on the concept inventory post test, while those at four institutions without activities score 56% (N=143), a statistically significant improvement ($p<0.01$). Because not every test site performed every activity, there is not yet sufficient data to draw conclusions about the impact of the "Hot Pot" activity specifically. Further testing is ongoing and should remediate this problem soon.

CONCLUSION

Repairing student misconceptions requires first that we document their existence and then that we adopt effective techniques for conceptual change. In this paper, we considered the development of a single concept question in the area of Equilibrium vs. Steady State as well as the creation of a corresponding inquiry-based activity. Preliminary testing of this activity as well as those for other related concepts has shown promise.[9] Through broader testing, we hope to demonstrate, using concept inventory results, at least two successful activities for each of the nine target concept areas within thermodynamics and heat transfer.

ACKNOWLEDGMENTS

The study was funded through NSF DUE 0717536. We gratefully acknowledge the participation of faculty and students at our test-site institutions as well as much constructive feedback from Ron Miller, Ruth Streveler, John Perschetti, and Jeff Stein.

REFERENCES

1. Lightman, A., and P. Sadler, "Teacher Predictions Versus Actual Student Gains," *The Physics Teacher*, **31**, 162 (1993)
2. Novak, J.D., *A Theory of Education*, Ithaca, NY: Cornell University Press (1977)
3. Bransford, J., A. Brown, and R. Cocking, *How People Learn: Brain, Mind, Experience and School*, Washington, D.C.: Commission on Behavioral and Social Science and Education, National Research Council (2000)
4. Hausfather, S., "It's Time for a Conceptual Change," *Science and Children*, Nov/Dec 1992, 22-23
5. Hake, R.R., "Interactive-Engagement vs. Traditional Methods: A Six-Thousand-Student Survey of Mechanics Test Data for Introductory Physics Courses," *American J. Physics*, **66**(1), 64 (1998)
6. Laws, P., D. Sokoloff, and R. Thornton, "Promoting Active Learning Using the Results of Physics Education Research," *UniServe Science News*, **13** (1999)
7. Inquiry Descriptions From the Exploratorium Institute Inquiry Forum, Accessed May 5, 2004
8. Prince, M., M. Vigeant, and K. Nottis, "Assessing Misconceptions of Undergraduate Engineering Students in the Thermal Sciences," *International J. Eng. Ed.*, **26**, 880 (2010)
9. Prince, M., M. Vigeant, and K. Nottis, "A Preliminary Study on the Effectiveness of Inquiry-Based Activities for Addressing Misconceptions of Undergraduate Engineering Students," *Ed. for Chem. Engineers*, **4**(2), 29 (2009)
10. Streveler, R., B. Olds, R. Miller, and M. Nelson, "Using a Delphi Study to Identify the Most Difficult Concepts for Students to Master in Thermal and Transport Science," Presented at ASEE Annual Conference, at Nashville, TN (2003)
11. Thermal and Transport Concept Inventory, <http://www.thermalinventory.com/surveys.html>, Accessed March 14, 2011
12. Miller, R.L., R.A. Streveler, B.M. Olds, M.T.H. Chi, M.A. Nelson, and M.R. Geist, "Misconceptions About Rate Processes: Preliminary Evidence for the Importance of Emergent Conceptual Schemas in Thermal and Transport Sciences," Presented at ASEE Annual Conference, Chicago (2006)
13. Olds, B., R. Streveler, R. Miller, and M.A. Nelson, "Preliminary Results From the Development of a Concept Inventory in Thermal and Transport Sciences," Presented at ASEE Annual Conference, Salt Lake City, UT (2004)
14. Suen, H.K., *Principles of Test Theories*, Hillsdale, NJ: Lawrence Erlbaum (1990)
15. Kaplan, R.M., and D.R. Saccuzzo, *Psychological Testing: Principles, Applications, and Issues*, 4th ed., Pacific Grove, CA: Brooks/Cole

(1997)
16. Huck, S.W., and W.H. Cormier, *Reading Statistics and Research*, 2nd ed., New York: Harper Collins (1996)
17. Fraenkel, J.R., and N.E. Wallen, *How to Design and Evaluate Research in Education*, 7th ed., New York: McGraw-Hill (2009)
18. ASTM, 2001, "Standard Guide for Heated System Surface Conditions That Produce Contact Burn Injuries," In Section 4: Construction, Volume 04.06, *Thermal Insulation and Environmental Acoustics*, West Conshohoeken, PA: ASTM (2001)
19. Hand, B., L. Hohenshell, and V. Prain, "Examining the Effect of Multiple Writing Tasks on Year 10 Biology Students' Understandings of Cell and Molecular Biology Concepts," *Instructional Science: An International Journal of the Learning Sciences*, **35**(4), 343 (2007)
20. Hohenshell, L.M., and B. Hand, "Writing-to-Learn Strategies in Secondary School Cell Biology: A Mixed Method Study," *International Journal of Science Education*, **28**(2-3), 261 (2006)

APPENDIX: STUDENT HANDOUT FOR INQUIRY-BASED ACTIVITY

Inquiry-Based Activity 1: Hot Pot

Student Name or Number______________________

The following experiment is going to simulate cooking on a stove. One pot with water will be heated on a hot plate while a second pot, also with water, will sit on the lab bench. You will be comparing the temperatures of each of the pots at the marked locations and recording them in the table provided. Following the experiment, there will be a series of questions to answer about what was observed in the experiment.

Materials:

2 Covers for the pots

1 Hot plate

1 Infrared thermometer

1 Timer or stopwatch

Either

3 Computer-enabled thermocouples, and a computer with data-logging software

or

At least 2 thermocouples or thermometers

Safety:

In this laboratory you will be boiling water and several objects can get extremely hot and will have the potential to burn you. Carefully follow the instructions and only touch objects where and when you are instructed to do so.

Directions:

1. You are going to be heating the water until it is boiling, in a pot with a metal handle. When the water is boiling, do you believe the handle will be at a high enough temperature to burn you? Why or why not?

2. When your group is finished answering the first part, put one pot of water on the hot plate. Set the second pot on the lab bench to the side of the hot plate.

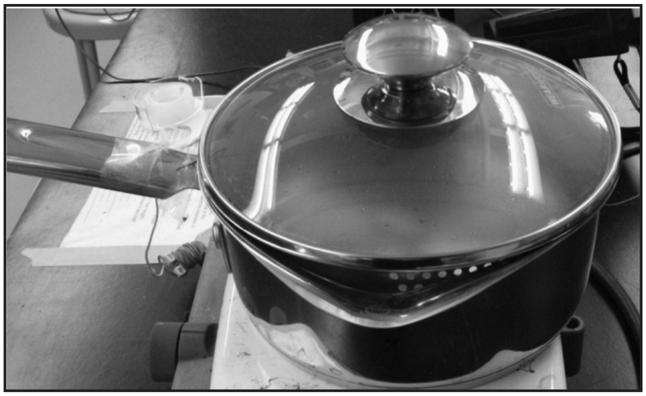

Figure A1. *Correct positioning of the pot lid.*

3. Place a lid on each of the pots. Position the lid so that half of the holes on the side of the lid are visible at the sides as shown in Figure A1.

4. Measure the initial temperatures for both pots at the marked locations and record these values in the table on the next page (if using a computer data logger, you need not record the temperatures by hand).

5. Turn the hot plate on to the highest setting and start the timer or stopwatch.

6. After each minute, take measurements of the temperature at the marked locations for the pot on the hot plate. Record the temperatures in the table on the next page. Take periodic measurements on the counter-top pot, as shown in the table.

7. Once the water boils, turn the setting down to half of the maximum power. The goal is to maintain the boiling water at a low but constant rate of evaporation.

8. Continue taking measurements while the pot is boiling until temperatures measured at each location remain constant. Record your measurements in Table A1 (next page).

9. **Do NOT actually do this, but think about the situation.** While the pot on the hot plate is boiling at steady state, would you consider putting your hand in the water? Would you consider touching the hot plate? What about the handle in the marked spot?

10. The ASTM/OSHA standard for a stovetop burn is about 120 °F (50 °C). Could the marked spot on the handle burn you?

11. If your measurements indicate that the handle is safe to touch, and if someone is comfortable doing so, have him or her pick up the pot in the appropriate spot. Did that person get burned?

12. Turn off the hot plate and save your data if you are using the computer.

***Analysis** – to do after class/lab and hand in:*

1. What did you see in this experiment and how does your

TABLE A1
Temperature Data

	Hot Plate Pot			**Lab Bench Pot**		
Time (min)	Location 1	Location 2	Location 3	Location 1	Location 2	Location 3
0						
1						
2						
3						
4						
5						
6						
7						
8						
9						
10						
11						
12						
13						
14						
15						
16						
17						
18						
19						
20						

observation compare with your prediction? If what was observed contrasts your prediction, explain what happened and why. Discuss this with your group before answering.

2. For the pot on the hot plate, plot the temperature at a given location as a function of time. What happens to the temperature?

3. For the pot on the lab bench, plot the temperature at a given location as a function of time. What happens to the temperature?

4. For each of the pots consider the temperature profile at points 1-3. How do the temperatures compare throughout?

5. Using your answer from the previous question, which pot was at steady state but not equilibrium? Which pot came to thermal equilibrium?

6. Using the terms unsteady state, steady state, and equilibrium, which one applies to each of the following situations and why:

- *a. A pot just filled with room-temperature water is heated by an open flame for a few minutes and does not come to a boil.*
- *b. A heat exchanger continuously cools styrene monomer from 300 °C to 150 °C using 20 °C water.*
- *c. A distillation column continuously separating a 50:50 mixture of ethanol and water to 80% by mole of ethanol in the distillate.*
- *d. A single tray of a distillation column performing the same separation mentioned in part c.*
- *e. A turkey that has cooked in the oven at 250 °C for 12 hours.*
- *f. A piece of road is heated by the sun on a hot summer day*

7. Determine if the following situations would burn you if you grabbed the handle of the hot pot at point 3:

- *a. The temperature of the pot is in equilibrium with the air.*
- *b. The temperature of the pot is in equilibrium with the hot plate.*
- *c. The temperature of the pot is at steady state with the heat transferred from the hot plate.*

8. Hand in your original prediction and your comparison to question 1 above, specifically noting if and how your thinking has changed with respect to the experiment. What, if anything, did you learn?

9. Remember to put your name or identifying student number on each page of your response. ❐