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The Use of Analogies in an Industrial Environment to Facilitate Status Changes for Radiation Science Concepts

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THE USE OF ANALOGIES IN AN INDUSTRIAL ENVIRONMENT TO FACILITATE STATUS CHANGES FOR RADIATION SCIENCE CONCEPTS

by

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The focus of this study was the effect of two analogies on the status of industrial technical center employees for three radiation science concept areas. The analogies used were of melting ice and falling tacks. The three radiation concept areas examined were radioactive material decay, radioactive material half-life, and radioactive material activity.

Forty-four adults participated in the study. Thirty-five of these participants took pre- and post-lesson multiple-choice tests to determine the effect that the analogies had on their intelligibility of the three radiation science concept areas. Nine participants also took pre- and post-lesson clinical interviews to assess their intelligibility, plausibility, and fruitfulness for the three radiation science concept areas. These interviews were audio taped and transcribed for interpretation utilizing subcategories of status in large part derived from the works of Thorley (1990, 1991, 1992).

The two analogies were presented on transparencies during lecture presentation sessions. A melting-ice setup was demonstrated during the presentations. In addition, the participants were given an opportunity to

individually take part in a falling-tacks exercise.

The study found that the use of the analogies resulted in increased statuses in all three concept areas. In addition, learning steps for the Decay-two concept were identified and associated with ancillary knowledge required to advance through the steps. The statuses that the learners held for this concept fluctuated as they progressed through the learning steps.

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CHAPTER I

INTRODUCTION

Status

The theory of constructivism can be briefly summarized in the statement "Knowledge is constructed in the mind of the learner" (Bodner, 1986). The theory of constructivism states that "the meaning of the idea cannot be understood apart from its conceptual home in the broader theory" (Strike and Posner, 1985). That is, the meaning of a concept for any individual person depends on its relationships to other ideas within one's conceptual ecology.

Bodner (1986) also stated that students bring alternative conceptions (conceptions that conflict with accepted theory [Clement, 1993]) to science classes and that, sometimes, these alternative conceptions are remarkably resistant to instruction. This view of the resistance of prior conceptions to change has also been voiced by others (Minstrell, 1984; Clement, 1982; Halloun and Hestenes, 1985), although Chaiklin and Rogh (1986) found that not all preconceptions are deep seated. When faced with an anomalous situation, the learner would typically prefer to choose a different alternative instead of revising a prior conception (Strike and Posner, 1985). These

alternatives include (a) rejection of the new information, (b) finding the new information to be irrelevant, (c) compartmentalizing knowledge to prevent conflict between the new and prior beliefs, and (d) attempting to assimilate the new information into the prior conception.

The Conceptual Change Model (CCM) of learning was developed by Strike and Posner (1988), Posner, Strike, Hewson, and Gertzog (1982), Hewson (1980,1981), and Hewson and Hewson (1981, 1988). This model presents a theoretical structure of how, as Bodner mentions, knowledge is constructed in the mind of the learner, and why prior conceptions are resistant to change. The model's predominant concern is how learners react to new conceptual information. The model lists four possible reactions when new conceptual information is encountered: (1) rejection (outright or until further investigation suggests otherwise), (2) rote memorization (no reconciliation with existing conceptions required), (3) conceptual exchange or accommodation (the replacement of a prior conception with a new conception with which it is incompatible), and (4) conceptual capture or assimilation (the addition of a new conception to a prior compatible conception). The last two reactions, conceptual exchange and capture, are collectively referred to as conceptual change.

The Conceptual Change Model (CCM) uses two major components to address how a person evaluates conceptual information. The first component is the "conditions" that a concept needs to satisfy in the mind of

the learner. For any given concept, there are three conditions to be considered: (1) intelligibility, (2) plausibility, and (3) fruitfulness. According to the CCM theory, a concept is intelligible if it is understandable. An intelligible concept is also plausible if it is believable. An intelligible and plausible concept is also fruitful if it opens up new areas of inquiry or explains additional phenomena.

The second component is that segment of a person's current concepts, referred to as the "conceptual ecology" (Toulmin, 1972), which governs the adoption or rejection of concepts. The conceptual ecology contains several kinds of concepts that are especially important when one is comparing prior and new concepts. These concepts are composed of: (a) anomalies, (b) analogies and metaphors, (c) epistemological commitments, (d) metaphysical beliefs about science and concepts of science, (e) knowledge in other fields, and (f) competing concepts. For example, in a study where college-level physics students had to explain the claim of Einstein's special theory concerning the relativity of the length of objects, they frequently explained it as a distortion of perception. This was done to protect the students' metaphysical commitments (beliefs about the nature of the universe, such as a belief in absolute length) (Hewson, 1982). The conceptual ecology is important because if a new conception violates one of its elements, the conception will appear to be counterintuitive, and will not be accepted in a conceptual change process (Posner, Strike, Hewson, &

Gertzog, 1982).

Status of a Conception

The state of the conditions that a learner has for a concept is referred to as the "status of that concept". The measures of status (conditions) are intelligibility, plausibility, and fruitfulness. A concept can have no status (no conditions satisfied) or have the statuses of being intelligible only, of being intelligible and plausible, or of being intelligible, plausible, and fruitful.

Intelligibility

Intelligible conceptions are understandable though not necessarily believed to be true. In a study where physics students and instructors thought aloud about concepts in special relativity, intelligibility required an understanding of words, symbols, syntax, and a learner-supplied construction of a logical representation of what the concept meant (Posner et al., 1982). At a minimum, a concept must be intelligible in order to replace a prior concept in a person's conceptual ecology.

Plausibility

A plausible conception is consistent with other knowledge. It is believable. There are several ways in which a conception can become

initially plausible: (a) by being consistent with one's current metaphysical beliefs and epistemological commitments, (b) by being consistent with other theories or knowledge, (c) by being consistent with one's sense of what the world is or could be, or (d) by being capable of solving anomalies.

An example of the importance of one's epistemological commitments was illustrated by the "thinking aloud study" where students already firmly committed to the metaphysical belief of absolute space and time found the special relativity theory to be counterintuitive and therefore not plausible (Posner et al., 1982).

A study of the relation between strength of commitment to a theory and rejection or reinterpretation of data also illustrated the importance of existing beliefs (Chinn and Brewer, 1993b). Subjects who initially preferred the meteor impact theory to explain Cretaceous extinctions rated anomalous data as less believable than subjects who initially preferred the volcano theory of Cretaceous extinctions where the additional data were not anomalous.

Fruitfulness

Fruitful conceptions should be useful, for example by opening up new areas of inquiry. If a conception were intelligible and plausible, and it could resolve previous anomalies and lead to new insights and discoveries, then it would also be fruitful and it would seem to be more persuasive.

Conceptual Change and Dissatisfaction

The status of an existing concept compared with the status and irreconcilability or reconcilability of a new concept determines the types of conceptual change that can occur. Given two irreconcilable conceptions, the status that a learner has for the two concepts can result in dissatisfaction with the prior conception (resulting in conceptual exchange) or dissatisfaction for the new conception (resulting in its rejection). For conceptual exchange to occur the status the learner has for the existing conception must be lowered. That is, the learner must become "dissatisfied" with the existing conception. Also, the status that the learner has for the new conception must be raised. The lowering of the existing conception's status requires that the individual lose faith in the ability of his current conceptions to solve some puzzles or to account for anomalous data. Dissatisfaction with an existing conception can occur if the conception is no longer necessary, violates an epistemological standard, or is irreconcilable with new knowledge which cannot be ignored (e.g. an anomaly) (Strike and Posner, 1985).

There are several factors which are involved in the determination of which choice a person will take when faced with anomalous data (Chinn and Brewer, 1993a, 1993b): (a) entrenchment & extent of current knowledge, (b) quality & availability of a new theory, (c) credibility of the

data, and (d) presence or absence of deep processing. According to the CCM, dissatisfaction with new information occurs if: (a) the new information is seen to be irreconcilable with firmly held existing conceptions, (b) the new information has unacceptable implications, or (c) the new information's experimental or logical basis appears to be doubtful.

Reconcilable concepts must have equal status and be at least intelligible (Hewson, 1981). The learner's relative strengths of commitment to the competing conceptions determines whether rejection or conceptual capture of the new concept occurs. If the learner becomes dissatisfied with the new conception, it will be rejected.

Status Change During Instruction

Some researchers have investigated status changes during instruction. One example, that is based on a constructivist view of learning, is the Children's Learning in Science Project (Needham and Hill, 1987). This teaching method follows the sequence: (a) orientation to the concept area, (b) prior idea elicitation, (c) idea restructuring, (d) idea application, and (e) review to modify, extend, or replace existing ideas. Changes in understanding (i.e. status) are monitored through a variety of individual and social-oriented activities such as small group discussions, personal writing, personal diaries, and project work.

Hewson & Hennessey (1991) conducted a study of sixth-grade

students that concerned status changes involving a book-on-table instance of the concept of force. Prior to the study, the students learned the technical language of CCM, which included generating a set of descriptors for intelligibility, plausibility, and fruitfulness. The unit was covered in a classroom environment where student ideas were discussed and teaching was not viewed as a process of imposing meaning on students. Data concerning the status of concepts was gathered using recordings of classroom discussions. The researchers also utilized a questionnaire that asked participants to choose an explanation of the forces involved in the instance from six options, to give reasons for their choice, and to comment on the status of their choice using the technical language of the CCM. The authors decided that more complex explanations signified indirect evidence of intelligibility. The authors also discovered that students' verbal comments concerning the balanced forces in the book-on-table instance revealed uncertainty in the plausibility of their choices that was not evident in the written questionnaire process.

Brown and Clement investigated (1987) the plausibility that learners had for science concepts, although they did not identify their dependent variable as such. The researchers measured the "confidence" that students had for their answers to Newton's Third Law questions. Resistance to tutoring and spontaneous expressions of belief for science concepts were also observed by Brown and Clement (1989).

Operational Definition of Status

Hewson and Hewson (1991) gave a general schema for determining the status that a learner has for a conception:

1. Identify statements of concept representations (e.g., the atom is like the solar system, [analogy]).

2. Identify metaconceptual statements (statements concerning a concept, e.g., thinking of the atom as similar to the solar system is a useful idea).

3. Interpret these statements using the technical language of the conceptual change model.

The authors concluded that metaconceptual comments are needed to determine status. They also recommended four specific approaches that a researcher can take to determine the status that a learner has for a conception:

1. The researcher can review non-technical interviews (interviewee does not know CCM technical language).

2. The researcher can review non-technical classroom discourse.

3. The researcher can review technical interviews (the interviewee knows the technical language and can be directly asked questions about the status that he has for the conceptions).

4. The researcher can review technical classroom discourse.

Thorley (1990, 1991, 1992) clarified and expanded a system of categories developed by Strike and Posner (1985) for classifying the status that learners had for concepts. Thorley's work focused on concepts about forces and motion and photosyntheses. He approached this task by observing naturally occurring non-technical classroom discourse. The status categories that were developed in this study strongly incorporated the elements of the conceptual ecology and illustrated that status can be represented and judged in a variety of ways. Thorley's categories consisted of: (a) Representational Mode - intelligibility (analogy, image, exemplars, critical attributes, language, representation or formulae of a conception, and kinesthetic); (b) Consistency Factors - plausibility (consistent with: other knowledge, past experience, epistemological beliefs, ontological basics or metaphysical, analogy, lab experience, thought experiment, hypothesis, and anomaly resolution); (c) Reality Factors - plausibility (appear to be "true" through: real mechanisms, neotheory); and (d) Fruitfulness Categories (usefulness of concept due to: power, promise, competition, extrinsic, anomaly resolution).

Analogies

Applications of Analogies

Researchers have utilized analogies to influence student knowledge.

Clement (1993) investigated the ability of a structural chain of bridging analogies to produce learning gains in three areas of mechanics: (1) static normal forces, (2) frictional forces, and (3) Newton's third law for moving objects. In this technique, bridging analogies were introduced to help students link intuitively understood anchoring conceptions with the target learnings. The anchoring analogies were used to draw out preconceptions that were intuitively in large agreement with scientific understandings. The target learnings were not generally intuitively understood by the students. Clement found that this teaching method resulted in significant gains measured with an instrument designed to detect common alternative conceptions.

To enhance learning gains, Glynn utilized the Teaching-with-Analogies Model. This model was developed through an analysis of the analogies used in 43 science textbooks (Glynn, 1989; Glynn, Britton, Semrud-Clikeman, and Muth, 1989). The recommended steps in this model are (Glynn, 1991): (a) introduce the target, (b) cue retrieval of the analog, (c) identify relevant features of target and analog, (d) map similarities, (e) draw conclusions about target, (f) indicate where analogy breaks down.

Duit (1991) and others (Thiele and Treagust, 1994) used analogies as a means of comparing similarities with the student's real world, of encouraging consideration of the students prior knowledge by the teacher, and of enhancing student motivation.

Thagard (1992) mentioned that student-generated analogies presented to teachers can be used to help detect and correct false mappings and misunderstandings. Teachers can help students correct their misconceptions by pointing out the misunderstandings in the student-generated analogies.

Usefulness of Analogies

Posner, et al. (1982) stress the need to use analogies as a means of providing initial meaning and intelligibility and plausibility of new concepts.

Schwartz (1993) views analogies as one of several approaches to helping learners develop structural understandings of novel information. Schwartz mentions other techniques that have also been used to accomplish this such as concept maps, advanced organizers, planning, data organization, and illustrations.

Wong (1993) studied the outcomes of having secondary school teacher candidates generate analogies from incomplete prior knowledge to explain air-pressure phenomena. He found that this technique resulted in a greater understandings of scientific concepts through new explanation construction and important question generation, important questions being those whose answers could lead to greater understanding for the concepts under consideration. Wong also noticed that the self generation of

analogies triggered the remembrance of associated knowledge. The self generation of analogies also enabled the participants to use their prior factual knowledge in one domain to support and guide understanding in an unfamiliar domain. Although the learners in this study generated different analogies, they all experienced growth toward more accurate scientific understandings.

How Analogies Function

Duit (1991) and others (Thiele and Treagust, 1994) view analogies as a mechanism for providing additional visualization of abstract concepts. Some researchers have characterized the use of analogies as a mapping of source domain understandings to the target domain (Gick and Holyoak, 1983).

Clement (1993) used bridging analogies and explanatory models constructed from anchoring examples. He thought that the bridging analogies were a type of "plausibility reasoning process" that increased the arena of application of anchoring intuitions. Brown (1993) perceived Clement's bridging analogies as facilitating student reattribution of agencies or responses toward the scientifically accepted version of scientific concepts. According to Brown, analogies help in the reorganization of the attribute cluster in relation to the target situation. For example, Brown examined the act of a cue ball striking another billiard ball. Initially, some learners

would view the cue ball as possessing the attribute of an "initiating agent" and the second billiard ball as possessing the "affected responder" attribute. In this situation the cue ball would transfer force to the second ball. After being exposed to an anchoring analogy and a series of bridging analogies, some learners would view the second billiard ball as an agent instead of just a responder, now possessing the attribute of "reactive agent", where the second billiard ball acts when acted on in response to another agent (the cue ball). This change represented a shift of attributes intuitively assigned to the second billiard ball, a reattribution process.

Analogy Design Considerations

Duit (1991) reviewed research on the use of analogies from a constructivist position. He recommended that analogies map substantial portions of target domains.

Guidelines for the use of analogies in instruction were given by Thagard (1992). The researcher stated that the analog should be more familiar than the target domain. The downside of this is that the analog may lack semantic and structural correspondence to the target. Where no semantic similarity exists, the teacher must point out the analog/target correspondences.

Thagard (1992) stated that in order to facilitate adequate analog/target correspondence, the analog should not be too cryptic, the

analog should not be too long, unshared analog/target attributes should be explicitly pointed out, and multiple analogies should be used.

Glynn (1991) stated that an analogy is good if it meets three criteria: (1) a large number of analog/target correspondences; (2) the features compared are easy to identify, thus the analog should be familiar to the learners; and (3) significant features are compared.

Dangers in the Use of Analogies

Duit (1991) pointed out that learners may be misled by an unfamiliarity with the analog domain, by unmapped analog/domain features, and by analog misconceptions. He recommended the use of multiple analogies to help avoid analogy-induced misconceptions. Spiro, et al. (1989) also advocated the use of multiple analogies to avoid the overextension of an analogy.

Thagard (1992) mentioned that a potential problem with the use of analogies is that non-corresponding features between the analog and the target can be compared by the learner. This can lead to misunderstandings. For example, a comparison of electricity in a conducting wire to water in a hose could lead one to incorrectly believe that cutting the wire would allow the electricity to leak out (Glynn, 1991).

Thiele and Treagust (1991) also stated that analogies can create misconceptions that can hinder further concept development. This can

occur if learners incorrectly generate analog/target mappings. This generation of new features of the target due to inferences about the analog are also mentioned in Gentner's structure mapping theory (Gentner, 1983).

Learner Requirements

According to Clement (1993), the three major requirements for the effective use of analogies are: (1) an understanding of the analogy; (2) plausibility for the analog/target correspondences; and (3) an application of the findings for the analog to the target.

Goswami (1991) reviewed research in the area of measuring the development of "system" analogical ability which consists of correspondences between sets and involves both objects (e.g. sun & nucleus) and relations (e.g. orbits). His interpretation of the review indicated that the ability to perform analogical reasoning required a metacognitive understanding of analogy and a knowledge base of the relations involved in the analogy.

Gick and Holyoak (1983) stated that analogical reasoning requires a well-developed analog domain, convergence schema, and an ability to identify the target as an example of the analog convergence schema. Others have also indicated a need for the learner to have the ability to imagine the correlations between the analogy and the target (Freidel, Gabel, and Samuel, 1990; Gabel and Sherwood, 1990).

Analogies and Status

Research examining the effect of analogical teaching on conceptual learning compared an experimental group with a control group that was taught the same refraction-of-light concept, but without the use of an analogy (Treagust, Harrison, Venville, 1993). Data were gathered using student interviews and a work sheet. No direct questions about status were asked but questions like "How would you explain that to a friend?" were used to elicit status information. The interview transcripts were examined for the use of descriptors such as those described by Hewson and Hennessey (1992) to determine the status that the learners had for the refraction of light concept. The authors found that the students taught the concept of refraction by analogy achieved increases in intelligibility and plausibility compared with those not taught by analogy.

Statement of the Problem

The preceding survey of pertinent literature introduced the conceptual change model with its emphasis on changes in status that a learner must experience for conceptual change to occur, gave some examples of instructional practices geared toward generating conceptual change, and examined studies that concerned the process of monitoring status. The literature survey also commented on guidelines for the use of

analogies and the value of using analogies to bring about changes in statuses for learners of new concepts. These areas are germane because this study concerns the effects of an analogical teaching approach on the status that learners have for three concept areas in radiation science.

This discussion also indicated that conceptual change requires the student to establish the status of existing and new concepts in the process of learning. Given two irreconcilable conceptions, the relative strength of commitment to each will determine which loses status resulting in eventual rejection of the new concept or conceptual exchange. For reconcilable concepts, the relative strengths of commitment determines whether rejection or conceptual capture of the new concept occurs. Faced with an existing and a new conception, a learner's choice among (a) rejection, (b) conceptual exchange, or (c) conceptual capture is a function of seven considerations: (1) a comparison of the status that the learner has for the two concepts, (2) the reconcilability or irreconcilability of the concepts, (3) the learners particular conceptual ecology with respect to the concepts, (4) the level of commitment the learner has for the existing concept, (5) the strength of the new concept, (6) the depth of processing that the learner engages in, and (7) the usefulness of the concepts to the learner. In either type of conceptual change process (capture or exchange), the status of a new concept must increase to at least the same status as the learner's preconceptions. Thus, any pedagogical strategy that assists in increasing the status of a conception

will be a useful teaching aid. The literature concerning the conceptual change model mentioned that analogies could be helpful in establishing the intelligibility and plausibility (status conditions) of a new concept (Posner, et al. 1982, Hewson, 1981). Also, Ausubel, Novak, and Hanesian (1978) stated that one of the requirements for meaningful learning was a "relevant" cognitive structure, that is, concepts to which new knowledge can relate. It was indicated by Goswami (1991), Duit (1991), and Thagard (1992) that analogies can be useful if proper care is taken in their design. Thus, an analogical teaching approach may, if properly designed, facilitate status increases for new concepts. The discussion also indicated that mechanisms have been established to categorize and monitor classroom discourse and science-concept interviews. These typically require extensive examinations of the transcripts of video- or audiotaped interviews. The interpretation of interviews is typically done by reference to the principles of the conceptual change model. However, no systematic method of evaluating the data for status has been utilized.

Hypotheses

This work and the opportunities available to the researcher lead to the following three closely related hypotheses:

1. Analogy-based teaching will assist learners in developing higher status for some scientifically accepted concepts relating to radioactive

material decay compared with their conceptual status prior to the presentation of the lesson.

2. Analogy-based teaching will assist learners in developing higher status for some scientifically accepted concepts relating to radioactive material half-life compared with their conceptual status prior to the presentation of the lesson.

3. Analogy-based teaching will assist learners in developing higher status for some scientifically accepted concepts relating to radioactive material activity compared with their conceptual status prior to the presentation of the lesson.

The uniqueness of this study is threefold. The first is in the particular method utilized to monitor status changes. This is a unique attempt to objectively use a systematic approach to monitor changes in all three conditions of status as a result of a learning experience.

Second, monitoring the effect of an analogy-based teaching experience (independent variable) on status (dependent variable) has only been sparsely investigated. One group of researchers (Treagust, et al., 1993) investigated status changes concerning the refraction of light concept in grade school. However, they did not utilize a systematic procedure for defining or measuring the plausibility and fruitfulness conditions.

Third, the particular topic area and population are unique. This study involved status changes for adults as a result of an analogy-based

lesson concerned with radiation science. Also, the study occurred in an industrial training environment in surroundings different than those found in a more formal school setting.

CHAPTER II

METHODS

Subjects

The sample consisted of the employees at a major paper company's technical center who agreed to participate in this study as part of their required radiation science and radiation safety training. The researcher was the radiation safety officer for this facility and was responsible for conducting or arranging this annual training. Annual training in radiation science and/or safety is a requirement of all radioactive material holders as cited in the state's regulations concerning protection from ionizing radiation.

Personnel in four different areas of this facility required training: (1) Analytical Sciences, (2) Coating Process and Materials, (3) Paper Technology and Materials departments, and (4) the Safety Committee. The research procedure used in this study consisted of pre-testing, followed by an analogy-based lesson, followed by immediate post-testing. Data were collected from two groups.

Eleven people initially comprised group one. In this group, pre- and post-testing involved a multiple-choice content test and a personal

interview. Two people who started in group one did not complete their participation. However, both did complete the pre-testing, composed of an interview and a multiple-choice test. They also completed the falling-tacks activity described in the procedure sub-section of this document. One person did not complete the study because of a meeting conflict during the lesson presentation. The post-lesson multiple-choice test was administered to this participant and included, along with their pre-content test, with the data used to determine the test/retest reliability of the content test. The 2nd person could not break away for his work to take the post-test before contaminating information was presented to him by an outside source. None of the data from this participant was included in the study.

All of the first group agreed to participate in the study. Since group-one participants came from four different areas, potential participants were recruited until 3 people were selected from each of the Analytical Sciences and Paper Making & Materials departments, 2 were selected from the Safety Committee, and 1 was selected from the Coating Process and Materials department. The 2 participants that did not complete the study were members of the Coating Process and Materials department and the Safety Committee. Six (67%) of the group-one participants were males and 3 (33%) were females. Their ages ranged from approximately 26 to 55 years. This reflected a total mix of 81.7% men and 18.3% women in these four work areas, with an approximate age range of 20 to 60 years. In terms

of the highest formal degree obtained, 3 (33%) of the participants had a high school diploma, 2 (22%) had a bachelor's degree, 3 (33%) had a master's degree, and 1 (11%) had a doctorate degree in a physical science.

Group two consisted of 35 participants. In this second group, the pre- and post-testing involved only written content tests. The participants in this group attended a 45 minute presentation on some radiation science concepts during a departmental or committee meeting. Group-one and group-two participants attended this lesson at the same time.

The potential maximum number of group-two participants in this study was 62. These 62 people came from the same four areas as the group-one participants. These 62 potential participants were composed of 81.7% males and 18.3% females. From the 62 potential participants, 35 completed the pre-content test, the lesson, and the post-content test. The data from these 35 people along with the data from the 9 group-one participants were used to calculate the effects of the analogy-based lesson on the statuses that the learners had for the radiation science concept areas presented in the lessons.

Six people took the content test twice, approximately a month apart. These people did not participate in the lesson, but their scores were used to determine the test-retest reliability of the content test using the Pearson Product Moment Correlation Coefficient. Five of these people came from two departments which did not receive the analogy-based lesson that the

researcher administered to the participants in the study. The 6th participant was originally in group one, but could not attend the lesson presentation due to a work conflict. After it became apparent that she could not attend the lesson, she was asked to complete the post-content test. Her data were then included in the data used to determine the test's reliability. This person was a member of the Safety Committee. 66.7% of the participants in the reliability study were males and 33.3% were females. Their ages ranged from approximately 30 to 55 years. In terms of the highest formal degree obtained, 4 of the participants had a high-school diploma, 1 had a bachelor's degree, and 1 had a master's degree.

Participant Solicitation

Potential participants in group one were verbally asked if they would be willing to participate in the research. It was mentioned that the lesson was being given to fulfill state mandated annual radiation safety training. At the time of recruitment, they were informed that the researcher was interested in having them participate in a research project that he was undertaking to fulfill a requirement for a Ph.D. degree in science education through Western Michigan University. The researcher also mentioned that the research concerned how analogies assist people in making sense of three radiation science concepts, and that their participation would require them to complete a learning activity, to take

two multiple-choice tests, and to participate in two tape-recorded interviews, in addition to spending about 45 minutes during a future department meeting examining a series of overhead transparencies pertaining to radiation science. The potential participants were then told that their name would not be associated with any of the data, but that they would be asked to choose a fictitious name to identify themselves on these assessment tools. They were also told that after the researcher collected all of the data, he would change the fictitious names again. In that way, their anonymity will be doubly protected. Candidates who were willing to participate in the study were asked to read and sign a consent form. This consent form is in Appendix A.

Potential group-two participants were contacted by the researcher through a written memo that was placed on each of their desks. In this memo, the potential participants were informed that the researcher was interested in having them take part in a research project that he was undertaking to fulfill a requirement for a Ph.D. degree in science education through Western Michigan University. They were also informed that the research concerned how analogies assist people in making sense of some radiation science concepts. They were informed that their participation would require that they take two multiple-choice tests, spend about 45 minutes with the researcher during a future meeting examining a series of overhead transparencies, along with having an opportunity to take part in a

learning activity (the falling-tacks analogy). The candidates were informed that they should use a fictitious name on their data, but that they should remember their choice so they could put it on the multiple-choice test that they would be taking at a future time. It should be noted that on a few occasions, participants forgot the fictitious name that they had originally selected. In these situations, the researcher showed the participants the list of fictitious names and the participants were able to recognize the name that they had originally adopted. Those participants who agreed to participate were asked to complete the multiple-choice test that was attached to the memo and return it to the researcher through internal mail.

The six people whose scores were used to determine the test-retest reliability of the content test were verbally asked if they would be willing to participate in this research.

Apparatus

The physical apparatus used in this study consisted of colored pencils, tacks, overhead transparencies, melting-ice equipment composed of ice in a glass funnel that dripped into a two-liter graduated cylinder when melting, and a recorder/transcriber. The colored pencils were available for the group-one participants to use during the clinical interview. The tacks were used during the "falling-tacks" activity and during the presentation of the analogy-based lesson. The researcher selected tacks that had a half-life

different than one drop. That is, a fraction of the tacks different from one-half fell on their sides, as opposed to their tops, during each drop of the tacks. The "half-life" of the chosen tacks was 1.25 drops. The overhead transparencies and melting-ice equipment were used by the researcher during the presentation of the analogy-based lessons. The recorder/transcriber was to record and transcribe the group-one participants' clinical interviews.

Instrumentation

The instrumentation used consisted of a multiple-choice test and a clinical interview. Each participant was also given the opportunity to complete a learning activity involving the dropping of tacks. The accumulated data from this activity was then used during the presentation of the falling-tacks analogy during the lesson sessions.

Content Test

A sample of the pre-test is illustrated in Appendix B. The 10 question multiple-choice test obtained information pertinent to the learners' intelligibilities for the radiation science concept areas that were investigated. The tests contained questions concerning the concept areas of radioactive material decay, half-life, and activity. The specific concepts covered by each question are illustrated in Figure 1. The item numbers

Radioactive Material Decay.

Nucleus-one (item one): Radiation is emitted from the nuclei of radioactive materials.

Decay-one (item three): Parent material decays into progeny material.

Decay-two (item six): Decay continues until the parent material is entirely changed into its progeny.

Decay-three (item seven): For a given radioactive material, all nuclei have an equal probability of decaying.

Radioactive Material Half-Life.

Half-Life-one (items two and five): The time required for one-half of the parent material to decay into its progeny is referred to as half-life.

Half-Life-two (item nine): Half-life is a constant for a given radioactive material.

Radioactive Material Activity.

Activity-one (item four): The number of nuclei of a radioactive material that decay per second is referred to as the activity.

Activity-two (items eight and 10): The activity of a radioactive material decreases with decay.

Figure 1. Concept Areas Covered on Concept Tests.

refer to the pre-test. The test was reviewed by an expert committee to determine its appropriateness and face validity. Inappropriate or ambiguous items were reworked or discarded and replaced until the test was acceptable. The content test was designed to comply with most standard test conventions (Nitko, 1983). In accordance with this convention, the test was designed without negatively worded items, with most of the question contained in the item's stem, each item having only one best response, no linking of items (the answer to a subsequent item is dependent on responding correctly to a previous item), no cluing (correct response to an item is suggested by another item), all alternatives were appropriate to the stem, the use of functional alternatives (attracts at least one of the learners who do not have the requisite knowledge), five alternatives per item, all alternatives in an item were homogeneous, all alternatives are grammatically related to the stem, no overlapping alternatives (one option includes one or more other options as a subset), and "none of the above" or "all of the above" were never used as options.

The same items were used on the pre-test and on the post-test. However, the item order and the order of the alternatives were randomly changed on the post-test. This selection of the item order for the post-test was done by placing ten equally sized slips of paper with the numbers one through ten on them into a bowl. The numbers on the slips of paper corresponded to the item number in the pre-test. The slips were removed

without replacement until all ten slips had been selected. The order of selection of the numbers on the slips determined the item order for the post-test. The order of the alternatives for each item was obtained in a similar fashion.

The test-retest reliability of the content test was determined by administering the pre-test and post-test one month apart to six technical center staff who did not participate in the analogical-teaching study. The Pearson Product Moment Correlation Coefficient was used to assess this reliability. For the six sets of pre- and post-tests, the coefficient was 0.81.

Clinical Interview

Interview Design

In order to determine what conceptions a learner had for radioactive material decay, half-life, and activity, and to ascertain the learner's status for these conceptions, a type of clinical interview was used that "centered around a contrived task designed to reveal the nature of a certain aspect of the subject's intelligence" (Posner and Gertzog, 1982). This interview instrument is also similar to the "Interviews-about-Instances" procedure used by Osborne and Gilbert (1980). These types of interviews are fashioned after the "open interview" developed by Piaget (1929).

In the Posner and Gertzog (1982) interview format, the interviewee

thought aloud as he completed a task. This process helped to identify misconceptions and faulty reasoning, and probed the interviewee's operative conceptual scheme (Posner and Gertzog, 1982).

In the present study, interview questions were designed to elicit information in all three status categories, (1) intelligibility, (2) plausibility, and (3) fruitfulness.

In order for the interview process to be successful in clarifying status changes, general guidelines needed to be followed. These guidelines were considered during the design of the interview questionnaire, the actual interview protocol, and in the interpretation of the interview transcripts. The guidelines were taken from Posner and Gertzog (1982) except where otherwise indicated. The general guidelines are as follows:

1. Subtleties or word order and phrase (on the part of the examiner) can induce suggested convictions.

2. To distinguish between suggested convictions and liberated and spontaneous convictions, the examiner should make counter suggestions after a short interval in the interview. Suggested convictions can be detected because they tend to be unstable. In addition, the lack of connection between a particular response and the learner's other conceptions may indicate a suggested conviction (Piaget, 1929).

3. The interviewer must be alert, and ready to respond, to unexpected responses.

4. The interview should be guided by a definite plan but still refrain from being suggestive. Part of the guiding plan is an awareness of how the interview responses are to be interpreted. This awareness will help to ensure the correct interview path is followed.

5. An interviewer must be sensitive to the following kinds of cognitive features:

Note that these considerations become important in ensuring that the interview process follows the correct path to elucidate the learner's status conditions. They are also important when an interpretation of the interview responses is undertaken. The considerations were (a) the learner's metaphysical and epistemological assumptions, (b) extraneous ideologies or purposes, (c) counterintuitive notions, (d) operative conceptual schemes, (e) assimilative strategies, and (f) misconceptions and invalid reasoning.

The learner's metaphysical and epistemological assumptions refer to assumptions about the relation between theory and data, and the relation between everyday experience and "classroom knowledge" strongly affect the direction and extent of conceptual change (Posner et al., 1982). For example, learners can avoid the need for conceptual change by maintaining a separation between classroom experiences and real world experiences.

Extraneous ideologies or purposes refer to resistance to conceptual change which may occur because of basic ideology. For example, Christian

fundamentalists resist Darwinian evolution for theological reasons.

Counterintuitive notions refer to why learners find some ideas to be counterintuitive (and thus difficult to accept) They can provide an understanding of learners' inabilities to make conceptual changes.

Operative conceptual schemes are comprised of all of a learner's current theories and concepts. They result from changes in prior notions. Thus, identification and representation of a learner's pre-instruction conceptual scheme is important in understanding the success or failure of the analogical teaching presentation in affecting conceptual change.

Assimilative strategies are used when learners attempt to assimilate (conceptual capture) information into their existing frameworks rather than undergo an accommodation (conceptual exchange). This can result in bizarre conclusions. For example, learners attempt to "Newtonize" some aspects of Einstein's theory by interpreting relativistic phenomena within a framework based on absolute time and space (Posner, et al., 1982). The use of misconceptions and invalid reasoning by learners indicated that it is important to identify any mistake the learner is making regardless of the validity of their conclusion. This is because, beginning with false premises, learners often reach invalid conclusions from sound reasoning or even valid conclusions from unsound reasoning.

(Items 6.-12. were taken from an article by Anderson (1992).

6. General open-ended questions are useful in ascertaining a

learner's current conceptual scheme. For example, asking a learner to respond to a written statement in terms of its validity and its degree of agreement with his own beliefs has been found to be useful in determining the learner's conceptual structure and metaphysical assumptions (Posner et al., 1982). An examiner could ask a learner to state what he knows about a topic and the ways he has used the information. Non-specific follow-up questions could take the form of "Do you recall anything else?".

7. The examiner should not normally mention terms and concepts relevant to the interview until after the learner has had a chance to bring them up on his own. After the learner labels what he sees, the interviewer may ask about specific terms that the learner hasn't mentioned.

8. After getting the learner started on a task, the examiner should follow the learner's leads, probing for the nature and depth of his understanding.

9. Use phrases like "do you think" or "can you remember" to avoid a focus on correct or incorrect answers.

10. Encourage detailed and thoughtful answers, but avoid indicating whether the answers are correct or incorrect.

11. Don't assume that because a learner uses a term that they understand it. Question the meaning of terms that they use.

12. Avoid questions that can be answered with one or two words unless they precede a "why" question.

The work sheet that was designed for this study is illustrated in Figure 2. This work sheet was designed to be used in conjunction with researcher-asked questions (Appendix C, the interview protocol) during the clinical interview to elicit information in all three status categories, (1) intelligibility, (2) plausibility, and (3) fruitfulness. The interviews were audio-taped and transcribed. Copies of the transcripts are available from the author upon request.

During the interview, the researcher asked questions to obtain additional information about the learner's thinking concerning the situations depicted in the work sheet. This interview protocol is illustrated in Appendix C. The interview protocol called for only one or two initial questions for each condition, but these focused on each of the three concept areas of radioactive material decay, half-life, and activity. When a participant was asked "Do you think that your explanation of what is occurring is true?" they would frequently reply that they did not know. However, if the same participant was then asked 'Do you think that your explanation of what is occurring has the potential to be true?" the participant would sometimes begin to compare their remembrance of their responses to their conceptual ecology and would then provide information that was useful in determining the status that they had for their conception. Asking the interviewee to talk about the potential of a conception, in effect, gave permission to speculate about the response in relation to the learner's

TIME ZERO (START), A QUANTITY OF A RADIOACTIVE MATERIAL IS IN THE DISH ON THE TABLE. INDICATE WHAT THE MATERIAL, THE METER'S DIAL, AND THE CLOCK LOOK LIKE AT THE START, AT THE TWO INTERMEDIATE TIMES, AND AT THE END. (ASSUME THE MATERIAL ONLY UNDERGOES A ONE-STEP DECAY). NOTE THAT THE DIAL SHOULD INDICATE THE AMOUNT OF RADIATION THAT IT IS EXPOSED TO. COLORED PENCILS ARE PROVIDED FOR YOUR USE AS YOU COMPLETE THIS EXERCISE, EXPLAIN YOUR THINKING ALOUD.

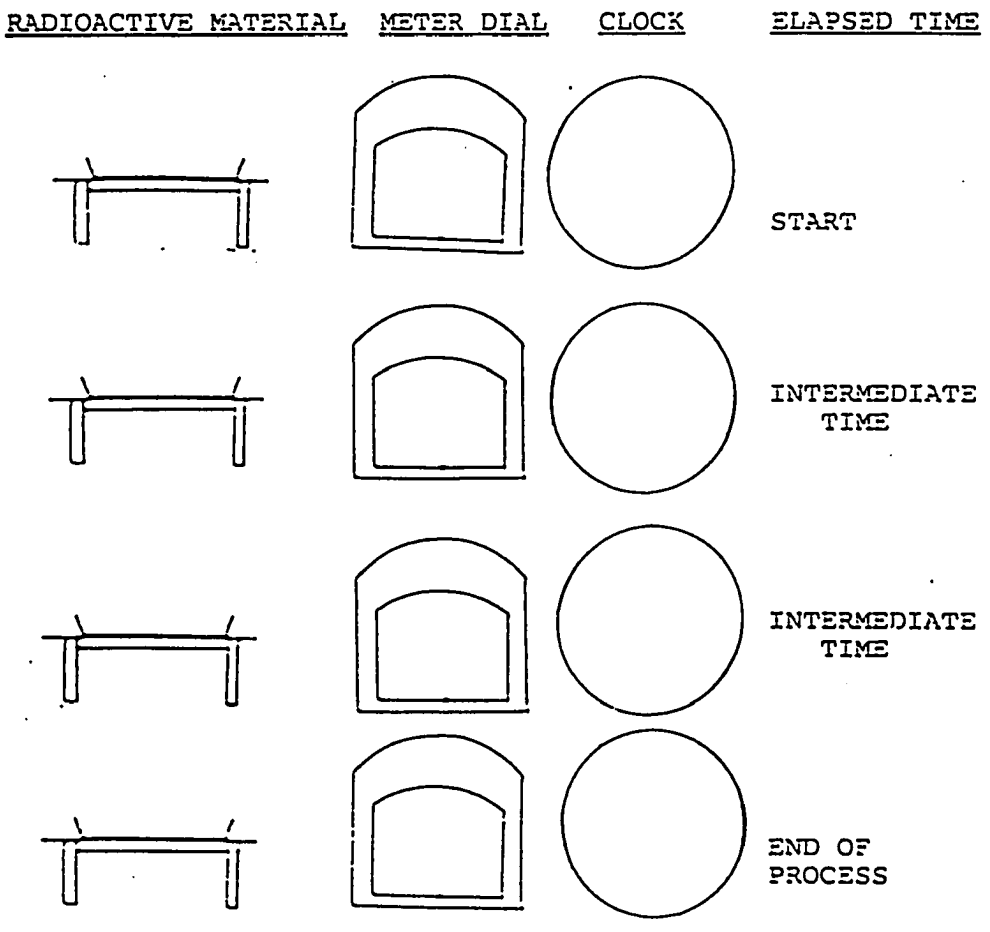


Figure 2. Interview Work Sheet.

conceptual ecology.

Note that there were two phases to the intelligibility questions (Hafner, 1994). Phase one consisted of general open-ended questions designed to encourage the participants to freely express their thinking about the three concept areas. After a participant had been given ample opportunity to express his thinking, phase-two questions were asked. These questions were directed at asking the learner to explain the meaning of each of the terms listed in the interview protocol document, Appendix C. Terms from this list that the learner used in Phase I were mentioned first, followed by any terms that the learner did not spontaneously mention in Phase I.

Note that during the post-interviews, the researcher attempted to get the participants into a compare/contrast conversation. This was done to establish an environment that was conducive to eliciting metacognitive status talk (Hewson, 1994). To accomplish this, two things were done during the post-interviews:

1. After the participant has had a chance to fill out the work sheet, the researcher showed the learner his completed pre-lesson work sheet and asked questions designed to encourage the participant to make comparisons in each of the three condition arenas .

2. After the participant has had a chance to respond to the questionnaire, the researcher showed the participant a scientifically-correct completed interview work sheet and/or a scientifically-incorrect completed

completed interview work sheet and/or a scientifically-incorrect completed interview work sheet, illustrated in Figures 3 and 4, respectively. The researcher stated that these were completed by another participant. The researcher asked questions designed to encourage the participant to make comparisons in each of the three condition arenas.

An additional part to the interview was suggested by Dr. Robert Hafner. In the last portion of the post-interview the participants were asked questions designed to obtain information concerning how the analogies helped to raise their status for the radiation science concepts under study. Information obtained from this portion of the interviews may serve as a basis for future research studies rather than as a main focus for this research. Questions meant to obtain this information were also included in the interview protocol.

Interview Administration

The interviews were all conducted in a private office. Prior to beginning the interview, every attempt was made to put the participant at ease. This typically involved some talk about issues unrelated to the interview. However, many participants were typically a bit eager to get the process completed. This is because they were taking time away from their work to partake in this study and often wished to return to their work responsibilities as soon as possible.

TIME ZERO (START), A QUANTITY OF A RADIOACTIVE MATERIAL IS IN THE DISH ON THE TABLE. INDICATE WHAT THE MATERIAL, THE METER'S DIAL, AND THE CLOCK LOOK LIKE AT THE START, AT THE TWO INTERMEDIATE TIMES, AND AT THE END. (ASSUME THE MATERIAL ONLY.UNDERGOES A ONE-STEP DECAY). NOTE THAT THE DIAL SHOULD INDICATE THE AMOUNT OF RADIATION THAT IT IS EXPOSED TO. COLORED PENCILS ARE PROVIDED FOR YOUR USE AS YOU COMPLETE THIS EXERCISE, EXPLAIN YOUR THINKING ALOUD.

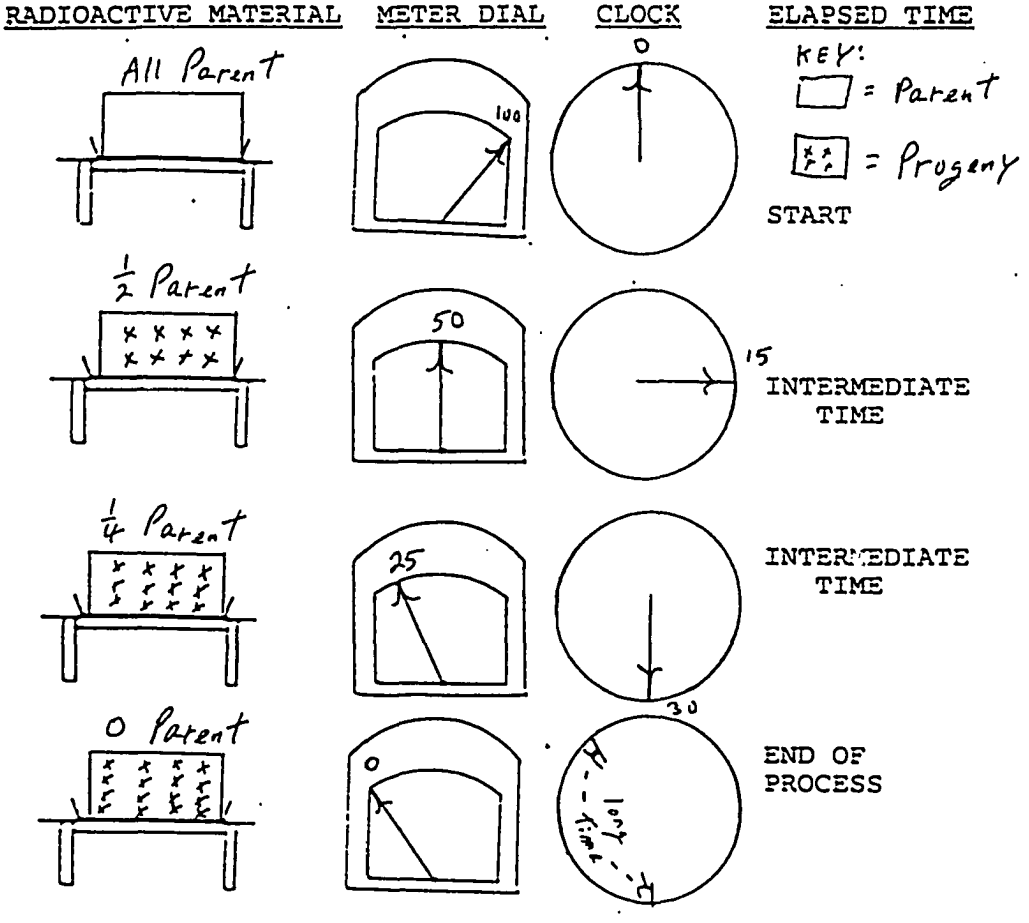


Figure 3. Correctly Completed Interview Work Sheet.

TIME ZERO (START), A QUANTITY OF A RADIOACTIVE MATERIAL IS IN THE DISH ON THE TABLE. INDICATE WHAT THE MATERIAL, THE METER'S DIAL, AND THE CLOCK LOOK LIKE AT THE START, AT THE TWO INTERMEDIATE TIMES, AND AT THE END. (ASSUME THE MATERIAL ONLY UNDERGOES A ONE-STEP DECAY). NOTE THAT THE DIAL SHOULD INDICATE THE AMOUNT OF RADIATION THAT IT IS EXPOSED TO. COLORED PENCILS ARE PROVIDED FOR YOUR USE AS YOU COMPLETE THIS EXERCISE, EXPLAIN YOUR THINKING ALOUD.

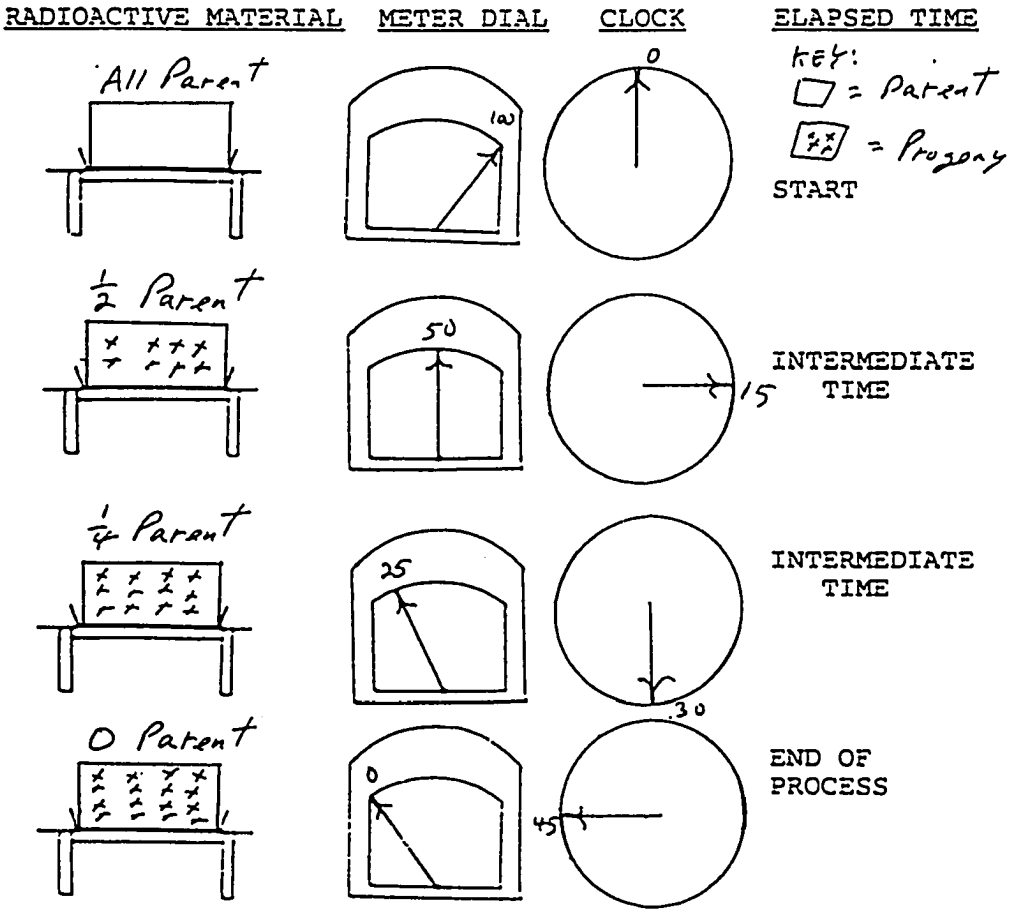


Figure 4. Incorrectly Completed Interview Work Sheet.

The initial step in the actual interview process was to inform the participant that the purpose of the interview was to obtain information about how people thought about some concepts involving and/or related to radiation. An important consideration was to establish the correct atmosphere during the interview. In order to do this, it was emphasized that the purpose of the interview was not focused on whether or not the learner gave a correct or incorrect response to the interview questions. Instead, one purpose of the research was to determine why a person's opinions "made sense" to them. It is hoped the perception that the researcher was the "master of the correct response" was minimized, and the participants' responses were, therefore, less inhibited (Hewson, 1994). The researcher further indicated that the learner's responses would be used but that the participants would not personally be identified. The participants were also informed that the interview was being conducted as part of the researcher's Ph.D. dissertation in Science Education at Western Michigan University.

The participants were shown the work sheet in Figure 2. The learner was then asked to explain what was occurring over time in the instance depicted in this work sheet. A box of colored pencils was available that the learner could use to illustrate his answer. The learner was asked to verbally express his thinking (think aloud) as he completed the task. (Note that asking a learner to "think aloud" as he solves a problem or answers a

question helped to identify the learner's misconceptions, faulty reasoning, and notion of the problem space, which could suggest their operative conceptual scheme. (Newell and Simon, 1982). The participants were then informed that during the interview, the researcher would ask questions to extract useful information. A tape recorder was then pointed-out. Finally, the participants were asked to read and sign the permission form (Appendix A).

Interview Interpretation

Each interview was transcribed so it could be effectively analyzed for its disclosure of the learner's status for the concepts of radioactive material decay, half-life, and activity. Some things that were considered when evaluating the learners interview responses are listed below. These interview evaluation considerations are taken from Posner et al. (1982) and Posner and Gertzog (1982). Further explanations for each of the listed items were given in the previous interview design section. The considerations were: (a) the learner's metaphysical and epistemological assumptions, (b) extraneous ideologies or purposes, (c) counterintuitive notions, (d) operative conceptual schemes, (e) assimilative strategies, and (f) misconceptions and invalid reasoning.

The steps that were taken to analyze interview transcripts for the purpose of gaining information about a learner's conception and his status

for that conception are as follows:

1. The flow of the interview was examined to determine if the concepts elicited from the learners were acceptable or unacceptable. Only acceptable responses were further examined. The categories of acceptable and unacceptable responses are as follows (Posner and Gertzog, 1982). Unacceptable responses were: (a) an answer at random, (b) romancing, and (c) a suggested conviction.

An answer at random refers to the first thing that comes into a learner's mind, not related to the question under consideration. Romancing refers to an invented answer that a learner does not really believe but is given for the purpose of amusement. A suggested conviction is stimulated or suggested by the questioner's choice of words or question sequence or is given to satisfy the interviewer.

Because an adult population was involved in this research, only the suggested conviction type of unacceptable response was detected.

Acceptable responses most directly uncover the learner's understandings, logic, and beliefs. Acceptable responses are: (a) liberated conviction - a result of reasoning, and (b) spontaneous conviction - a result of previous original reflection.

2. The concepts to which the participants' statements related were identified. Except for the Nucleus-one concept, only the concepts covered by the two analogies were identified. These concepts were previously

illustrated in Figure 1.

3. For each concept's set of statements, those that elucidated the learner's status were selected. For the vast majority of dialog, the condition (intelligibility, plausibility, fruitfulness) each passage referred to was identified using a categorization system. The majority of this system was taken from work by Strike and Posner (1985) that was expanded upon by Thorley (1990, 1991, 1992) (used with Thorley's permission). An addition to Thorley's categories was the direct categories for each condition, which were taken from Hewson and Hennessey (1991) and the plausibility-authority category which has not been previously discussed in the literature. The individual categories of intelligibility, plausibility, and fruitfulness, along with examples, are listed in Appendix D.

No assumptions concerning conditions were made. For example, if a learner expressed no intelligibility for a concept, it was not assumed that he did not possess plausibility. If no evidence for his plausibility was available, a rating of unknown was assigned.

The categorization scheme illustrated in Appendix D is quite useful, especially when determining which statements concern the conditions of plausibility and fruitfulness. To exhibit developing fruitfulness, the learner was required to state at least one use of his understanding of the concept.

4. For the concept area's intelligibility statements, it was determined if the concept representations partially or fully agreed with the scientifically

accepted versions of the concepts that explain the phenomena under consideration or whether the representation illustrated an alternative conception. This step was accomplished by comparing the learner's understanding of the concept as revealed in his intelligibility statements with the accepted scientific view, as enumerated in the content section of the teaching lesson. Then, on the basis of this examination, comments were made about the learner's intelligibility for the decay, half-life, and activity concepts.

This analysis determined if the learner's condition of intelligibility for the scientifically accepted version of the three concept areas under study was absent, developing, present, or unknown. If the learner understood all elements of the concept, his intelligibility was rated as being present. If some of the elements were present, he was rated as developing. If the learner expressed no understanding or an alternative understanding, his intelligibility was rated as absent. If insufficient evidence was available from the interview transcript, the condition was rated as unknown.

5. The plausibility that the student had for his understanding of each of the concepts was determined by logically examining the identified plausibility conditions statements. This condition may have been absent, developing, present, or unknown. On the basis of this examination, comments concerning the learner's condition of plausibility for the decay, half-life, and activity concepts were made.

Plausibility was present if the learner possessed intelligibility for the concept and believed his understanding to be true. If the learner believed his developing understanding to be true, he was given a developing plausibility rating. A rating of developing plausibility was also assigned if the learner expressed some doubts about a concept that he found to be intelligible. Plausibility was absent if the learner expressed that he did not believe in a concept that he found intelligible. A rating of no plausibility was given if a learner expressed belief in an alternative understanding that was incompatible with the scientifically accepted view of the concept. A rating of no plausibility was also given if a learner expressed that he did not know if an intelligible or unintelligible concept was true. Plausibility was unknown if insufficient evidence existed to assign one of the above ratings.

6. For each concept, the fruitfulness that the student had for his conception for each of the concepts was determined by considering the pertinent fruitfulness condition statements. The fruitfulness may have been absent, developing, or unknown. The condition of full fruitfulness was not detected. No learner demonstrated this degree of experience with any of the concept areas. On the basis of this examination, categorization of a learner's condition of fruitfulness for the decay, half-life and activity concept areas was made. A full fruitfulness rating would have been assigned if a learner had demonstrated a broad network of interconnected

conceptual understandings that indicated abundant experience with and resultant varied applications of the concept under study. This type of rating is expected to only be found in experts with considerable experience. Fruitfulness was developing if the learner was able to give one or more examples of the usefulness of the concept. If no example could be cited, the fruitfulness was absent. If insufficient evidence existed to make a rating, the fruitfulness was unknown. If a learner only expressed that experts could find an understanding of the concept to be useful, this was given a rating of no fruitfulness because the learner had no personal awareness of the concept's usefulness. If the learner expressed that an understanding of the concept would be useful in a lot of situations, but no specific examples were given, this was rated as unknown fruitfulness. If the learner demonstrated usefulness for an alternative intelligibility, this was rated as no fruitfulness for the concept under study.

Acceptable information from the pre- and post-interviews was collected and analyzed according to the above scheme. A comparison of the pre- and post-interview information on an individual basis furnished data for judging the research hypotheses (do the melting-ice and the falling-tacks analogies assist learners in developing higher status for the scientifically accepted radioisotope decay, half-life, and activity concepts compared with their conceptual status prior to the presentation of the two analogies).

Falling-Tacks Activity

The falling-tacks analogy was suggested by Dr. Larry Oppliger (1994) of Western Michigan University. If one drops a sample of tacks onto a surface, some of the tacks will land sideways and others will land on their heads with the point up. If one considers the tacks landing on their sides to be analogous to nuclei that have undergone radioactive decay, then the successive dropping of the remaining tacks (remove the ones landing on their sides) illustrates the half-life concept. For example, consider a sample of 80 tacks. Successive rounds of tack release are illustrated in Table 1.

Each participant was given the opportunity to complete the falling-tacks activity. The researcher selected tacks that had a "half-life" different than one drop. That is, a fraction different from one-half landed on their sides during each drop of the tacks. The half-life of the chosen tacks was 1.25 drops. This means that, on average, a group of the tacks had to be dropped 1.25 times before half of them fall onto their sides as opposed to falling onto their heads. If a different type of tack had been used, the half-life may have been different.

To complete the falling-tacks activity, a participant was given a box containing one-hundred tacks. The participant then dropped all of the tacks onto a hard surface. When dropped, the tacks fell either on their

Table 1

Falling-Tacks Data

Drop Number	Total Number of Tacks	Number of Tacks Landing on Their Sides
zero	80	43
one	37	21
two	16	9
three	7	4
four	3	1
five	2	0
six	2	2

sides or on their heads. The tacks that fell on their sides were counted and removed. This count was recorded on the data sheet illustrated in Figure 5. The remaining tacks (those that fell on their heads) were then dropped again onto the same surface and the tacks that fell on their sides were counted and removed. This count was entered into the data sheet. This process was continued until all of the tacks had fallen onto their sides. This falling-tacks exercise is analogous to radioactive material decay in several respects related to decay, half-life, and activity concept areas. The correspondences between the analogy and the targets are illustrated in Table 2. Note that both object and relationship correspondences exist.

The non-correspondences between the analog and the targets are illustrated in Table 3.

NAME _____

DATE	DROP NUMBER	NUMBER OF TACKS LANDING ON SIDE
	1 -	
	2 -	
	3 -	
	4 -	
	5 -	
	6 -	
	7 -	
	8 -	
	9 -	
	10 -	
	11 -	
	12 -	
	13 -	
	14 -	
	15 -	
	16 -	
	17 -	
	18 -	

Figure 5. Falling-Tacks Data Sheet.

Table 2

Correspondences Between Falling-Tacks Analog and Target

Falling-Tacks Analog	Target Correspondence
Tacks in Hand	Parent Material
Tacks Falling	Parent Material Decaying
Tacks on Sides	Progeny Material
Falling Continues Until All Tacks are on Their Sides	Decay Continues Until Parent is Entirely Changed Into its Progeny
All Tacks Have an Equal Probability of Falling on Their Sides	All Parent Nuclei Have an Probability of Decaying
Amount of time Required for One-Half of the Tacks to Fall on Their Sides	Half-Life
Amount of Time Required for One-Half of the Tacks to Fall on Their Sides is the Same Regardless of the Number of Tacks that Have Already Fallen	Half-Life is a Constant
Number of Tacks Falling on Their Sides Per Release	Activity
Number of Tacks Falling on Their Sides Per Release Decreases with Subsequent Releases	Activity Decreases as Decay Decay Proceeds (for a Single Step Decay)

Table 2-Continued

Falling-Tacks Analog	Target Correspondence
The More Tacks Remaining, the Greater the Number of Tacks Falling on Their Sides During That Release	The More Parent Material Present, the Greater the Activity

Table 3

Non-Correspondences Between Falling-Tacks Analog and Target

Falling-Tacks Analog	Target Correspondence
Tacks are Always the Same Substance	Parent and Progeny are Different Materials
Dropping Tacks is a Discrete Event	Decay is Continuous

Melting-Ice Analogy

The melting-ice analogy was discussed in an article by Wise (1990) describing how melting ice is analogous to the decay of a radioisotope. In this article, Wise specifically compared the melting of ice to radiometric dating. In the Wise analogy, which considered the room temperature melting of ice cubes, the plot of volume of meltwater produced versus time

was linear (i.e. subject to zero order kinetics), except for the very early stages before thermal equilibrium was reached and at the very early stages before thermal equilibrium was reached and at the very end where to little ice was left to keep the funnel temperature constant. For the purposes of this research, a modification to this analogy was made to improve the mapping between the analog (melting ice) and the target (radioactive decay, half-life, and activity). The modification considered the rate of melting to follow first-order reaction kinetics (i.e. exponential melting). Thus the meltwater production decreased as the amount of remaining ice decreased. This modification was a better parallel than Wise's original analogy to radioisotope material decay, half-life, and activity phenomenon. These radiation science phenomenon follow first-order kinetics.

During the lesson presentation, the researcher informed the participants that model data was being used instead of real melting data. They were asked to compare how radioactive materials compare with the melting of ice using the model data.

During the lesson, this analogy was presented through a physical set up of melting ice, a verbal description, and melting-ice data that corresponded to an exponential melting phenomenon (i.e. model melting data, not actual melting data). For example, given ice with a half-life of 30 minutes, one-half of the ice will melt every 30 minutes so the rate of meltwater production will be cut in half every 30 minutes. Data relating to

this situation are illustrated in Figure 6. Note that the data parallel radioactive material decay in the sense that the half-life of the ice remains constant through the melting process. These data are plotted in Figure 7 as amount of remaining ice versus elapsed time. The amount of remaining ice corresponds to the amount of a radioactive material remaining.

Plotting these data as melting rate versus elapsed time results in an exponential melting-rate curve that is analogous to a radioactive material activity curve. Note that the amount of ice that melts in each thirty-minute interval decreases as the melting process progresses. The activity of a radioactive material parallels this in that activity also decreases as the decay process progresses. This plot is illustrated in Figure 8. The melting rate corresponds to the activity of a radioactive material.

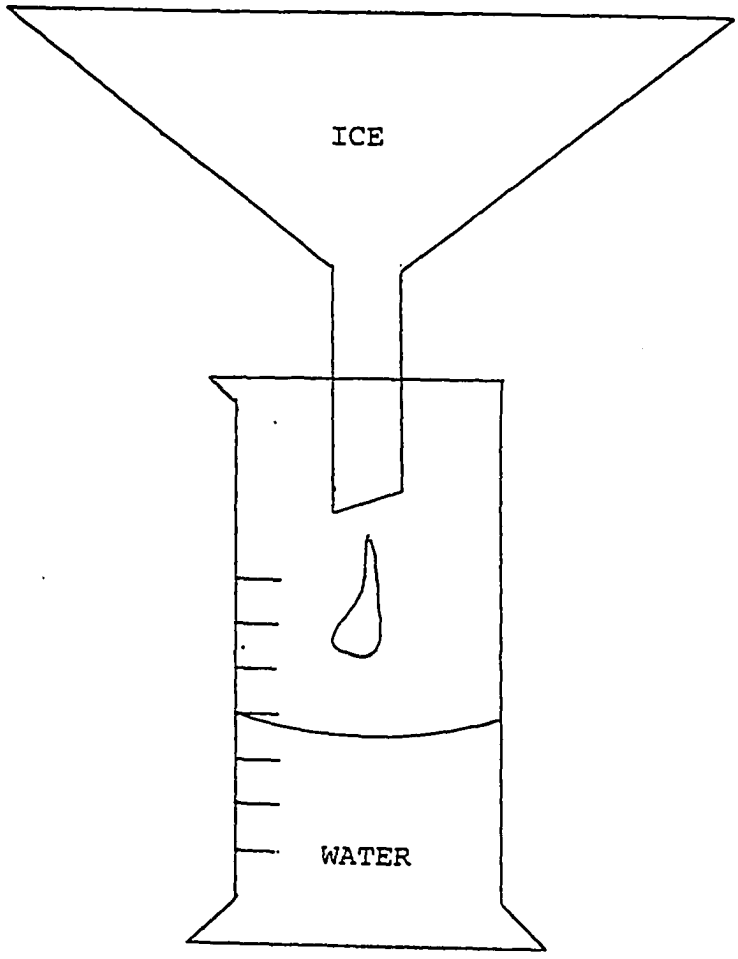
The correspondences between the analogy and the targets are illustrated in Table 4. Note that these represent both object and relationship correspondences.

The non-correspondences between the analog and the targets are illustrated in Table 5.

Lesson

The lesson was presented in a lecture format. During the lecture, eight concepts relating to the behavior of radioactive materials were presented through two analogies, the melting-ice and falling-tacks

TIME ZERO	30 MINUTES	60 MINUTES	90 MINUTES	120 MINUTES
1000g ice	500g ice	250g ice	125g ice	62.5g ice



0ml H_2O	500ml H_2O	750ml H_2O	875ml H_2O	937.5ml H_2O

Figure 6. Melting-Ice Data.

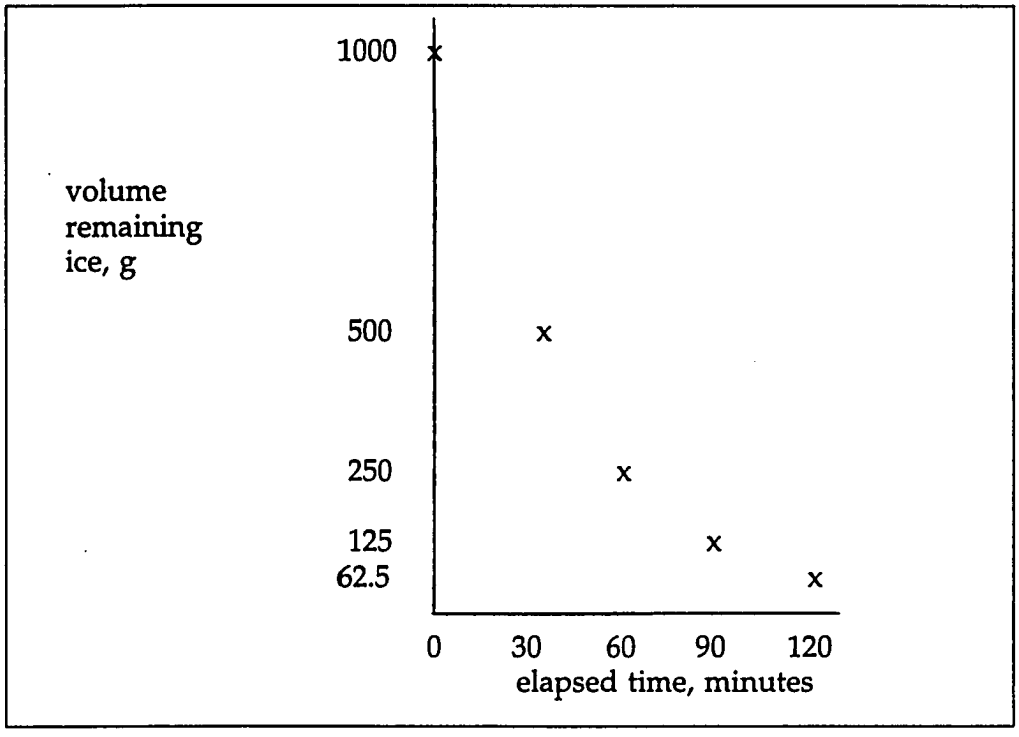


Figure 7. Plot of Melting-Ice Data Analogous to Radioactive Material Decay.

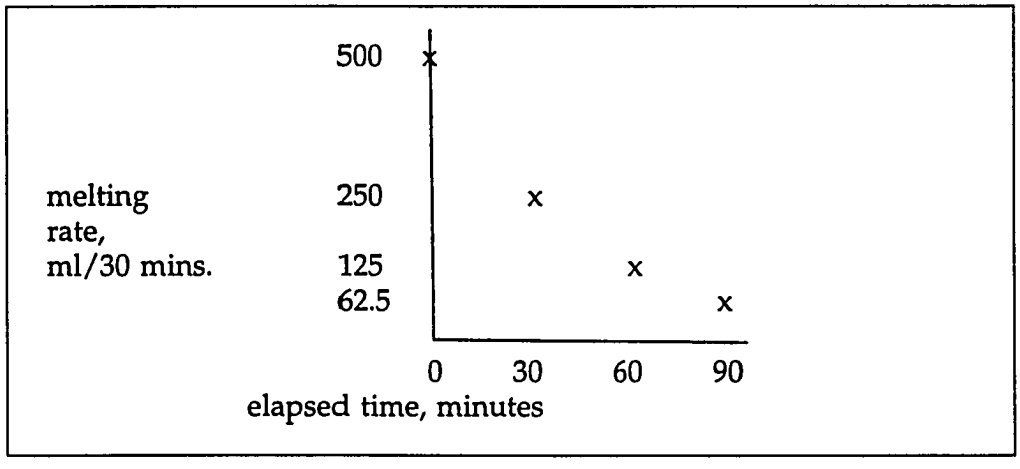


Figure 8. Plot of Melting-Ice Data Analogous to Radioactive Material Activity.

Table 4

Correspondences Between Melting-Ice Analog and Target

Melting-Ice Analog	Target Correspondence
Ice	Parent Material
Melting	Decay
Melt-Water	Progeny Material
Melting Continues Until All Ice Becomes Melt-Water	Decay Continues Until Parent is Entirely Changed Into Progeny
Amount of Time Required for One-Half Ice to Melt	Half-Life
Amount of Time Required For one-half of Remaining Ice to Melt Is Constant Regardless of the Extent of Melting	Half-Life is a Constant
Amount of Ice Melted Every 30 Minutes	Activity
Amount of Ice Melted Every 30 Minutes Decreases as Melting Proceeds	Activity Decreases as Decay Proceeds (For Single Step Decay)
The More Ice Present, The Greater the Amount of Ice Melted per Time	The More Parent Material Present, the Greater the Activity

Table 5

Non-Correspondences Between Melting-Ice Analog and Target

Melting-Ice Analog	Target Correspondence
Ice and Water are Chemically the Same Substance	Parent and Progeny are Chemically Different Substances
Surface Ice Melts Before Internal Ice	All Parent Nuclei Have an Equal Probability of Decaying
Melting Process is Reversible	Decay Process in Not Reversible
Melting Process is Temperature Dependent	Decay Process in Not Temperature Dependent

analogies. These two analogies were represented through a series of overhead transparencies.

The eight concepts covered during the lesson were related to the broader concepts usually labeled as radioactive material decay, half-life, and activity. This material was taken from works by Mortimer (1986); Castellan (1983); Ehmann and Vance (1991), and Dorin, Demmin, and Gabel (1989). Four of the eight concepts concerned radioactive material decay, two concerned radioactive material half-life, and two concerned radioactive material activity. These concept areas are summarized in Figure 1. Except for the first concept concerning the fact that radiation is emitted from the

atomic nucleus, all of the concepts have correspondences with both of the two analogies presented during the lesson. The overhead transparencies used during the lesson presentations sessions are in Appendix E.

The general format of the lessons closely followed the steps of the Teaching-with-Analogies model (Glynn, 1989; Glynn, Britton, Semrud-Clikeman, and Muth, 1989). This model was based on an analysis of the analogies used in 43 science textbooks. The recommended steps are (Glynn, 1991): (a) introduce the target, (b) cue retrieval of the analog, (c) identify relevant features of target and analog, (d) map similarities, (e) draw conclusions about target, and (f) indicate where analogy breaks down.

The presentation of this lesson consisted of presenting information concerning a radioactive material concept area and then showing how the analogy corresponded with the information. This process was first done for each of the three concept areas, radioactive material decay, half-life, and activity, using the melting-ice analogy. Following this, the people present at the lesson presentation were asked to identify any non-correspondences between the three concept areas and the melting-ice analogy. Their responses were compared with the those identified by the researcher which were listed on an overhead transparency. This overhead transparency is included in Appendix E. Next, the same process was completed with the falling-tacks analogy. Finally, the correspondences between the three concepts areas and the two analogies were covered concurrently.

Glynn (1991) stated that an analogy is good if it meets three criteria: (1) a large number of analog/target correspondences; (2) the features compared are easy to identify, thus the analog should be familiar to the learners; and (3) significant features are compared. The analogies used in this lesson meet these criteria. An examination of the overhead transparencies used in this lesson (Appendix E) reveals that numerous significant correspondences were drawn between the two analogues and the decay of a radioactive material.

The use of two different analogies to teach the concepts of radioisotope half-life and activity were useful because each analogy emphasized different aspects of the concepts. The melting-ice analogy emphasized the continuous nature of radiation decay while the falling-tacks analogy stressed the discrete and probabilistic nature of the nuclear decay phenomena. One potential benefit of use of multiple analogies to teach science concepts was that the learner was required to determine which aspects of both analogies were pertinent and which were not. This may, in some cases, help diminish the formation of misconceptions compared with the use of only a single analogy (Duit, 1991). These analogies also fulfilled another requirements set forward by Duit (1991), substantial portions of the analog and target were mapped. Goswami's (1991) criteria that the analogies used in this situation were familiar to students in terms of the objects (ice, water,tacks) and the relations (melting, falling, melting rate,

falling rate) was achieved. In addition, four of Thagard's (1992) guidelines concerning the use of analogies in instruction were satisfied: (1) the analogues were more familiar than that the target, (2) the analogues were not cryptic, (3) the analogues were not too lengthy, and (4) the non-correspondences between the analogues and the target were explicitly pointed out during instruction. For some learners, the melting-rate relation did not satisfy requirement two, that the analog not be cryptic. Some learners commented during the interviews that the model melting rate was not believable.

CHAPTER III

EXPERIMENTAL DESIGN

The research procedure used in this study consisted of a pre-test, followed by an analogy-based lesson, followed by an immediate post-test. The object of this study was "human subjectivity" (Johansson, Marton, and Svensson, 1985) in that peoples' ideas about concepts were being examined rather than the concepts themselves. Data were collected from two groups. Group one consisted of nine participants. In this group, pre- and post-testing involved written content tests and personal interviews. Group two was composed of 35 participants. In this second group, the pre- and post-testing involved only the written content tests. Members of both groups were present during the same analogy-based lesson sessions.

Group One

The research design consisted of very similar methodologies for group one and group two. For group one, approximately two-weeks prior to the treatment the participants received a written multiple-choice content pre-test designed to determine their intelligibility (understanding) for the radioactive material decay, half-life, and activity concepts. In addition, each

subject participated in a pre-lesson interview. The anonymity of the group-one learners was ensured by having each subject choose a fictitious name that was assigned to all of their data. In addition, once all of the data were collected, the researcher assigned a second fictitious name to all of each subject's data. In this way, no data were recognizable to anyone else, including the subjects. After all of the data had been collected, the real names/fictitious names list was destroyed.

Falling-Tacks Activity

At the time of the pre-testing, each group-one participant was given 100 tacks to drop and asked to count the number of tacks falling on their sides during successive drops until all of the 100 tacks had landed on their sides. These data were later used by the researcher during the lesson presentation to illustrate various phenomena related to radioactive material decay.

Lesson

Approximately two weeks after the pre-testing, an analogy-based lesson was conducted during three departmental staff meetings and one Safety Committee meeting as part of the radiation safety training that is given to these work areas per requirements of the state's rules pertaining to ionizing radiation. All three departmental lessons were held within the

same week. The lesson held during the Safety Committee meeting was held two weeks after the departmental lessons. During the lessons, the researcher presented information concerning radioactive material decay, half-life, and activity. The lesson was presented in a lecture format using overhead transparencies. At the beginning of the lesson, and through-out the lesson, the participants were encouraged to verbally participate at any time. This was done to encourage the learners to take advantage of opportunities to mentally negotiate and reflect upon the meaning of these concepts.

The first overhead covered the sub-concepts involved in the radioactive material decay portion of the lesson. Following this, the melting-ice analogy was presented. A set-up of melting ice was available for inspection by the participants. Following the presentation of the melting-ice analogy, the correspondences between the analogy and radioactive material decay, half-life, and activity were covered through overhead transparencies. The above activities were designed to give the learners an opportunity to develop an understanding of correspondences that exist between the melting-ice phenomenon and the decay, half-life, and activity of a radioactive material. The participants were then asked if they believed that the correspondences between the melting of ice and radioactive material decay, half-life, and activity represented, or had the potential to represent, how radioactive materials actually behaves in nature.

The phrase "had the potential to represent" was included to give the learners who were unsure of their proficiency in this area permission to speculate about the behavior of radioactive materials. Thus, the participants were given the opportunity to compare the lesson-based analogy correspondences with their internal array of networked-conceptions, their "conceptual ecology". This question was designed to elicit participant responses and to stimulate subsequent class discussion concerning the learner's plausibility (believability) for the presented material. Since the sessions were composed of relatively small group (10 - 20 participants per session), an enthusiastic discussion frequently occurred.

Next, the falling-tacks analogy was presented through an overhead transparency. The falling-tacks data that had been previously collected were used to illustrate the concepts of radioactive material decay, half-life, and activity during this portion of the lesson. Through the use of overheads, correspondences between the falling tacks and the decay, half-life, and activity concepts were explained.

The participants were next asked if they believed that the correspondences between the falling-tacks analogy and radioactive material decay, half-life, and activity represented, or had the potential to represent, how radioactive materials actually behave in nature. This was done to elicit participant responses and to stimulate subsequent class discussion concerning plausibility for the presented material.

Following this, the non-correspondences between the two analogies and radioactive material decay, half-life, and activity were covered explicitly in an open-class discussion and recorded on an overhead transparency.

Within three days after the end of each training session, the content post-test and post-interviews were again administered to all group-one participants.

Group Two

For the second group, a methodology similar to that used for group one was followed. However, this group was only pre- and post-tested using the multiple-choice content test designed to probe their understandings (condition of intelligibility only) for the three concept areas. One other difference between group-two and group-one methodologies was that the group-two content-tests were not identified by participant. Instead, at the time of pre-testing, all group-two subjects were invited to put a fictitious name (first and last name) on their pre-test document. At the time of post-testing, the participants were reminded to put their choice of a fictitious name on the test document. The few participants that forget their chosen fictitious name were shown a list of possible names. All were able to pick their chosen name from the list of possibilities. The fact that the pre- and post- test had the same name allowed for test matching. This

ensured that pre-test/post-test mean comparisons could be protected from experimental mortality effects (Cook and Campbell, 1979). "Mortality" refers to the dropping out of persons from groups being compared in an experiment. If not accounted for, this could result in a bias due to slower learners differentially dropping out. The procedure also ensured that the participants remained anonymous because an individual participant's response was not traceable to a specific subject.

Note that both group-one and two participants attended the teaching during their department meetings or a Safety Committee meeting. Thus, people from both groups were present during these teaching sessions. Also, the researcher followed a teaching agenda to keep the instruction in all four sessions as consistent as possible. The lag between the pre- and post-tests, and, where applicable, the pre- and post-interviews was done to minimize any practice or memory effects (Cook and Campbell, 1979).

Content Tests

The content tests were scored by the researcher using a key.

Interviews

The interviews were audio-taped and transcribed. When interpreting a transcript of an interview, the goal was to determine what conception the learner had for the phenomena under consideration and the status that the

student had for that conception. A comparison of the interviews prior to and after the analogy-based lesson gave information concerning status changes as well as conceptual changes. The administration of the interviews followed the procedure outlined under the Interview Administration portion of this document. This is found on pages 39-43. The researcher used the guidelines reported in the interview interpretation section of this document to interpret the interview responses (see pages 43-48).

CHAPTER IV

RESULTS

The results of this study fit into two main categories. One category concerns the results of the interview interpretations. The second category pertains to the multiple-choice content tests taken by both group-one and group-two participants.

In addition, information concerning how these analogies worked was obtained. This was done by examining statements made by the learners that revealed how they used the analogies and comparing these findings with what other researchers have found. The study was designed to provide these data as secondary information rather than to provide data to confirm or reject the research hypotheses.

Interview Results

The results of the interview interpretations were a consequence of qualitative analyses of the nine sets of pre- and post-interviews from the group-one subjects. The basic strategy for this interpretation was explained in the interview interpretation section of this document. The qualitative interpretations were based on the conceptual change model following

ground work laid by prior researchers, e.g. Posner and Gertzog (1982),Posner, et al. 1982), Strike and Posner (1988), Hewson and Thorley (1989), and Thorley (1990, 1991, 1992). The interpretation protocol was described in Chapter II. The codes for the condition classifications for learner statements, along with examples, are listed in Table 6. These codes follow each segment of dialogue. For example, a code of (I-t) means the statement fits within the intelligibility condition's attribute category. A code of (I-t;P-n) means a statement fits within the intelligibility condition's attribute category and the plausibility condition's neotheory category. A single statement may fit into several different categories, however, all categories may not be indicated. Only the codes of immediate interest to this study were recorded. Each of the nine sets of group-one interviews is summarized for each of the concepts under study. Only one representative set of interview interpretations is included in the body of the text for each concept area. The other interview interpretations are placed in Appendix F. A summary of the aggregate data is also given for each concept. Interview sets are present for Margaret, Felix, Mark, Edgar, Fred, Wilbur, Jennifer, Florence, and Ralph. The researcher has used the abbreviations I, P, and F for the status conditions intelligibility, plausibility, and fruitfulness, in the codings of the interviews interpretations.

Some examples of coded statements follow:

"Ya, well ya the ice is the parent. The water is the progeny." (I-a)

Table 6

Status Codes

Code	Condition	Sub-Category
I	Intelligibility	
d		Direct
a		Analogy
i		Image
e		Exemplar
t		Attribute
l		Language
P	Plausibility	
d		Direct
r		Real Mechanism
n		Neotheory
o		Other Knowledge
p		Past Experience
e		Epistemology
t		Ontology
a		Analogy
u		Authority

Table 6-Continued

Code	Condition	Sub-Category
l		Laboratory Experience
h		Thought Experiment
y		Hypothesis
m		Anomaly
F	Fruitfulness	
d		Direct
p		Power
r		Promise
c		Competition
e		Extrinsic

"I would think . after . . . certainly after ah . . . eight half-lives, . . it will. you know, be almost undetectable." (I-t;P-h)

"It can give you, a again, like a carbon-13 type of dating . system. Um it can tell you . . . . um . . . yes, I I I think there there is a significance . to knowing that that there are half-lives to these. Um . . you know, and and how quick. Ah as far as can I name them all? No. But . you know, it it can help . scientists . . determine, again, how long things have been

around." (F-p)

Nucleus-one Concept

Radiation is emitted from the nuclei of radioactive materials.

Evaluation of Nucleus-one Concept

Intelligibility for this concept was demonstrated if the learner expressed an understanding that radioactive material decay involved the atomic nucleus. If a learner had an understanding that the decay process involved the atom in general, this was viewed as an expression of no intelligibility for the Nucleus-one concept.

Results of Nucleus-one Concept Interview Interpretations

Two increases in intelligibility and three increases in the plausibility condition were experienced by the participants. No increases in fruitfulness were detected. Of the nine group-one participants, three were positioned such that they could experience a status increase for this concept in that their pre-interview status was lower than I,P, and developing F. The statuses for this concept increased for all three of these people. Six learners had the potential to retain the same status and three retained that same status. Three learners were positioned such that their statuses could go down because their pre-interview status was higher that no I, no P, and no

F. No learners decreased in status for this concept. Three learners had unknown status changes because their pre-interview statuses were unknown I, unknown P, and unknown F. Thus, regardless of their post-interview statuses, the change from the pre-interview status could not be determined.

The statuses that the group-one learners held for this concept increased for Margaret, Mark, and Wilbur due to a change in intelligibility and/or plausibility categories. This increase occurred for Margaret and Wilbur because of the conceptual exchange of the understanding that radioactive material is a nuclear event from the alternative understanding that it is a molecular event, with a concomitant increase in the plausibility that the learners had for this understanding. Mark experienced an increase in his plausibility for his understanding that decay is a nuclear event.

No status changes for Felix, Fred, and Ralph were detected. Fred and Ralph demonstrated no change in the I and P conditions, with the F change unknown. Felix demonstrated no change in the I condition, with the P and F changes unknown.

Edgar's, Jennifer's, and Florence's status changes could not be determined because the state of all three of their conditions were unknown from the pre-interviews, and in one case, for both the pre- and post-interviews.

Representative Interview Interpretation Set

For all interview transcriptions in this document, the following codes are used.

Interview Interpretation Codes:

R - Researcher
L - Learner
. . . - pause, one . per second
(??) - unintelligible
[ ] - researcher comments enclosed in brackets

Margaret's Pre-interview, Nucleus-one Concept. During the pre-interview, Margaret did not make any spontaneous statements about the decay of a radioactive material as a nuclear event. However, in response to a question by the researcher about what was happening during radioactive material decay, Margaret responded "I have no . idea. Is it the molecules? I have no idea." (I-d) Margaret demonstrated no intelligibility for this concept in the sense that she understood that the process occurred on the molecular level, instead of at the nuclear lever. Also, her uncertainty of the truth of this statement indicated that she had no plausibility for the concept. Since no other statements were made, her fruitfulness was unknown. Thus, during the pre-interview, Margaret demonstrated no intelligibility, no plausibility, and unknown fruitfulness for this concept.

Margaret's Post-interview, Nucleus-One Concept. During the post-interview, when talking about the decay of a radioactive material, Margaret mentioned that the process was continuous and that the "nuclei keeps breaking down". (I-t;P-r) She also made this comment.

> Well as a . as a radioactive material breaks down . um it's called decay. And it's um . it's the activity that goes and when the ah . . I guess when the nuclei break down and um that's would that's what the decay would be, the breaking down process (I-t;P-r).

These statements indicated that Margaret had intelligibility for the Nucleus-one concept. The plausibility features of the statements indicated the existence of plausibility for the concept. No statements were made concerning Margaret's fruitfulness for this concept.

Margaret's Status Changes, Nucleus-one Concept. The comparison of the pre- and post-interviews revealed that Margaret's status changed from no I, no P, unknown F to a status of I, P, unknown F. This involved the conceptual capture of the understanding that radioactive material decay is a nuclear process. Thus, for Margaret, the intelligibility and plausibility increased for this concept after she attended the analogy-based lesson. The stability of the condition of fruitfulness is unknown. However, regardless of the uncertainty concerning the fruitfulness, it is apparent that the status increased for Margaret after she attended the analogy-based lesson.

Decay-one Concept

Parent material decays into progeny material.

Evaluation of Decay-one Concept

Intelligibility for this concept was demonstrated by statements indicating an understanding that the original material changed, and that it changed into a different substance. Also, the learner had to understand the meanings of the terms parent and progeny as they related to radioactive material decay. If the learner held the understanding that the initial material disappeared or just that it somehow changed, this was considered to be a demonstration of developing intelligibility. This is because the learner understood that the initial material changed, but he was unaware of what it changed to.

Results of Decay-one Concept Interview Interpretations

For this concept, eight increases in intelligibility, nine in plausibility, and one in fruitfulness were experienced by the learners. The statuses that the learners held for this concept increased for all nine group-one participants. All of these participants had pre-interview statuses that would also have allowed them to exhibit no status change. Eight of these participants had pre-interview statuses such that they could also have

experienced a decrease in status.

Margaret went from having no status to complete intelligibility and plausibility and developing fruitfulness for this concept. Felix increased his status by conceptual capture and conceptual exchange processes. The learner added knowledge about the meaning of the terms parent and progeny. In doing so, a conceptual exchange occurred because the learner become dissatisfied with and replaced his pre-interview idea that the "Eventually it's gonna all become . it's just gonna decompose to nothing because it's all released as energy." Mark and Edgar increased their statuses for this concept by acquiring a richer understanding of the meaning of the term progeny and plausibility in their new knowledge structures. Wilbur, Ralph, Jennifer, and Florence acquired an understanding and believability in the meanings of the terms parent and progeny, and one of them acquired plausibility for his understanding of the decay process as well. Fred experienced an increase in plausibility for the terms parent and progeny.

Representative Interview Interpretation Set

Felix's Pre-interview, Decay-one Concept. During the pre-interview, Felix held the conception that a radioactive material broke down into atomic particles and energy through a mechanism that required collisions between atomic particles. This understanding was best expressed in the

statements "It's the particles flying around and neutrons, I think it was the main one, is flying as it breaks down . emits neutrons are likely to hit another atom. Knock that apart and it continues" (I-t;P-r) and "It's emitting its energy outward. Coming from the source and spreading out all around the source. Radiating out from the source." (I-t)

Felix demonstrated that he did not have a firm understanding that the initial radioactive material changes into some other material through the process of decay. This was apparent in his response of "No." (I-d) and "Nope." (I-d) when asked by the researcher if he had ever heard the terms parent and progeny. Also, in response to a question concerning what would be left if the material on the dish were a hundred percent pure uranium, Felix responded "It would release energy. The energy . . would . . there's a decomposition. Release that decomposition. Eventually it's gonna all become . it's just gonna decompose to nothing because it's all released as energy." (I-t;P-r) In addition, at another point in the interview, he stated "A hunk of uranium. You'd probably have nothing left. It would break down into its atomic particles, or whatever." (I-t;P-r) What is demonstrated in these responses in relation to concept Decay-one is that even though his ideas about the mechanism of radioactive material decay were different from the scientifically accepted version, Felix still understood that a radioactive material changes. Thus, Felix demonstrated developing intelligibility for this concept because he did not understand the terms

parent and progeny, or the parent to progeny relationship. However, he did understand that the initial material changed into something else.

Felix also demonstrated plausibility for his understanding of concept Decay-one through the above statements which represented real mechanism category responses. Consequently, he exhibited developing plausibility for concept Decay-one.

When asked if he found his column one work-sheet information to be useful, Felix replied "for generating electricity, you have to know how long that core's gonna last. So they . whoop, there it's gone. Nobody has any power anymore." (F-p) He then went on to state "For medicine . you gotta know how long it's gonna last so that they aren't having it running around or disposed of improperly." (F-p) In addition to relating to concept Decay-one, these statements also relate to the half-life concepts. But, in terms of their applicability to the decay-one concept, Felix was able to cite specific areas where a knowledge that a radioactive material will change was useful. This indicated that he possessed developing fruitfulness for his concept of how radioactive materials decay.

Felix's Post-interview, Decay-one Concept. During the post-interview, Felix articulated his thoughts about the process of radioactive material decay. Early in the interview, Felix indicated that there is no radioactive material remaining at the end of the decay process. In response

to the question "What happens to that radioactive material?", Felix responded

> It gives off, as it decomposes, it gives off energy. And . the energy . . is de caused by the decomposition of the material due to nuclei or whatever flying around in there. Splitting the atoms apart. Releasing energy. Of course, energy is really matter. I guess. Eventually, there's nothing left of it." (I-t,P-r)

In view of his statements later in the interview, "nothing left of it" is interpreted to mean that there is nothing left of the parent material, but not that there is nothing left at all. During a subsequent portion of the interview, Felix indicated that he understood that something is left at the end of the decay process. When asked to describe the process of radioactive material decay, Felix responded

> It's . . I guess the compound's unstable. And . a nucleus will . or an electron flies off, hit another . atom . . the half-life is at half . the atoms in that . mass have been hit by particles and changed to a different material. To a different element. Because you've changed the atomic structure of it. (I-t;P-r)

Later in the interview, when asked "What is the parent material?", Felix responded "That's the initial radioactive material." He also stated, in response to the question "Then what is the progeny progeny material?", "Think that's what's left after the decay." When asked to state what the correspondence was between the melting-ice analogy and the decay of a radioactive material, Felix stated that "Well your parent material is your initial source. And the prodigy is your . is what is left after all the radioactivity is gone." (I-t;P-a). These statements displayed that Felix

thought that through atomic-level collisions, a radioactive material lost stored energy (in the form of sub-atomic particles and an undefined "energy") as it decayed, and in the process changed into a different substance. It appears that Felix had incorporated features of fission with his ideas about the process of natural radioactive material decay. In spite of the fact that his understanding of the mechanism of radioactive material decay (like his pre-interview thoughts) was still alternative to the scientifically accepted view, he displayed intelligibility for concept Decay-one in that he understood the meaning of the terms parent and progeny, and he understood that a radioactive material changes into another material as it decays. Thus, he demonstrated intelligibility for the features embodied in the Decay-one concept.

As indicated with the code marks, the above statements also revealed through their real mechanism and analogy category features that Felix had plausibility for the Decay-one concept.

When asked if he felt that his knowledge concerning the decay of radioactive materials was useful, Felix replied "Oh ya, probably. I think for generating . nuclear power . . they have to know . . about how much . how long . their core material will last." (F-d,p) This statement demonstrated that Felix could see usefulness to the knowledge that a radioactive material decays. Accordingly, he demonstrated developing fruitfulness for the Decay-one concept.

Felix's Status Change, Decay-one Concept. During the pre-interview, Felix's status for concept Decay-one was developing I, developing P, and developing F. During the post-interview, his status was I, P, and developing F. Thus, comparing the pre-interview and post-interview, Felix's status for this concept increased. This was by the conceptual capture and conceptual exchange processes. Felix added knowledge about the meaning of the terms parent and progeny through the conceptual capture process. His knowledge about the parent material changing into the progeny material involved conceptual exchange because he had to become dissatisfied with and replace his pre-interview idea that "Eventually it's gonna all become . it's just gonna decompose to nothing because it's all released as energy." with the idea that the initial material was "changed to a different material".

Decay-two Concept

Decay continues until the parent material is entirely changed into its progeny.

Evaluation of Decay-two Concept

Intelligibility for this concept required the learner to understand that the initial radioactive material is completely gone at the end of the process. This understanding could take the form of rote memorization or a full

comprehension. A learner that had gained, through rote memorization, an understanding that the end of the radioactive material decay process was represented by zero parent material was viewed as possessing intelligibility for this concept.

A full comprehension required the learner to have reconciled two other concepts that relate to the Decay-two concept. First, the learner must understand that the mass of a radioactive material is cut in half during a half-life interval, and that mathematically dividing any real number by two is an infinite process.

For instance, consider if a learner understood the infinite ability to divide a real number by two. Relating this to the decay of a radioactive material, he would reason that the mass of a radioactive material would keep diminishing, and that this process asymptotically approached, but never reached, zero parent material.

A learner who could mentally represent that the parent material would, eventually, be completely gone was viewed as possessing intelligibility for this concept. However, if he also possessed this first understanding, it would diminish his believability in the complete decay understanding, and he would therefore be viewed as possessing developing plausibility or no plausibility, depending on his level of disbelief.

The second related knowledge required the learner to understand that nuclei are discrete and therefore, they are either parent or progeny.

Thus, once the last nucleus undergoes decay, there are no parent nuclei left. If the learner possessed both the first and second ancillary understandings, he would understand that the mass of parent material approaches zero in half-life steps, but that eventually the last nucleus will change into the progeny material. Thus, the end of the process will result in zero parent material. A learner possessing this level of understanding was viewed as holding intelligibility and plausibility for this concept. This assumes that the learner possessed an epistemological foundation which requires that all of these concepts have coherence.

Results of Decay-two Concept Interview Interpretations

A comparison of the pre- and post-interview results indicated that two increases in intelligibility occurred. In addition, five increases and three decreases in plausibility occurred. Out of six learners with the potential to increase in status, five increased. Three decreased out of seven with the potential to go down and one out of nine with the potential to remain the same maintained that same status. Margaret increased in plausibility by capturing the understanding that a radioactive material completely decays. Felix experienced no change in status. Mark experienced an increase in dissatisfaction with his understanding that the decay process goes to completion. During both the pre- and post-interview, he understood that the division of a real number by two is an

infinite process, but this knowledge made him become more dissatisfied with the Decay-two concept during the post-interview compared with the pre-interview.

Edgar and Florence experienced conceptual exchanges that resulted in their understandings of complete decay becoming implausible. The exchange occurred because the learners became dissatisfied with and replaced their pre-interview knowledge that complete decay occurred with the idea that the process never ended. The learners acquired the knowledge that the division of a real number by two is an infinite process. This knowledge was not evident during their pre-interviews. Ralph went from no plausibility to developing plausibility for this concept. This occurred because the learner acquired the infinite divisibility knowledge.

As a result of a conceptual exchange, Fred increased in plausibility for the Decay-two concept. During the pre-interview, this learner understood the infinite divisibility of a real number by two. During the post-interview, the learner had acquired the additional knowledge that decaying nuclei are discrete entities which are either decayed or are not decayed, so once the last nucleus decays, no more parent material remains. This knowledge resulted in the learner becoming dissatisfied with and replacing his belief in the infinite life of a radioactive material.

Between the pre- and post-interviews, Wilbur acquired both the infinite divisibility and discrete nuclei understandings. These learnings

resulted in his gaining intelligibility and plausibility for the Decay-two concept.

Between the pre- and post-interview, Jennifer gained intelligibility for the knowledge that a radioactive material completely decays. She also acquired the infinite divisibility knowledge, and it caused her to have some doubts about her understanding of the completeness of the decay process. Thus, she experienced a gain from no intelligibility and no plausibility to intelligibility and developing plausibility for the Decay-two concept.

Representative Interview Interpretation Set

Fred's Pre-interview, Decay-two Concept. When filling out the work sheet, Fred made the comment

> At this point [end of process position] I have zero percent of . U 237. And at this point the whole thing would be ah . . . like I had said it we're calling it U 235 . you know ah um . would be one hundred percent. . Now the that point, this is a non-radioactive material. . . So my needle . would be over to low or zero . . amount. Um, my calendar now. I've got to change that. The end of the process. I'm gonna put a note here. All U 237 . . is gone. (I-e,t)

This statement revealed that Fred understood that the parent material (U 237) would entirely change into the progeny (U 235) during radioactive material decay. Thus, he demonstrated intelligibility for concept Decay-two.

However, a few sentences later in the interview, Fred made the liberated conviction statement "And I guess, if you have a half-life . . .

theoretically, do you ever get to the end state if you're only only losing half of it. Fine. That's a again . . that's there's there's probably always a little bit there." (P-o) A little later in the interview, Fred was asked if he believed his column number one work-sheet information to be true. During his response, he commented "Um . . . . and I know that there is a half-life associated with these things. . . And I don't think that you ever really get down to . completely wiped out." (P-o) These statements revealed that Fred understood that the mass of parent radioactive material decreases by half during every half-life interval. He also understood that mathematically, dividing a given quantity by two will asymptotically approach zero, but will never reach it. Thus, the understanding that he expressed earlier in the interview, that the parent material eventually completely changes into the progeny material, was not believable to him. Thus, he possessed no plausibility for the Decay-two concept.

Fred made no statements concerning the usefulness of the Decay-two concept. Thus, his fruitfulness for this concept is unknown.

Fred's Post-interview, Decay-two Concept. While filling out the work sheet, Fred spontaneously commented "I have a chunk of radioactive material. And I know you said . in your talk the other day, that . eventually you would get down to . . having no radioactive material . left." (I-l,t) A little later in this process, Fred commented "Alright ah end of

process. Where there is no radioactive material left, is what you're telling me. So . . I've got . . parent. . I've got nothing there. . . . And progeny, everything is now . down to . . the progeny." (I-l,t) These statements revealed that Fred found the Decay-two concept to be intelligible.

When the researcher asked Fred if he believed his column one information to be true, the learner replied

> Yes um once you get down to, I think we discussed this the last time [referring to pre-interview] and I felt you probably never would actually get down to the end. But, ... once you get down to. the last atom . in there . . it's either gonna decay or not. You can't go any farther in in the half-life. Er, I can't I can't cut the thing in half. Oh, well, I guess they can nowadays, but I I'm not cutting the thing in half. So, once that last atom . . kicks out the the proton, . or the neutron, it decays, it's over. . . So, yes, it it does finally make it to the end. I guess we discussed it the last time. Theoretically, under mathematical terms, I guess you'd never get to zero. If you're always taking a half, you can get down to . . um . . sub-one numbers. But, in physical . properties . no you can't. I mean, I've got one atom left, it decays, that's it. end of story. (I-t,l;P-e,o,r)

Near the end of the interview Fred was talking about the falling-tacks analogy. During his comments, he remarked

> Ya. That that did, that was good cause it did help ta . get a little bit more familiar with it. I guess um . . the way you talked about to me the way you talked about the . . getting down to zero . . . is what I I learned. And you did change my mind on that. I I do agree with at . like I I'm pretty sure I would havelast time that . . theoretically you're never gonna get there. But as faras we can measure, you you would get down to a zero. But I agree . now. Thinking in physical terms, again, mathematically if you're always taking a half you're never gonna get to zero. You can go on . to infinite . by cutting into half. But when you talk in physical terms, . you're, I mean, real . atoms . . you can't . you're gonna get down to where you have one left, at some point or another, . and it will decay. . . And when it decays, that's it. It's gone. (I-t,a;P-l,o,e,r)

These comments revealed that Fred found his understanding of the Decay-two concept to be plausible.

Fred made no statements concerning the usefulness of his understanding that a radioactive material completely decays. Thus, his fruitfulness is unknown.

Fred's Status Change, Decay-two Concept. During the pre-interview Fred possessed the status of I, no P, and unknown F. During the post-interview his status was I, P, and unknown F. Thus, his status increased. The increase occurred because Fred found his understanding that a radioactive material decays to completion to be plausible. This occurred because he gained the understanding that decaying nuclei are discrete entities which are either decayed or are not decayed. Thus, the mathematical ability to infinitely divide a given quantity by two does not apply to this phenomena. This understanding caused Fred to be dissatisfied with his idea that a radioactive material is never completely gone, and to replace this with the understanding that a radioactive material does eventually completely decay. Thus, Fred experienced a conceptual exchange as a result of the analogy-based lesson.

Decay-three Concept

For a given radioactive material, all nuclei have an equal probability

of decaying.

Evaluation of Decay-three Concept

Intelligibility for this concept required the learner to understand that every nuclei of a radioactive material has the same probability of decaying at any given moment. If the learner understood this in terms of atoms, or molecules, rather than nuclei, they were still viewed as possessing intelligibility for this concept. The fact that radioactive material decay is a nuclear process was previously covered under the Nucleus-one concept area.

Results of Decay-three Concept Interview Interpretations

Changes in statuses were unknown for eight of the group-two learners. This occurred because all pre-interview conditions were unknown for each participant. Obviously, the interview protocol was not effective in extracting information applicable to this concept. No change was detected for Ralph. His pre- and post-interview statuses were I, P, and unknown F. Thus, Ralph could have remained the same or decreased in status, but he stayed the same.

Representative Interview Interpretation Set

Mark's Pre-interview, Decay-three Concept. Mark was asked during

the pre-interview how the term probability would relate to his work sheet. He responded "Um . . . . . well I suppose that . . . based on . very short term measurements, you would have to project . very long term effects. And . to a certain extent you you would have to say that . . um . . it this projection is based on a . . certain probability that what you're . predicting is true . and accurate." (I-t;P-o) Even though Mark expressed an understanding of and believability in this concept, his ideas do not directly relate to concept Decay-three. Since no statements were made relating to Decay-three during this pre-interview, Mark's intelligibility, plausibility, and fruitfulness are unknown.

Mark's Post-interview, Decay-three Concept. When asked how the term probability related to radioactive material decay, Mark responded "Um . . . . . I guess one way . . . . that um each atom has an equal probability of decaying." (I-t) This statement revealed that Mark had post-interview intelligibility for concept Decay-three. Since no other statements were made relating to this concept, his plausibility and fruitfulness remained unknown.

Mark's Status Change, Decay-three Concept. During the pre-interview, Mark exhibited a status of unknown I, unknown P, and unknown F. His post-interview status was I, unknown P, and unknown F. Thus, no determination can be made concerning his change in status.

Half-Life-one Concept

The time required for 1/2 of the parent material to decay into its progeny is referred to as half-life.

Evaluation of Half-Life-one Concept

Having intelligibility for this concept required the learner to have knowledge of the fact that half-life referred to an amount of time, and that it referred to a change in the remaining mass of the initial radioactive material. An understanding of only one of these areas was viewed as developing intelligibility. For example, if a learner understood that half-life referred to the amount of time required for a radioactive material to lose half of its activity, this would be viewed as developing intelligibility because it related half-life to activity, not mass.

Results of Half-Life-one Concept Interview Interpretations

Between the post- and pre-interviews, three increases in intelligibility and one increase in plausibility occurred for the learners. Three out of a potential of six learners increased in status and six out of a potential of nine remained the same. Eight learners were positioned such that they could have experienced a decrease in status, but none did so.

Margaret gained the knowledge that half-life concerns time and

material decay. However, at the post-interview, she could not consistently determine the half-life, given hypothetical situations. Therefore, she exhibited only developing I and P.

Felix, Edgar, Fred, Wilbur, Florence, and Ralph did not undergo any status change.

Mark underwent conceptual exchange. He substituted the knowledge that the definition of half-life involves diminishing mass for the alternative understanding that it involves diminishing radioactivity.

Jennifer underwent a conceptual capture process. She gained the understanding that half-life involves the loss of mass over time, not just an amount of time.

Representative Interview Interpretation Set

Margaret's Pre-interview, Half-Life-one Concept. Margaret did not spontaneously contribute any information concerning concept Half-Life-one. When the researcher asked her if she knew the meaning of the term half-life, she gave a direct intelligibility category response of "No.". In her work sheet, Margaret showed that the time involved for a radioactive material to change was one, three, five, and seven hours to the end of the process. When asked by the researcher how much faith she had that her work-sheet response represented the time involved for an actual radioactive material to go through its changes, she responded "I have no no concept of it." (P-d)

When further asked if her description had the potential to be true, she responded "Probably not" (P-d) and she was unable to give a reason why she replied this way. These responses revealed that Margaret had no intelligibility or plausibility for the Half-Life-one concept. When asked if having a knowledge of the time involved for a radioactive material to change would be useful information, she responded "It would be useful if you were working with this material. I'm had a if if what I'm saying is true, my concept. It would be very important if you were doing some special tests with this material." (F-e) These statements showed that she believed that having this knowledge could be useful, but since Margaret did not have a personal understanding of the concept, she did not appreciate, personally, any usefulness of the concept. Thus, the learner was judged to exhibit no fruitfulness for the concept.

Margaret's Post-interview, Half-Life-one Concept. During the post-interview, Margaret's understanding of this concept was expressed as vacillations around a core idea which represented a partial understanding for the Half-Life-one concept. For example, when completing the first intermediate position of the work sheet the learner spontaneously made the statements "then after . . two hours . . it'd be two o'clock." and "my parent material is now down in half" (I-e,t) When referring to the second intermediate position of the work sheet, she made the statements that "once

again, now it will decay half again" (I-t) and "it would be two more hours ah . that would have gone by. So it would be four o'clock by that time." (I-e) Later in the interview, in response to researcher question "In your's (referring to her work sheet), what's the half-life?", Margaret made the statement "My half-life would be one. And from the twelve to the two would be one (??) a half-life." (I-e) When asked by the researcher "What's the half-life in this one?" (referring to the incorrect comparison work sheet that represented a 15 time unit half-life), Margaret responded "This would be seven point five." (I-e) In addition, when the researcher asked Margaret to define the meaning of the term half-life, Margaret made the exemplar category statement that "if it takes four hours to go from start to the intermediate, then the half-life would be two hours." (I-e) Later in the interview, when asked what the half-life correspondence was between a radioactive material decaying and melting ice, Margaret made the statement

> Like the the half-life, it would be like um . say if you start with the ice the way it was and . um it takes one hour to get . . to trans to decay into the water . um a half after thirty minutes would be the half-life. (I-a;P-a)

These statements indicated that Margaret recognized that half-life involved the two ideas of time and the decay of half of a given amount of radioactive material. However, Margaret's inconsistent responses and her inability to consistently describe or identify the half-lives in the work sheet, or to correctly define the concept, indicated that she had not made the

connection between these two ideas. This could possibly be a result of rote memorization of the meaning of the half-life term without the presence of an underlying self-constructed meaning for this term. In any case, Margaret demonstrated only developing intelligibility for this concept.

When responding to questions by the researcher that were meant to draw out her plausibility for this concept, Margaret revealed a lack of commitment to the scientific understanding of the concept. For example, when the researcher asked "Do you think that that relationship is true? . but in terms of the . inter in terms of the increments.", Margaret responded "Ya, I suppose so." (P-d) A little later, while still being questioned as to her plausibility, she made a second response "I'll say yes." (P-d) This lack of a firm commitment to her understanding of the concept indicated that her plausibility for this concept was only developing.

Margaret gave no evidence of her fruitfulness for concept Half-Life-one.

Margaret's Status change, Half-Life-one Concept. A comparison of Margaret's pre- and post-interview responses indicated that her status for concept Half-Life-one changed from no I, no P, and no F to developing I, developing P, and unknown F. Thus, her status increased. This occurred because Margaret gained an understanding that half-life involved time and the decay process. However, she did not consistently give the same

description of half-life in similar circumstances. Therefore, she was not judged to possess full intelligibility. Margaret underwent a conceptual capture of an understanding that half-life involved the concepts of time and mass, although she did not understand the correct relation between these two concepts.

Half-Life-two Concept

Half-life is a constant for a given radioactive material.

Evaluation of Half-Life-two Concept

To demonstrate intelligibility for this concept, a learner had to have the knowledge that the initial material decayed in half-life steps. This could be expressed as the fractions of material left, or by statements such as "half to half to half". Another pertinent point is that this change could be expressed as a decrease in mass or a property related to the mass, such as activity. The fact that half-life is defined in terms of a decrease in mass was emphasized under the Half-Life-one concept. However, expressing the change as a decrease in the half-life time was viewed as no intelligibility or developing intelligibility, depending on what other pertinent understandings were exhibited by the learner. Another important point is that if a learner expressed that only three half-life steps were required for the process to reach its end point (one, one half, one quarter, zero), this was

viewed as developing intelligibility. This is because a learner who expressed this understanding did not have the knowledge that a large number of half-life steps are required for any detectable amount of a radioactive material to decay. If a learner only had the understanding that a radioactive material completely decayed in two half-life steps, this was viewed an no intelligibility. This exhibits a lack of understanding of the numerous half-life steps involved in the decay process. This is because a learner who expressed this understanding indicated that a given quantity of radioactive material is cut in half during the first half-life interval, and this same quantity of parent is lost after a second half-life interval.

Results of Half-Life-two Concept Interview Interpretations

Between the pre- and post-interviews, four increases in intelligibility, two plausibility increases, and one fruitfulness increase were detected. Four out of five learners with the potential to undergo a status increase demonstrated an increase in status, four out of a potential of eight demonstrated no change, and one was unknown. Four learners were positioned such that they could have decreased in status, but none did.

Margaret acquired the knowledge that radioactive materials decay in half-life steps and thereby increased her intelligibility. She also found this understanding to be believable. However, she never reached the understanding that the number of half-life steps was typically greater than

three.

No changes in statuses were detected for Felix, Fred, Wilbur and Ralph.

Mark's status change was unknown. Edgar acquired the knowledge that radioactive material decay is an exponential process. However, he simultaneously held onto his pre-interview knowledge that radioactive material decay takes two half-lives to reach completion. Thus, he went from no I and no P to developing I and developing P. He also exhibited developing F for this concept during the post interview.

Jennifer went from no I to developing I because she acquired the knowledge that radioactive material decay is a step wise process involving half-lives.

Florence went from no I and no P to I and P by capturing and believing the knowledge that radioactive material can be described in terms of a half-life decay sequence.

Representative Interview Interpretation Set

Edgar's Pre-interview, Half-Life-two Concept. By examining the intelligibility and plausibility statements in Edgar's pre-interview Half-Life-one concept discussion, it was determined that Edgar did not have an understanding of the Half-Life-two concept. He thought that a radioactive material completely decayed in two half-lives. Thus, he possessed no

intelligibility, unknown plausibility, and unknown fruitfulness for this concept.

Edgar's Post-interview, Half-Life-two Concept. By examining the Half-Life-one concept discussion, Edgar stated his understanding that a radioactive material completely decayed in two half-lives. He also expressed plausibility for this understanding.

However, later in the interview, Edgar was asked to recall any correspondences between the falling-tacks analogy and a radioactive material. In response, he commented

> Ya, that's ah . . . that's true. Um . then at the initial drop of a hundred tacks, you had about roughly 50% of your tacks, in most cases . ending up on their sides. And ah . . that seemed to repeat itself throughout subsequent . drops. Approximately 50% would end up on their sides . . with each subsequent drop. . . . That . . . . . that your initial decay would be . faster than subsequent decays. . You would lose more radioactivity initially . than you would over . . a longer period of time. (I-t,a;P-a)

This statement indicated that Edgar could mentally represent the idea that the amount of a radioactive material would follow an exponential decay pattern where "You would lose more radioactivity initially . than you would over . . a longer period of time." Thus, Edgar revealed that he had intelligibility for the Half-Life-two concept. However, he did not express full plausibility for the scientifically accepted version of the half-life concept which was represented by the falling-tacks analogy. This conclusion is based on the fact that Edgar made statements that had plausibility features

for both his alternative and the scientifically accepted version of the Half-Life-two concept. Thus, he possessed developing plausibility for this concept. It is interesting to note that Edgar simultaneously expressed understanding and believability for two different and mutually exclusive versions of the Half-Life-two concept. Since the two understandings are mutually exclusive, once the learner becomes aware of the conflict, rejection of one of the understanding will be necessary. This is obviously the first step in the conceptual exchange process. This is true providing the learner has an epistemological commitment to consistency and that the learner does not separate "school learning" from "real world learning".

When asked if he found any usefulness to his understanding of the time involved for radioactive materials to change, Edgar responded

> Um . ok . . um . well if I were in the business of ah . disposing of radioactive material, it would be useful to me. Um, that includes materi hospital waste, ah, fuel from spent nuclear, ah, reactors. Um . . but personally, like like I said, it . . should be aware of radioactive radioactivity and try to avoid it . . when possible. (??) personal safety." (F-p)

Edgar cited two areas where his knowledge of the time required for a radioactive material to change would be useful. Thus, he exhibited developing fruitfulness for this concept.

Edgar's Status Change, Half-Life-two Concept. During the pre-interview, Edgar possessed the status of no I, unknown P, and unknown F. During the post-interview, he demonstrated the status of I, developing P,

and developing F. Thus, his status for concept Half-Life-two increased. This occurred because the learner acquired (conceptual capture process) the knowledge that radioactive material's undergo exponential decay. He also demonstrated plausibility for this knowledge. However, he simultaneously held unto his pre-interview understanding, and also expressed believability in the prior understanding, that a radioactive material decays in two half-life steps. This possession of two mutually exclusive concepts constitutes developing rather than full plausibility for this concept.

Activity-one Concept

The number of nuclei of a radioactive material that decay per second is referred to as the activity.

Evaluation of Activity-one Concept

Intelligibility for this concept area required the learner to understand that activity is related to the rate of decay of the initial radioactive material. This needed to be expressed as decay per time or as amount of radioactivity per time. A statement that activity was related to the disintegration of the parent material was viewed as developing intelligibility because no time factor was included.

Results of Activity-one concept Interview Interpretations

Eight increases in intelligibility and one increase and one decrease in plausibility occurred between the pre- and post-interviews. Seven learners, out of eight with potential, experienced an increase in status. One learner, out of four with the potential to show a decrease, experienced a status decrease. No change in status was detected for one of the nine participants with the potential to show no change.

Margaret underwent a conceptual capture because she started to understand, and believed her partial understanding, that activity relates to the disintegration of parent nuclei.

Felix increased in intelligibility but decreased in plausibility between the pre- and post-interviews. His intelligibility increased because he gained a mental representation of the rate of radioactive material decay. He decreased in plausibility because he believed that activity remained constant through-out the decay process. This alternative understanding was caused by the learner's idea that the amount of radiation reaching the detector was related to the ratio of the number of disintegrations to the mass of the remaining parent.

Mark increased in intelligibility because he gained the mental representation of activity as the amount of radiation emitted per time. Florence gained intelligibility for her partial understanding of the Activity-

one concept. Jennifer gained developing intelligibility for this knowledge.

Edgar acquired the knowledge that activity was related to the amount of radioactive decay, albeit not decay per time. He also developed plausibility for his newly acquired knowledge.

Fred replaced the knowledge that activity relates to the velocity of the decay process with the understanding that activity relates to the amount of radiation emitted per time. Similarly, Wilbur replaced knowledge that activity relates to the "strength" of the radiation with the understanding that activity relates to the amount of radiation emitted per time.

No change in status was detected for Ralph.

Representative Interview Set

Wilbur's Pre-interview, Activity-one Concept. While filling out the work sheet, Wilbur spontaneously commented "And ah the meter dial would tell me the the level of the radioactivity that's being sent." (I-i,t) Later in the interview, Wilbur was asked to explain the meaning of the term activity as it related to radioactive materials. A portion of his response was "Well I guess you can ah ah define it as ah . strength. Ah ah . if something . . is very radio radioactive or has high activity, you'd have to take . greater precautions I I would imagine." (I-t) Wilbur was then asked what he was protecting himself against. Part of his response was

"The radiation that may affect your your your body." Wilbur was then asked the meaning of the term radiation. During his response, he stated "Radiation is ah . . emissions . of . . one sort or another." (I-t) and

> Radioactive materials. That ah some . . . ah . . (??) . . some ah . . . . . if if you that alpha particles, or beta particles, or the gamma ah radiation has been emitted. And and ah can be . sensed by Geiger counters, or whatever they have that's probably more sophisticated now. (I-t;P-r)

These statements indicated that Wilbur understood that activity was related to the "strength" of radiation emitted by a radioactive material. Accepted science perceives activity as the number of disintegrations per time. Wilbur saw activity in terms of "strength" of radiation, which is related to, but not the same as, the number of disintegrations. Also, he did not understand that activity related to the degree of this process occurring per time. Thus, he demonstrated developing intelligibility for this concept.

When Wilbur was asked if he believed his column two information to be true, his response included the statement ". . . Ya I I believe that's true." (P-d). When asked why he believed this information to be true, the learner responded "I guess just from my past ah education or . readings. I have no no real . concrete . working . experience with it." (P-u) These statements indicated the Wilbur believed what he understood about the Activity-one concept to be true. Thus, he exhibited developing plausibility for this concept.

During the interview, Wilbur was asked to define the term activity.

Part of his response included the statements

> Ah ah . if something . . is very radio radioactive or has high activity, you'd have to take . greater precautions I I would imagine. Ah . . if you you're working with it in a lab, you might have to work behind lead shields, or whatever. If it it has a low level of activity maybe . . you wouldn't have to take such strenuous ah ah rigorous ah precautions. (F-p)

and

> The radiation that may affect your your your body. The cells in your your body. Ah . . whether it's ah . . bone or or tissue. . . I guess ah different different levels can give you ah . . burns or else ah ah affect ah . . . cells in your body. (F-p)

These statements indicated that Wilbur could cite examples of where his Activity-one concept knowledge would be useful. Thus, he exhibited developing fruitfulness for this concept.

Wilbur's Post-interview, Activity-one Concept. In response to a question concerning the meaning of the term activity, Wilbur responded ". . . . . Well ah . . to my mind activity means um . . . how much . . . radiation is coming off . at a given time." (I-t) This statement showed that the learner understood that activity related to the amount of radiation being produced per time. Thus, Wilbur demonstrated intelligibility for the Activity-one concept. When Wilbur was asked if he remembered the correspondence between the melting-ice analogy and the activity of a radioactive material, he responded "I'm afraid that that that escaped my mind." When then asked about the correspondence with the tacks analogy,

he responded ". . . . . I forgot." This revealed that although Wilbur had a partial understanding for the definition of activity, he did not see the correspondence between the term and the two analogies that were presented during the lesson. Thus, his representation of the Activity-one concept relied on attribute knowledge as opposed to an understanding of the object or relation correspondences between the concept and the analogies presented during the lesson.

Since no plausibility statements were made, his plausibility is unknown.

When asked if he found his column two information to be useful, Wilbur responded

> . . Maybe in a in a limited range. If you could see it something something decaying or . . ah . . something that maybe . . there is no . ah . probably wouldn't . wouldn't detect it even. Probably wouldn't ah realize that maybe the . the danger of something like that. Were as something if you could see it, you you you could see well, you know, this is this is . this could be potentially very dangerous. . . . . Well I I guess you could use that as a . sensor. anyway without without it even moving if if it . if it if ah . a geiger counter shows you got a of radioactivity . it's it's a safety thing. . Or . you're you're exploring, you're lookin for . some kind of radioactivity, it might might very useful from that that . in that sense. and you need a sensor for it. (F-p)

Wilbur was able to cite two uses of his knowledge of activity. Thus, he possessed developing fruitfulness for the Activity-one concept.

Wilbur's Status Change, Activity-one Concept. Wilbur's pre-

interview status was developing I, developing P, and developing F. His post-interview status was I, unknown P, and developing F. Therefore, a change in Wilbur's knowledge of this concept was detected. Prior to the lesson, the learner understood that activity related to the "strength" of radiation emitted. After the lesson, he understood that activity related to the amount of radiation produced per time. Thus, the fact that activity involves radiation level per time rather that just radiation level indicated Wilbur underwent a conceptual capture process that increased his status for the Activity-one concept.

Activity-two Concept

The activity of a given radioactive material depends on the amount of the material that is present, thus the activity of a radioactive material decreases with decay.

Evaluation of Activity-two Concept

Intelligibility for this concept required the learner to understand that the disintegration rate, or observations related to the disintegration rate such as the meter dial reading, decreased as the decay process proceeded. An understanding of the mechanism causing this decrease was not required to demonstrate intelligibility. Also, an understanding of the Activity-one concept was not necessary for a learner to possess intelligibility for this

concept. The learner could understand that the disintegration rate, or observations related to the disintegration rate, diminished with decay without necessarily relating this process to the term "activity".

Results of Activity-two Concept Interview Interpretations

Two plausibility increases, one plausibility decrease, and one increase in fruitfulness occurred between the pre- and post-interviews for this concept. Two learners, out of two with this potential, increased their status. From eight learners with the potential to show a decrease, only one did. One learner exhibited unknown status change and no change in status was detected for five of the learners from eight participants who were positioned such that they could have exhibited no change in status.

Margaret's plausibility for her understanding of this concept was higher at the time of the post-interview. She was also able to cite an example of the usefulness of her understanding during the post-, but not the pre-interview.

Felix's status decreased because he lost plausibility for the knowledge that activity decreases over time. During the post-interview, Felix thought that the activity remained constant and the meter dial reading went down due to an increased level of absorbance of emitted x-rays.

No change in status was detected for Mark, Edgar, Fred, Wilbur, and Ralph.

Jennifer's plausibility for her understanding of activity increased between the pre- and post-interviews. During the post-interview, she related the decrease in the meter dial reading to other knowledge that a decrease in "radioactivity" of the parent material also took place.

Florence's change in status was unknown because her pre-interview did not yield any information concerning her status for this concept.

Representative Interview Interpretation Set

Jennifer's Pre-interview, Activity-two Concept. While filling out the work sheet, Jennifer commented "Ok. So then like the dial would be . like if this is very radioactive, dial would be way over here somewhere [referring to high reading]" (I-t) During this process, she later stated "I don't know. That's got a long . time. I think. Alright so then if it's done . . then there should be like way down here somewhere [referring to the end of process meter position]." (I-t) When the researcher asked Jennifer what the meter dial responded to, she stated ". It's it's measuring the amount of . um . exposure that you got to that radioactive material." (I-t) These statements revealed that Jennifer was aware that the meter dial responded to the level of radiation emitted per her statement "exposure that you got to that radioactive material". Her statements expressed this thought because they indicated that the meter was a measure of the amount of activity of the radioactive material. She also understood that the meter dial went

down as the decay process proceeded. These statements indicated that Jennifer could mentally represent the idea inherent in the Activity-two concept, that the activity, expressed as meter dial reading, decreased as the decay process proceeded. Thus, she exhibited intelligibility for this concept.

When the researcher asked Jennifer if she believed her column two work-sheet information was true, she responded "Those are all relatively guessing. I really don't know how . to be honest. It would have to start high. You're saying this material's radioactive in it's beginning." (P-d,o) This statement revealed that she did not strongly believe that her conception of the meter dial's behavior was accurate. She believed that it had to start at a high reading, but she was not sure of the readings following this position. Thus, she possessed developing plausibility for the Activity-two concept.

Jennifer made no statements concerning the usefulness of this concept. Thus, her fruitfulness is unknown.

Jennifer's Post-interview, Activity-two Concept. While filling out the work sheet, Jennifer made several comments relating to this concept. "So this is radioactive to begin with so it's like over here somewhere I guess." [referring to placing meter dial at high] (I-t) and "Now in the middle . . like ah this is still probably radioactive in here. Yes. The meter dial. So this is still pretty radioactive . Maybe it's getting less so we'll put it like

that [between high and zero] maybe." (I-t) and "It goes down. Then it goes down some more and then it goes down to almost zero at the end." (I-t) and "End . that'd be zero. So maybe somewhere around zero. There. How' that? A little above, ya. At the end position." (I-t) A little later in the interview, when Jennifer was asked to describe the process of radioactive material decay, she commented ". over a certain period of time you get less and less ah . it it's less and less radioactive." (I-t) These statements indicated that Jennifer was cognizant of the decreasing reading on the meter dial as decay progressed. Thus, she manifested intelligibility for the Activity-two concept.

When asked by the researcher if she believed her column two information to be true, Jennifer remarked ". . I guess so. The activity would go down." (P-d) When then asked why, she stated ". . I guess I'm thinking about . the material becoming less radioactive over time." (P-o) Thus, Jennifer believed her mental representation that the meter dial's reading diminished over time, because she thought that less radioactivity was emitted as decay progressed. Therefore, she possessed plausibility for the Activity-two concept.

When the researcher asked Jennifer if she found her column two information to be useful, she stated "No." (F-d) Thus, she had no fruitfulness for the Activity-two concept.

Jennifer's Status Change, Activity-two Concept. The learner's pre-interview status was I, developing P, and unknown F. Her post-interview status was I, P, and no F. Hence, her status increased due to an increase in the plausibility condition from developing to full. This change occurred because Jennifer went from the position of being unsure of the behavior of the dial to believing it decreased with decay because she associated it with the diminishing "radioactivity" of the material with advancing time. This process signified a conceptual capture process because Jennifer did not have to reject any previously learned knowledge. She only acquired additional knowledge about the connection between the meter dial and the radioactivity of the material on the dish.

Content-Test Results

Content-Test Validity

The potential number of group-one and two participants in the study was 71. From this participant pool, forty-four people completed the pre- and post-content tests and attended the lesson. The lesson was conducted on four separate occasions during three departmental meetings and one safety committee meeting. The delay between pre- and post-lesson content test administrations was between two to three weeks. The content-test data was designed to provide information germane only to the condition of

intelligibility.

Nine of these forty-four participants also completed pre-lesson and post-lesson clinical interviews. The clinical interview data gave information germane to all three conditions; intelligibility, plausibility, and fruitfulness. These interviews were transcribed and the transcriptions were interpreted following the procedure outlined in the interview interpretation section of this document. Since nine group-one learners participated in the pre- and post-interviews as well as the pre- and post-lesson content tests, their data was used to determine the correlation between the intelligibilities determined by the interviews versus the intelligibilities determined by the content tests. This gives one measure of the validity of the content-test instrument. This comparison is summarized in Table 7. This table gives the percentage of times that the intelligibility for the content-test item as determined by the interviews matches the intelligibility for the test item as determined by the learners' responses to the content-test item. Test items one and eight did not match with any of the intelligibilities probed during the interviews. Therefore, no validity comparisons were made for these two items.

If a learner correctly answered a test item, this was considered to represent intelligibility for the content area covered by that test item. To determine if the learners demonstrated interview-determined intelligibility for a test item, the learners' pertinent interview content area discussions

Table 7

Comparison of Interview and Content-Test Determined Intelligibilities

Test Item Number	Content Area Covered	Percent of Learners With Same Interview-determined and Content-Test-determined Intelligibilities
One	Not Applicable to Interview	Not Applicable
Two	Decay-two, Half-Life-one	72.2
Three	Decay-one	72.2
Four	Activity-one	70.6
Five	Half-Life-one	55.6
Six	Decay-two	77.8
Seven	Decay-three	100.0
Eight	Not Applicable to Interview	Not Applicable
Nine	Half-two	70.6
Ten	Half-Life-one & two, Activity-one & two	75.0

were reviewed and a judgement was made based upon their statements. For example, for test item three, the Decay-one interview discussions were examined for evidence of intelligibility for the knowledge that the original

material was referred to as the parent, the product of radioactive material decay was referred to as the progeny, and that the original material changed into a different material. Learners who demonstrated intelligibility for all three of these understandings were considered to possess intelligibility for the content area covered by content-test item three. A second example is test item five. This required that the learners provide intelligibility evidence in the interview that half-life was a time. Item two required that the learner possess both intelligibility and plausibility before they were given interview-determined credit for this item. This is because it became apparent through the interview interpretations that a hierarchy of learning steps was evident in the Decay-two concept area which strongly influenced how people thought about the eventual total decay of a radioactive material.

An examination of Table 7 indicates that for every item except item five, the interview and content-test intelligibilities matched for at least 70.6% of the learners' responses. Item five is clearly a poorer match, and is very probably a bad test item. In future administrations of this test, item five should be reworked or discarded. One thing to keep in mind when comparing the results on the interview-based intelligibilities and the content-test-based intelligibilities is that the two instruments measure different things. A similar discrepancy was noticed by Novak (1985) between typical course exams and scores on concept maps. Novak thought

that the typical course exam measured rote recall and the concept map score was an indication of something "substantially different", probably closer to a measure of meaningful learning (Ausubel et al., 1978). Therefore, it is not altogether surprising that the correlation between the intelligibilities determined by these two different methods have a degree of diversity. Similar to Novak's study, the content test probably measures something closer to rote recall and the interviews measure something more akin to meaningful learning.

Another source of the discrepancy between the content and interview results is the semantic similarity between the content test and the lesson overhead transparencies (Schwartz, 1993). The perceptual and semantic similarities could be a source of retrieval clues and perceived task demands.

The content area addressed by each item is also indicated in Table 7. For test items two and ten, more than one content area pertained. When determining the interview-determined intelligibility for these two items, the learner had to demonstrate intelligibility for all pertinent concept areas. Item two involved content areas Decay-two and Half-Life-one. The fact that a learner had to possess intelligibility for the Decay-two area became apparent when viewing the results of the pre-content test. 78.6% of the learners that selected an incorrect choice for this item chose item e. This choice stated that a radioactive material would "never be completely

depleted". Thus, this distractor attracted the attention of the learners who did not understand the Decay-two concept, that a radioactive material is eventually completely depleted.

Item 10 required that the learners have intelligibility for both the half-life and activity concepts.

Content-Test Reliability

An additional six people took the content test twice, approximately a month apart. These people did not participate in the lesson, but their scores were used to determine the test-retest reliability of the content test. The Pearson Product-Moment Correlation Coefficient was used to assess this reliability. For the six sets of pre- and post-tests, this was calculated to be 0.81. This is considered to be a significant at the 0.05 level (Gravetter and Wallnua, 1988).

Content-Test Responses

The 10 question multiple-choice test obtained information only pertinent to the intelligibility condition of the statuses that the learners had for the radiation science concept areas that were investigated. The tests contained questions concerning the concept areas of radioactive material decay, half-life, and activity. The concept areas covered by each question are illustrated in Table 7. For both the pre- and post-content tests, the

percent correct responses were calculated. In addition, t ratios (1-tailed test at the 0.5 level of significance) were determined. These results are tabulated in Table 8. The frequency of incorrect responses were also determined. These are illustrated in Table 9.

An examination of Table 8 indicates that, except for item number one, the percentage of learners that selected the correct choice for each item increased from the pre-test to the post-test. The greatest increases occurred for items 2 (Decay-two and Half-Life-one concept areas), 6 (Decay-two concept area), and 8 (Activity-two concept area). Intermediate percentage increases occurred for items 3 (Decay-one concept area), 7 (Decay-three concept area), and 10 (Half-Life and Activity concept areas). Low percent increases occurred for items 4 (Activity-one concept area), 5 (Half-Life-one concept area), and 9 (Half-Life-two concept area).

Table 8

Content-Test Results, t-Test Values

Item	Concept Area	Pre-Test Mean Score	% Correct Pre-Test	Post-Test Mean Score	% Correct Post-Test	t-value	Significant
#1	Atomic Structure	0.909	90.0	0.864	86.40	0.2239	no
#2	Decay-two, Half-Life-one	0.364	36.4	0.795	79.5	2.6301	yes
#3	Decay-one	0.727	72.7	0.977	97.7	1.2557	no
#4	Activity-one	0.477	47.7	0.636	63.6	0.9886	no
#5	Half-Life-one	0.409	40.9	0.477	47.7	0.4749	no
#6	Decay-two	0.227	22.7	0.841	84.1	3.8933	yes
#7	Decay-three	0.705	70.5	0.955	95.5	1.2727	no
#8	Activity-two	0.295	29.5	0.682	68.2	2.5628	yes
#9	Half-Life-two	0.727	72.7	0.864	86.4	0.7089	no

Table 8-Continued

Item	Concept Area	Pre-Test Mean Score	% Correct Pre-Test	Post-Test Mean Score	% Correct Post-Test	t-value	Significant
#10	Half-Life-one Half-Life-two Activity-one Activity-two	0.455	45.5	0.705	70.5	1.522	no

Table 9

Frequency Distributions of Incorrect Responses

Item Number	Test	% Selecting Choice a	% Selecting Choice b	% Selecting Choice c	% Selecting Choice d	% Selecting Choice e	% Select -ing no answer
1	Pre	correct (40)	50.0 (2)	25.0 (1)	0	25.0 (1)	0
	Post	correct (38)	33.3 (2)	66.7 (4)	0	0	0
2	Pre	correct (16)	7.19 (2)	0	14.3 (4)	78.6 (22)	0
	Post	correct (35)	0	0	66.7 (6)	22.2 (2)	11.1(1)
3	Pre	8.3 (1)	correct (32)	41.7 (5)	25.0 (3)	16.7 (2)	8.3(1)
	Post	0	correct (43)	100 (1)	0	0	0
4	Pre	21.7 (5)	correct (21)	26.1 (6)	17.4 (4)	30.4 (7)	4.3(1)
	Post	12.5 (2)	correct (28)	50.0 (8)	25.0 (4)	12.5 (2)	0
5	Pre	88.5 (23)	correct (18)	3.8 (1)	0	7.7 (2)	0
	Post	87.0 (20)	correct (21)	8.7 (2)	4.3 (1)	0	0

Table 9-Continued

Item Number	Test	% Selecting Choice a	% Selecting Choice b	% Selecting Choice c	% Selecting Choice d	% Selecting Choice e	% Select -ing no answer
6	Pre	2.9 (1)	91.2 (31)	0	correct (10)	5.9 (2)	0
	Post	0	100.0 (7)	0	correct (37)	0	0
7	Pre	correct (31)	84.6 (11)	0	7.7 (1)	7.7 (1)	0
	Post	correct (42)	50.0 (1)	0	0	50.0 (1)	0
8	Pre	71.0 (22)	correct (13)	3.2 (1)	6.5 (2)	16.1 (5)	0
	Post	78.6 (11)	correct (30)	0	7.1 (1)	14.3 (2)	0
9	Pre	33.3 (4)	41.7 (5)	correct (32)	16.7 (2)	8.3 (1)	0
	Post	33.3 (2)	50.0 (3)	correct (38)	16.7 (1)	0	0
10	Pre	83.3 (20)	correct (20)	4.2 (1)	12.5 (3)	0	0
	Post	61.5 (8)	correct (31)	0	30.8 (4)	7.7 (1)	0

Note: The numbers in parentheses indicate the total number of participants who picked that choice.

CHAPTER V

FINDINGS, CONCLUSIONS, AND IMPLICATIONS FOR FURTHER RESEARCH

Findings

The interview findings are summarized in Table 10. This table, titled Statuses of Group-one Learners, presents the pre- and post-interview statuses for the group-one learners. In this table, the learners' names are along the left hand side and the concepts are across top heading. Some abbreviations were used in this table. In the top heading, I stands for intelligibility, P for plausibility, and F for fruitfulness. The body of the table contains the status for each learner for each concept. In the body, the letters I, P, or F indicate that the learner possessed that condition for the concept under consideration. N indicates that the learner did not possess that condition, D indicates that the condition was developing, and U indicates that the condition was unknown.

Hypothesis One

Hypothesis one states: The analogy-based teaching will assist learners in developing higher status for some scientifically accepted

Table 10

Statuses of Group-One Learners

Learner	Inter-view	Nucleus -one	Decay -one	Decay -two	Decay -three	Half-Life -one	Half-Life -two	Activity -one	Activity -two
		IPF	IPF	IPF	IPF	IPF	IPF	IPF	IPF
Margaret	Pre-	NNU	NNN	INN	UUU	NNN	NNN	NNU	INN
	Post-	IPU	IPD	IPU	UUU	DDU	DDD	DDU	IPD
Felix	Pre-	IUU	DDD	IPD	UUU	IPD	IPD	DDU	IPU
	Post-	IPU	IPD	IPD	IPU	IPD	IPD	INU	INU
Mark	Pre-	IDU	DDD	IDU	UUU	DUD	UUU	NUU	PD
	Post-	IPU	IPU	INN	IPU	IPU	IPU	IUU	IPD
Edgar	Pre-	UUU	DDD	IPU	UUU	DUD	NUU	NUU	IPD
	Post-	NUU	IPD	INU	UUU	DDD	IDD	DUD	IPU

Table 10-Continued

Learner	Inter-view	Nucleus -one	Decay -one	Decay -two	Decay -three	Half-Life -one	Half-Life -two	Activity -one	Activity -two
		IPF	IPF	IPF	IPF	IPF	IPF	IPF	IPF
Fred	Pre-	IPU	IDU	INU	UUU	IUD	IUD	DDD	IPD
	Post-	IPU	IPU	IPD	IUU	IUD	IUD	IDU	IPU
Wilbur	Pre-	NNU	DDU	NNN	UUU	DDD	DDD	DDD	IPU
	Post-	IPU	IPD	IPU	IPU	DUU	DDU	IUD	IPD
Jennifer	Pre-	UUU	DNU	NNU	UUU	DDD	NUU	NUU	IDU
	Post-	NUU	IPU	IDU	UUU	IDD	DDN	DDU	IPN
Florence	Pre-	UUU	DDD	IPU	UUU	IPN	NNU	NNU	UUU
	Post-	UUU	IPD	INU	UUU	IPU	IPU	DUD	IPD
Ralph	Pre-	IPU	DDD	INU	IPU	IPD	IPD	IPD	IPD
	Post-	IPU	IPU	IDU	IPU	IPD	IPD	IPD	IPD

concepts relating to radioactive material decay compared with their conceptual status prior to the presentation of the lesson. This study investigated three specific concepts related to radioactive material decay: (1) Decay-one concept, (2) Decay-two concept, and (3) Decay-three concept.

For the Nucleus-one concept, one learner's pre-interview status allowed for an increase, a decrease, or no change in status after the lesson. This learner experienced a status increase. Two could have undergone a status increase or have retained the same status. Both experienced a status increase. Three participants could have experienced no change in status or a status decrease. All three underwent no change in status.

No content-test item concerned the Nucleus-one concept. However, item one addressed pre-requisite information about atomic structure. 90.1% of the participants correctly answered this item on the pre-test and 86.4% answered it correctly on the post-test.

The interview data for the Decay-one concept revealed that all of the participants exhibited higher status in the post-interview compared with the pre-interview. All of these participants could also have retained the same status, and eight of them had the potential to show a decrease in status.

The number of correct responses to item number three of the content test, related to the Decay-one concept intelligibility condition, increased 25.0% between the post- and pre-testing.

The interview data for the Decay-two concept showed that of the

four participants who could have experienced an increase, decrease, or no change in status, three experienced a status increase and one decreased in status. Both of the learners who had the potential to increase in status or retain the same status underwent status increases. Of the three learners who could have gone down in status or have retained the same status, two went down and one remained the same.

Content-test items two and six concerned the intelligibility condition for the Decay-two concept. Between the pre- and post-tests, the learners increased 43.0% for item two and 61.4% for item six. The increases for both of these items were significant at the 0.05 level of significance.

Eight of the nine learners demonstrated unknown status changes for the Decay-three concept because their pre-interviews did not extract information germane to this concept. One learner exhibited no change in status. Item seven of the content test increased by 25.0% between the pre- and post-tests. This item concerned intelligibility for the Decay-three concept.

Hypothesis Two

Hypothesis two stated: The analogy-based teaching will assist learners in developing higher status for some scientifically accepted concepts relating to radioactive material half-life compared with their conceptual status prior to the presentation of the lesson. Information

related to the Half-Life-one and Half-Life-two concepts is germane to this hypothesis.

For the Half-Life-one concept, the interviews demonstrated that of the five learners who could have experienced an increase, decrease, or no change in status, two increased in status and three underwent no detectable status change. The one learner who could have gone up or retained the same status went up in status. All three participants who could have decreased in status or remained the same, retained the same status.

The content test also contained an item that related to the Half-Life-one concept, item five. This item did not have a large increase in the percentage of participants that answered it correctly during the post-test compared with the pre-test. 40.9% answered it correctly on the pre-test and 47.7% answered it correctly on the post-test.

For the Half-life-two concept, the interviews demonstrated that the one learner who could have increased, decreased, or retained the same status, underwent no status change. Four participants could have increased in status or retained the same status. All four underwent status increases. Three other learners could have decreased in status or have experienced no status change. They all experienced no status change.

Item nine of the content test had a 13.7% increase in the number of learners choosing the correct answer between the pre- and post-tests. This item related to the Half-Life-two concept.

Hypothesis Three

Hypothesis three stated: The analogy-based teaching will assist learners in developing higher status for some scientifically accepted concepts relating to radioactive material activity compared with their conceptual status prior to the presentation of the lesson. The Activity-one and Activity-two concept data is pertinent to this hypothesis.

For the Activity-one concept, three learners could have undergone an increase, a decrease, or no change in status. Two underwent status increases and one experienced an increase in intelligibility but a decrease in plausibility. Five other learners could have experienced status increases or no change in status. All five underwent status increases. One other learner could have decreased in status or retained the same status. He retained his pre-interview status.

Item four of the content test related to the intelligibility condition of the Activity-one concept. The percent increase for this item between the pre- and post-tests was 15.9%

For the Activity-two concept, of the two learners who could have increased, decreased, or experienced no change in status, both underwent status increases. Six other learners could have decreased in status or retained the same status. Five retained the same status and one demonstrated a status decrease.

The content test contained one item that pertained to the Activity-two concept, item eight. 38.7% more participants answered this item correct during the post-test compared with the pre-test. In addition, the t-test was significant at the 0.05 level of significance.

How Analogies Facilitate Status Changes

During this study, information was collected during the interviews to address the question of how analogies work to increase the status that learners have for radiation science concepts. The information supplied here is not meant to supply a comprehensive answer to this question, but only to serve as an introduction to facilitate further work in this area of research.

Gentner's Structure-Mapping Theory (Gentner, 1983) indicates that the correspondences between objects in the base (analog) and the target consist of both attribute (e.g. large sun in center of solar system/large nucleus in center of atom) and relation mappings (e.g. melting/decay). For analogies, as opposed to literal similarities, there are many relation mappings but few object-attribute mappings. The correspondences that exist between the two analogies and the target concepts for this research are given in Tables 1. and 3. Note that there are three object correspondences and seven relation correspondences involving these objects.

It must be noted that much status change occurred without a

concrete indication that the analogies were essential to these changes. One possible explanation for this phenomenon is that some of these learners did not find the target domain to be sufficiently difficult to necessitate the application of the analogies (Royer and Cable, 1976). Other learners may have found the relations involved in the analogs to be too difficult. However, analogies require structural similarities with the target to be useful (Curtis and Reigeluth, 1984; Gentner, 1983), which necessitated a somewhat involved development of the analog in this case. In other cases, analogies were not incorporated by the learners, but this behavior was a result of a lack of interest-generated-effort around the target information. This statement is made in recognition that consequences or rewards were not conferred as a result of learner effort at mastering the concepts immersed in the analogy-based lesson.

However, other cases did serve to illuminate how the analogies operated to affect learner statuses for these radiation science concepts. In order to investigate how analogies facilitated status changes, cases where the analogies helped increase status as well as cases where the analogies did not affect, or even lowered statuses are examined. All of these cases illuminate the role of the analogies in the learners' constructions of their statuses for the concepts.

The first example is illustrated by Wilbur. He did not understand the meanings of the terms parent and progeny prior to the lesson. He

demonstrated that an understanding of the objects inherent in the melting-ice analog corresponded with a conceptual capture of the meanings for the terms parent and progeny after the lesson.

"Ya well ya the ice is the ah parent. The water is the . the progeny."

Another case where the analogy served to enhance the learner's status occurred with Fred and the Decay-two concept. Prior to the lesson, Fred had the understanding that a radioactive material completely decayed, but he found this knowledge to be implausible due to his understanding that radioactive materials decay in half-life steps, and his knowledge of the infinite divisibility of any real number by two. After the lesson, Fred's plausibility increased to the point where he believed that a radioactive material did eventually completely decay. He credited the falling-tacks analogy with this insight.

> Ya. That [referring to falling-tacks analogy] that did, that was good cause it did help ta . get a little bit more familiar with it. I guess um . . the way you talked about to me the way you talked about the . . getting down to zero . . . is what I I learned. And you did change my mind on that. I I do agree with at . like I I'm pretty sure I would have last time that . . theoretically you're never gonna get there. But as far as we can measure, you you would get down to a zero. But I agree . now. Thinking in physical terms, again, mathematically if you're always taking a half you're never gonna get to zero. You can go on . to infinite . by cutting into half. But when you talk in physical terms, . you're, I mean, real . atoms . . you can't . you're gonna get down to where you have one left, at some point or another, . and it will decay. . . And when it decays, that's it. It's gone.

Mark gained intelligibility and plausibility for the Half-Life-one

concept following the lesson. This corresponded with an appreciation for the Half-Life-one relation in the falling-tacks analog.

> . . . Ya you could . . um . . if you chart out . the number of tosses versus the number of tacks on their side, . . you could . . um . . find . a point at which half of the tacks . . were on their side . and . . identify the number of throws that it . would take to have half the tacks on their side. And that would be . the half-life of the material.

Margaret transferred a misunderstanding concerning the ice analog to the target.

> Like the the half-life, it would be like um . say if you start with the ice the way it was and . um it takes one hour to get . . to trans to decay into the water . um a half after thirty minutes would be the half-life.

This example points out that in order to be useful, the learner must correctly understand the analog's relationships. In Margaret's case, she thought that if the ice took one hour to melt, then the half-life of the ice was 1/2 hour. She transferred this misunderstanding concerning the definition of half-life to the behavior of a radioactive material.

Another case worth examining is Mark's change in status for the Decay-two concept. Prior to the lesson, Mark possessed intelligibility and developing plausibility for this concept. After the lesson, his plausibility decreased. After the lesson, Mark believed that the parent material asymptotically approached complete change into progeny, but never completely changed into the progeny. However, he did understand that the melting-ice analogy represented a complete change of the ice into the

water. His explanation of the discrepancy between the behavior of a radioactive material and the ice was to view the analogy as inadequate.

> Um . . . . only that the ah . all that you were changing from one material to another. Um . . the . . the rate didn't quite work out. . . ah . wasn't a good analogy. . . Um because it . . it wasn't a ah . . . um . an asymptotic relationship to a radioactive decay.

Thus, Mark understood the analogy, but he did not find it plausible. Therefore, he did not transfer the correspondences to the target, but maintained that the analogy broke down in terms of the complete-decay relationship. This indicates that learners not only have to understand the analog/target correspondences, but must find the relationship to be plausible (Clement, 1993). In this study, the learners were informed that non-correspondences existed between the two analogies and the target. These non-correspondences were covered during the lesson. This exercise may have lead to this type of situation where the learner classified what they considered to be an anomaly as an example of a non-correspondence. This is a potential danger in the use of analogies when the non-correspondences are explicitly mentioned. However, in defense of the use of two analogies in this study, researchers have cited the need for the use of multiple analogies to avoid analogy-produced misconceptions (Spiro et al., 1989) or to aid in the learning of wider target domains (Duit, 1991).

Edgar expressed a lack of intelligibility for the Half-Life-two concept. He thought that a radioactive material decayed in two half-life steps.

However, he understood the Half-Life-two relationship within the confines of the falling-tacks situation:

> Ya, that's ah . . . that's true. Um . then at the initial drop of a hundred tacks, you had about roughly 50% of your tacks, in most cases . ending up on their sides. And ah . . that seemed to repeat itself throughout subsequent . drops. Approximately 50% would end up on their sides . . with each subsequent drop. . . . .

It is interesting to note that Edgar simultaneously expressed understanding and believability for two different and mutually exclusive versions of the Half-Life-two concept. However, he did not make the connection between the analog relation and a radioactive material. The learner had separated "school learning" from "real world learning" (Posner et al., 1982). This demonstrated that in order for an analogy to facilitate status changes, an understanding of the relations in the analog must be applied to the target situation (Freidel, et al, 1990; Gabel and Sherwood, 1990). Having an understanding of the relations between an analog and a target is possibly the first step in the conceptual exchange process. Since Edgar's two understandings were mutually exclusive, once he becomes aware of the conflict, rejection of one of the understandings must occur, providing the learner's epistemology contains a commitment to consistency.

Another important point concerning how analogies facilitate status changes was exemplified by Margaret's Decay-one status change. Margaret changed from having no understanding to having intelligibility and plausibility for this concept. She also demonstrated that she understood the

object-correspondences between ice/parent and water/progeny, and the relation-correspondence between melting/decay.

"Ok I'm going to use the same concept you used in the safety meeting. This [referring to start position of column one] will be a block of ice", "And . ah . . let's say it's . . . it's it's decayed. . . I'm . my parent my parent material is now down in half.", "I assume my progeny . . . would escape down melting and decaying . the the progeny would be . . . sitting around the dish I guess.", "it would have decayed into another form which would be the water that would have been left."

This dialogue also revealed that even though the learner understood the analog/target correspondence, and saw this correspondence as plausible, she saw the analog as being the target rather than having correspondences with the target (Toulmin's work, cited in Duit, 1991). Thus, it appears that one danger in the use of analogies is the incorporation of the analog into the learner's conception of the target .

During the post-interview, Felix expressed intelligibility, but a lack of plausibility, for the Activity-one concept. He could mentally represent activity as being disintegrations/time. However, when reflecting on his internally networked concepts related to Activity-one, he thought that activity was constant; being defined as the ratio of the number of disintegrations to the mass of remaining parent material. Felix also could see a correspondence between his alternative idea of activity and the

melting-ice and falling-tacks analogies:

"The rate of melting is basically constant, which would be the activity." and "If there was it was . . . . . the tacks . which way they fell. . . There was sort of a constant. . . There was sort of like a certain percentage. . . As your number went down . . . ".

These last two references to the analogies revealed that the learner still held the alternative understanding that the activity was related to the ratio of the number of disintegrations to the mass of parent rather than the number of disintegrations per second. Thus, it appears that in order for analogies to assist in enhancing a learner's status for a science concept, the learner must compare the appropriate relations. The melting rate and percentage of tacks falling do decrease over time, but these relations do not correspond to the scientifically accepted view of activity.

Conclusions

Hypothesis One

For the Nucleus-one concept, the lesson caused an increase in status for learners who possessed the pre-requisite atomic structure knowledge and who had pre-lesson status that allowed for an increase. The lesson did not cause a decrease in status in those cases where a decrease would have been possible.

For the Decay-one concept, the interview and content-test results both indicated that the learners increased in status for this concept between the pre- and post-tests. All of the participants underwent status increases even though they could have decreased in and/or retained the same status. Content-test items two and six of the content test related to the Decay-one concept, and both showed significant increases in the number of participants that chose the correct choice following the lesson. Thus, the results of the Decay-one interviews and content tests supported Hypothesis one.

The interview data concerning the Decay-two concept did not support this hypothesis. Three of the participants decreased in status after the lesson. Five other learners did experience a status increase.

The interview data did reveal some interesting information concerning status changes related to this concept. As mentioned in the discussion of the concept's interview results, there were two other ancillary concepts that needed to be learned in order for a learner to have complete intelligibility and plausibility for this concept. This finding is in agreement with Reif (1985) who stated that ancillary knowledge is required to make a concept usable. It also is an example of the Ausubelian learning theory concept of "integrative reconciliation" (Ausubel et al., 1978). Integrative reconciliation occurs when the meanings of two or more concepts are seen as being related in a new way. The first ancillary knowledge concerned the

potential of dividing any real number by two an infinite number of times along with a knowledge of concept Half-Life-two. The Half-Life-two concept stated that a radioactive material's decay can be described as a series of half-life decay steps. The second piece of ancillary knowledge is the fact that atomic nuclei are discrete entities that are either parent material or progeny material. Once the last nuclei has decayed, there is no parent material left.

An examination of the interview data suggested that there is a progression of learning steps that are involved in obtaining full knowledge of this concept. The sequence of steps involves both the conceptual capture and conceptual exchange processes. Also, progression through the steps involves a vacillation in the status that the learner has for the scientifically accepted version of the Decay-two concept, that a radioactive material decays to completion.

A learner at the first step has the status of no I and no P or I and no P. Through a conceptual process, he gains intelligibility and plausibility for the knowledge that a parent material's decay goes to completion, possibly through the process of rote memorization. This second step has the status of I and P. This transition from step one to step two was demonstrated by Margaret.

A learner who acquires the ancillary knowledge concerning the infinite potential of dividing a real number by two in conjunction with the

half-life decay sequence knowledge comes to doubt the plausibility of the idea that a parent material completely decays. This loss of believability in the Decay-two concept appears to be a result of a "discrimination" error (Reif, 1985). In this type of error, the learner incorrectly applies information to a phenomenon. Similarly, Stavy and Tirosh (1993) view this type of error as the formation of "inappropriate analogies between different theoretical frameworks". In their study, they found learners perceived successive division problems as analogous regardless of the problems' theoretical domains. They found that viewing a division problem as requiring finite or infinite steps depended on the learners age, the identity of the process (successive division), the visual aspects of the objects in the problem, and previous education in mathematics.

The acquisition of this infinite division knowledge signifies an advance to the third stage of this learning sequence with status I and developing P. A transition from step one to step three was demonstrated by Ralph. Jennifer also made the transition directly from step one to step three. She acquired the infinite divisibility knowledge between these two interviews.

The next step has the status of I and no P. In this step, the learner thinks that, like the infinite nature of dividing a real number by two, the decay process can be described as an infinite number of half-life decay steps. Thus, the idea that the parent material is eventually all decayed

seems totally implausible. The transition from step three to four was demonstrated by Mark. He possessed the infinite divisibility knowledge during the pre-interview, but it did not correspond with total implausibility with this concept until after the lesson. Edgar and Florence made the transition from step two to four. Both of these learners acquired the ancillary knowledge mentioned concerning infinite divisibility between the pre- and post-interviews.

The final step has the status of I and P. To advance to this step, the learner has to acquire additional ancillary knowledge, that atomic nuclei are discrete entities which can not be divided by two, but are either parent or are progeny material. Thus, when the last parent nucleus is reached, it eventually decays and no parent material is left. The transition from step four to five was demonstrated by Fred. He possessed the infinite divisibility and half-life knowledge during the pre-interview, and acquired the discrete nuclei knowledge between the pre- and post-interviews. Wilbur made the transition from step one to step five between the pre- and post-interviews. Also, between these two interviews, he acquired both ancillary knowledges.

Thus, even though the analogy-based lesson can lead to a decrease in status for some learners, the status decrease signifies a progression towards the accepted scientific understanding of the Decay-two concept.

On the other hand, the content-test data for the Decay-two concept

did support this hypothesis. Both content-test items showed significant increases in the number of participants who chose the correct response after the lesson. This discrepancy between the interview and content-test results is most likely an indication that these two instruments measure different things. While the content test is more a measure of rote memorizations (Novak, 1985), the interview is more a measure of meaningful learning (Ausubel, Novak, and Hanesian, 1978).

The content-test data for the Decay-three concept supported this hypothesis. However, the interview data concerning the Decay-three concept did not show support for this hypothesis. Eight of the pre-interviews and four of the post-interviews furnished unknown statuses for this concept. Obviously, the interview format was not efficient in drawing out this information.

Hypothesis Two

The interview data for the Half-Life-one concept disclosed that for learners with the potential to undergo a status increase, half increased in status and the other half retained the same status. None of the learners experienced a status decrease, although eight could have. The content-test data also showed this trend, albeit not as strongly as the interview data. Thus, the data supported Hypothesis Two because 50% of learners with the potential to undergo status increases because of the lesson did experience

increases. In addition, no learners experienced a status decrease.

The Half-Life-two interview and content-test data supported Hypothesis Two. This is claimed because the interview data for the Half-Life-two concept revealed that four of the five learners who could have experienced a status increase did so. The four learners who could have undergone a status decrease experienced no change in status. The content-test data also showed a post-test increase in intelligibility.

Hypothesis Three

The interview and content-test data gave support to the third hypothesis. For the Activity-one concept, the interview data lent strong support for this hypothesis. Seven of eight potential learners showed an increase in status for the Activity-one concept during the interviews. None decreased in status, although four were positioned such that they could have. The content-test data also supported the hypothesis, but not as strongly as the interview data. However, the content-test data did not give evidence contrary to this hypothesis.

Both the interview and content-test results for the Activity-two concept supported this hypotheses. Both learners with the potential to undergo status increases did so. Of the six learners who could have exhibited status decreases, only one did so. The other five retained their pre-interview statuses. The content-test data gave strong support for this

hypothesis, with a 38.7% increase in the number of participants correctly answering the Activity-two related item after the lesson.

How Analogies Facilitate Status Changes

The examinations of these cases support the claim that the analogies facilitated status changes by transferring structures from the analog to the target (Rumelhart and Norman, 1981). The examinations also pointed out that in order for analogies to function in this manner, the learner must: (a) find the target to be sufficiently difficult to understand, (b) be inclined to learn the target material, (c) understand the analog's relations, (d) find the analogy to be plausible, (e) apply the analogy relations to the target, (f) compare the appropriate analog relations to the target, and (g) correctly understand the analog's relations.

General Conclusions

These findings revealed that the analogy-based lesson used in this study resulted in increased statuses for all but one of the radiation science concepts in this industrial environment. Learners' statuses for the Decay-two concept could remain the same, increase, or decrease, depending on where they were positioned in the learning hierarchy for this concept. However, for all of the concepts, the learners moved toward greater sceintifically accepted knowledge.

The claim that the lesson can result in status increases is stated because the elements required to conclude that the lesson was the causal factor were present in this research (Ary, Jacobs, and Razavieh, 1985). The subjects pre- and post-statuses for the concepts were assessed. Between these measures, the lesson was administered. Thus, any change in the learner's statuses must be due to the lesson, provided no other explanation could account for the increase in status. The likely confounding causes were history (Campbell and Stanley, 1963), the Hawthorn Effect (Bracht and Glass, 1968), and diffusion (Borg, 1984; Cook and Campbell, 1979). The data for the one participant where a history interference occurred were eliminated. The threat of diffusion was intentionally but not aggressively addressed. It was decided that the learners would be unlikely to spontaneously talk among themselves concerning the lesson. On the other hand, it was felt that if they were admonished not to, they would be more likely to talk about the study.

In addition, the six participants that were used to determine the test/re-test reliability of the content test did not demonstrate a significant increase in their intelligibilities for these concepts. Even though this group of six did not constitute a control group because they were not drawn from the same population as the study participants, their test-scores consistency support the statement that extraneous causes did not account for the status increases demonstrated by the participants in this study.

Overall, this study illustrated that the learners moved towards greater knowledge in all of the concept areas investigated. The concepts studied ranged from simple, like the Decay-one concept, to complex, like the Decay-two concept. The Decay-two concept required that the learners acquire two ancillary understanding to reach full status.

Because the analogy-based lesson was effective with the wide range of concept difficulties encountered in this study, it can be stated with some assurance that an analogy-based lesson will result in a move toward more scientifically accepted knowledge for science concepts in general. Also, as indicated in the conclusion five discussion, if properly utilized, analogies themselves can be a powerful aid for acquiring intelligibility and plausibility for science concepts. This conclusion can be logically and justifiably extended to the claim that learners who want to grasp a difficult science concept would be wise to master the basic principles of analog/target mapping in order to effectively employ analogies in the acquisition of this knowledge.

Implications

The environment of this study differed from an academic setting. For example, the participants in this study were under no pressure to learn the presented material. No grade record of their performance was kept or recorded in any file associated with their name. This is viewed by the

researcher as beneficial because it demonstrated the power of the analogy-based lesson to affect an increase in the status that these learners had for these concepts. In an academic environment, the learners would be much more prone to study the material in preparation for an examination. Thus, in an academic setting, the power of the lesson to increase their statuses for science concepts would be confounded with their study-based learnings.

However, as stated in the general conclusions section, an analogy-based lesson is expected to facilite increased learnings that students have for science concepts in general. This is also anticipated to be true in milieus different from industrial-training environments. Further research could confirm this conclusion by investigating the effect of analogy-based lessons with different concepts and in different environments. These type of studies would be useful in supporting generalizations about the efficacy of analogies.

Another fruitful arena for research would be the development of instruments for assessing status. The method utilized in this research is effective, but a more efficient (i.e. less time consuming) method would open this avenue of research to broader applications.

If a further study of how analogies facilitate status increases for science concepts is of interest, a study designed specifically to do this could be undertaken. One method would be to follow the lead of problem-solving studies (Hafner, 1991) or studies of how people use analogies

(Gentner and Gentner, 1983).

Appendix A

Consent Form for Group-One Participants

Western Michigan University

Department of Science Studies

Principal Investigator: Robert Poel

Research Associate: Charles T. Lohrke

I have been invited to participate in an experimental research project entitled "The Use of Analogies in an Industrial Environment to Facilitate Status Changes for Radiation Science Concepts." I understand that this research is intended to study how analogies assist people in making sense of some radiation science concepts. I further understand that this project is Charles T. Lohrke's dissertation project and that the duration of the entire experimental portion of the project is 8-10 weeks.

My consent to participate in this project indicates that I will be asked to attend two, approximately 45-60 minute private sessions with Charles T. Lohrke. I will be asked to meet Charles T. Lohrke for these sessions in his office. The first session will involve completing a multiple-choice test and an audio-taped interview, both of which concern my understanding of some radiation science concepts. I will also be asked to complete an activity related to some radiation science concepts. I will also be asked to provide information concerning my level of education. The second session will involve completing a multiple-choice test and an audio-taped interview, both of which concern my understanding of some radiation science concepts. Between these two private sessions, I will be asked to attend a 60-90 minute session where Charles T. Lohrke will present some information concerning some radiation science concepts. This information will be presented with the aid of overhead transparencies and a demonstration.

As in all research, there may be unforeseen risks to the participant. If an accidental

injury occurs, appropriate emergency measures will be taken; however, no compensation or treatment will be made available to me except as otherwise specified in this consent form. I understand that potential risks are minor discomforts typically experienced by people when they are being tested or interviewed (e.g., boredom, mild stress owing to the testing situation). I understand that all the usual methods employed during testing to minimize discomforts will be employed in this study.

One way in which I may benefit from this activity is the achievement of a better and deeper understanding of some radiation science concepts. I also understand that other education researchers who study analogies and/or the categorization of knowledge levels may benefit from information that is gained from this research.

I understand that I have been asked to participate in this study because I am a XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX Corporation Technical Center employee who works in a department that uses ionizing radiation generating devices. I understand that all the information collected from me is confidential. That means that, except for this consent form, my name will not appear on any papers on which information is recorded. The data papers and audio-taped recordings will all contain a fictitious name, and Charles T. Lohrke will keep a separate master list with the names of participants and the corresponding fictitious names. I also understand that after all of the multiple-choice test and interview data is collected, Charles T. Lohrke will code all of my forms with another fictitious name. At this time, the master list of participants and corresponding fictitious names will be destroyed. I also understand that this permission form will be retained for three years in a locked file in the principal investigator's office, but there in no way can this consent form link my responses during this project to me.

I understand that I may refuse to participate or quit at any time during the study without prejudice or penalty. If I have any questions or concerns about this study, I may

contact either Robert Poel at 616-387-3336 or Charles T. Lohrke at 914-578-7498. I may also contact the Chair of Human Subjects Institutional Review Board at 616-387-8293 or the Vice President for Research at 616-387-8298 with any concerns that I have. My signature below indicates that I understand the purpose and requirements of the study and that I agree to participate.

_____ _____

Signature Date

Appendix B

Content Test

Name_____ Date_____
GENDER_____

CHOOSE THE BEST RESPONSE TO EACH ITEM

1. The structure of an atom is best described as -
   a) a nucleus containing protons and neutrons surrounded by fast moving electrons that occupy discrete levels.
   b) a random jumble of protons, neutrons, and electrons.
   c) a nucleus containing protons and neutrons surrounded by electrons that do not move or move only slightly at a slow speed.
   d) a nucleus containing electrons surrounded by fast moving protons.
   e) an compact sphere containing protons and electrons surrounded by fast moving neutrons that occupy discrete levels.

2. A radioactive material with a half-life of 50 years will -
   a) loose 1/2 of its mass during a 50 year period.
   b) undergo radioactive decay for 50 years before it is completely depleted.
   c) be completely depleted in 75 years.
   d) be completely depleted in 100 years.
   e) will never be completely depleted.

3. Indicate the correct description of radioactive decay.
   a) parent material melts and becomes progeny material.
   b) parent material decays into progeny material.
   c) progeny material decays into parent material.
   d) parent material may increase or decrease, depending on the particular radioactive material.
   e) parent material decays into progeny material, but only after being bombarded with high energy microwave radiation.

4. The activity of a radioactive material -
   a) is the time required for the radioactive material to undergo complete radioactive decay.
   b) is the amount of nuclear decay that occurs per time.
   c) is expressed in units of decay.
   d) is the time required for 1/2 of the radioactive material to decay.
   e) does not depend on the amount of radioactive material present.

5. A correct unit for half-life of a radioactive isotope is -
   a) decays/second
   b) minutes
   c) grams/minute
   c) minutes/gram
   e) kilograms

6. A radioactive material -
   a) increases in mass as the decay process progresses.
   b) will never completely disappear.
   c) glows in the dark.
   d) will someday not exist.
   e) refers to materials that emit radio waves when activated.

7. Each nuclei of a given radioactive material -
   a) has an equal probability of undergoing radioactive decay.
   b) has a greater probability of undergoing radioactive decay if it is located on the outside surface of the material.
   c) can undergo radioactive decay only if it is located on the outside surface of the material.
   d) can undergo radioactive decay only if it is located in the core of the material.
   e) can undergo radioactive decay only if it is heated to an extremely high temperature.

8. Consider a given amount of a certain radioactive substance and twice that amount of the same radioactive substance.
   a) the activities of both quantities are the same.
   b) the activity of the larger quantity is twice the activity of the smaller quantity.
   c) the activity of the smaller quantity is twice the activity of the larger quantity.
   d) the activities of the two quantities can not be theoretically compared, but must be experimentally determined.
   e) the activities can not be compared without knowing the specific radioactive material.

9. If the half-life of a given amount of a radioactive material is 14 seconds, in 28 seconds, its half-life will be -
   a) 3.5 seconds
   b) 7 seconds
   c) 14 seconds
   d) 28 seconds
   e) 48 seconds

10. If the activity of a given amount of a radioactive material is 10,000 decays/second, after three half-life intervals, the activity of the material will be -
   a) the same, 10,000 decays/second
   b) less than 10,000 decays/second
   c) greater that 10,000 decays/second
   d) no way to determine this without knowing the exact radioactive material in question.
   e) zero

11. On the back of this sheet, report any other information that you think is valuable to demonstrating your understanding of the concepts covered in this test.

Appendix C

Interview Protocol

Terms -

half-life

activity

radiation

radioactive material decay

parent

progeny

probability

Phase I Questions -

Initial question: Can you think of a way to explain to someone who knows nothing about this topic what is occurring in the picture? Note that the wording of this question is meant to elicit more complex explanations for the participants because they will be attempting to explain their understanding of the concept areas.

Potential follow up questions:

Can you explain that to me?

What else did you notice?

Can you think of a way to explain what is occurring in the picture?

Can you think of any other situations where this concept may apply?

Can you give examples that belong and that do not belong in this picture?

Phase II Questions -

Can you think of a way to explain to someone who knows nothing about this topic what you mean by the term _____?

Questions used to determine the condition of plausibility - (researcher will sequentially refer to the first (involves the decay concept area), second (involves the activity concept

area), and third (involves the half-life concept area) columns of the participant's completed work sheet.

Do you think that your explanation of what is occurring in column one/two/three is true or has the potential to be true? Note that the inclusion of the phrase "has the potential to be true" gives the participant permission to speculate about their understanding of the concept fits into their conceptual ecology.

Can you think of a way to explain to someone who knows nothing about this topic why you think that your explanation is not true/true

Questions used to determine the condition of fruitfulness - researcher will, again, sequentially refer to the first (involves the decay concept area), second (involves the activity concept area), and third (involves the half-life concept area) columns of the completed work sheet.

Do you think that your conception of what is occurring in column one/two/three could be useful or has the potential to be useful?

Can you think of a way to explain to someone who knows nothing about this topic why you think that your explanation is not useful/useful.

Questions specific to post-lesson interviews -

After the participant has had a chance to fill out the work sheet, the researcher will show the learner his completed pre-lesson work sheet and will ask (researcher will sequentially refer to the first (involves the decay concept area), second (involves the activity concept area), and third (involves the half-life concept area) columns of the two completed work sheets.

How does your conception of what is occurring in column one/two/three today compare with what you put down on the work sheet before the lesson?

Is either explanation true or have the potential to be true?

Can you think of a way to explain to someone who knows nothing about this topic why you think your choice is not true/true Do you think that your conception of what is occurring in column one/two/three could be useful or has the potential to be useful?

Can you think of a way to explain to someone who knows nothing about this topic why you think that your explanation is not useful/useful.

How does your conception of what is occurring in column one/two/three today compare with this work sheet completed by another person?

Is either explanation true or have the potential to be true?

Can you think of a way to explain to someone who knows nothing about this topic why you think your choice is not true/true

Do you think that your conception of what is occurring in column one/two/three could be useful or has the potential to be useful?

Can you think of a way to explain to someone who knows nothing about this topic why you think that your explanation is not useful/useful.

The following question were designed to obtain information about how the analogies helped to raise the status that the learners had for the radiation science concepts under study.

Do you remember what the two analogies were that the researcher presented during the lesson that you attended during your staff/safety committee meeting?

Do you remember any of the correspondences that were mentioned between a radioactive material's behavior and the melting-ice analogy?

What are the correspondences between the melting-ice analogy and the following?

radioactive material decay

parent material

progeny material

probability

half-life

activity

Do you remember any of the correspondences that were mentioned between a radioactive material's behavior and the falling-tacks analogy?

What are the correspondences between the falling-tacks analogy and the following?

radioactive material decay

parent material

progeny material

probability

half-life

activity

Appendix D

Status Categorization Scheme

Each category is explained by way of a written description followed by several examples. The examples are important for gaining an appreciation for how real-life statements fit into each of the categories. Note that these categories overlap and one segment of transcript may fit more that one category. For example, the use of an example may invoke vivid images and thus may be classified into both the image and exemplar intelligibility categories. These status categories, and much of the explanation of the categories, are taken largely, with permission, from Thorley's Ph.D. theses (1990). The direct categories came from work by Hewson and Hennessey (1991). The authority category has not previously been reported in the literature.

Intelligibility

People cannot understand what they cannot conceive. Therefore "understanding an idea requires that it be viewed within a context of other ideas, that is, finding a niche within a conceptual ecology." (Strike and Posner, 1988). The categories of statements concerning the condition of intelligibility that a learner has for a concept concern the method of representation of the learner's concept as constructed by the interviewer (a subtle but important distinction from the learner's conception or even the learner's representation of his conception) (Thorley, 1991). The categories are as follows:

Direct

A learner directly states that they "understand" a concept.

"No I don't think I've heard that that term."

"Progeny. No I haven't heard that term either."

Analogy

The learner sees the target concept through an analogy. The learner lacks an independent means of representing the concept under question and uses an analogy as the method of representation of that conception. Note that an analogy may also be used to describe the plausibility that a learner has for a concept and a statement may fit into one or both categories, depending on its use by the speaker. Analogies can also have an element of image to them.

"Alright . if . they (plants) get it from the soil . they get food from the soil OK . if that's true . is it like there's . what . little big-macs . in the soil?"

"Ya well ya the ice is the ah parent. The water is the . the progeny."

..the little one would have to exert a greater force to hold up the . bigger . person and the . bigger person would have to . not exert . as great a force .. not exert a bigger force .. to hold up the little person. If I . if I was to hold . a lead ball in this hand I would have to exert a greater force than if I was holding a feather .. with my . body" [also fits into plausibility-analogy category] {little one corresponds to feather, bigger person corresponds to lead ball, force corresponds to force}

". . Um . . yes that is . ice melts . . ah, it changes form . . um . as radioactive materials do."

Image

Images allow learners to construct visual frameworks in which to locate an idea. This includes the use of diagrams or pictures. In order for a learner's talk to be placed into this category, the image itself must be the object of discussion. This will be indicated by the use of such phrases as "picture", "imagine", or "I saw".

a diagram drawn on the board would fit into the image category "Are you

"picturing sugar . tell me ... in your mind . when they say sugar ... what picture is coming onto your mind? What does that sugar you're picturing look like?"

"I and this is what the radioactive material looks like

Exemplar

An exemplar is a standard case to which a framework has been applied.

"you define food as a material that you need to stay alive . and . you need water . right . since water helps you stay alive . "

> I don't know how, I know what half-life is. It . you lose half and . . the radioactive material . . or whatever it's life span. If it were a hundred years, in fifty years it'd be half as strong . in order for there to be half as much material. In a hundred years there'd be . a quarter of the material."

(reply of a student who was asked to describe what the statement that every action has an equal and opposite reaction meant to him) "um .. well . just kind . you get a gun or something and you shot it . you'd feel the same kick . on your hand. The kick on your hand would be equal . to the force on the bullet going forward."

Attribute

Regardless of what representation a learner has in mind (e.g. image, exemplar), he is likely to rely on attributes (essential components of concepts) of that representation when describing it. In addition to the use of attributes to describe a conception (e.g., an active force), this category also includes discussion of the conditions of application of rules of classification and discussion of the conditions of application of causal principles.

(learner comment during classroom discourse about force) "force is something active"

"as the material decays"

" . meaning water . water doesn't contain minerals" (reference to water not being a member of the class of things that contain minerals)

" .. is juice food according to what you said."

"is energy what is provided by water that's the question see you're debating I think whether or not we need it. ok. yes . we need it but it could be . considered a . food .. why . tell me."

" . there's water . ok . but . is the water providing the energy"

Language

A superficial form of intelligibility (Posner, et al, 1982). Language includes linguistic or symbolic representation of a concept such as activity being labeled aggressive or half-life represented by the formula $t_{1/2} = 0.693/k$. To fit into this category, there must be explicit reference to language, not just the use of language.

"you define food as a material that you need to stay alive . and . you need water . right . since water helps you stay alive . "

"Ok. I I understand, I think I understood what you were saying . is the radioactive material would be half left after one half- life."

Plausibility

Once a concept can be represented (is intelligible), plausibility may be considered. Initial plausibility can be thought of as the anticipated degree of fit of a new conception into an existing conceptual ecology. A concept can be plausible for many different reasons as indicated by the numerous categories for plausibility. The categories can be separated into four sub-groups, reality factors (the core of plausibility), consistency factors, transient, and additional. These categories are as follows:

Reality Sub-group

By the using one of these categories, the learner is attempting to reconcile how the phenomenon under question matches with his sense of how the world operates. The two categories in this sub-group are "real mechanism" and "neotheory".

Real mechanism

A causal mechanism is invoked in that the statements convey a sense of the mechanism that causes a phenomenon to occur.

"I said that it was just slightly more than 10 because it loses the buoyancy that the air gives it . as it . when the air is sucked out."

"Eventually it's gonna all become . it's just gonna decompose to nothing because it's all released as energy."

Neotheory (embryonic theory)

A component of the learner's sense of reality that comes from a generalization from multiple similar past experiences to generate an embryonic theory. Embryonic theories constitute less formal and rational forms of knowledge. To be classified as an embryonic theory, there must be evidence that the learner's concept cannot be reasoned with beyond much beyond the immediate phenomenon. A learner's comment that fits within the neotheory category must state the belief with or without an expressed phrase that indicates the lack of a reasoned foundation for the belief. Some phrases that show the lack of a reasoned foundation are "somehow", "I couldn't explain why", or "there's gotta be something". A learner's comment may or may not include an example. Another type of learner comment consists of one or more examples of phenomena that illustrate the belief.

Another type of learner comment that falls within this category is a statement of a belief along with a justification of the belief. However, no reasoned consistency between the belief and the justification is made like is done the other knowledge category.

"...and if it wasn't there it would fall to the ground ...so there's gotta be something."

"I guess one way . . . . that um each atom has an equal probability of decaying."

" . the larger the mass . the more . the force its . its exerting .. so I said in my answer I said the woman exerts more force."

" .. and the girl (is lighter that the woman) . in order to get the woman moving has to exert a greater force than the woman would have to . to get the girl moving."

"For each, if a half-life is a year, . . for every year . half of your remaining radioactive material is gone."

"When you're lifting weights . the heavier . the bigger weights ... are so much harder to pull up from the ground. So it seems that they would fall faster."

Consistency Factors

By using one of these categories, the learner is attempting to determine how the phenomenon under question concurs with the network of conceptions that he uses for evaluating information (his conceptual ecology). There are six categories in this sub-group. These categories are other knowledge, past experience, epistemology, metaphysical (ontological), analogy, and authority.

Other knowledge

One finds the conception to be consistent with other theories or knowledge. Requires an attempt at a reasoned consistency with this other knowledge, such as a deduced implication of the other knowledge. One clear type in this category is a reasoned

consistency between a real world phenomena and abstract theory-like knowledge. Another type involves a reasoned consistency between two real world phenomena. This comparison of two real world phenomena may be on the basis of theory. Two other types involve differentiation within or a generalization over conceptions. This category is similar to "past experience" category, but source of the knowledge is not from personal experience in this case.

" . or something that can be proven like gravity ."

" now . does this . equation stuff . does that . support that"

"And I guess, if you have a half-life . . . theoretically, do you ever get to the end state if you're only only losing half of it. Fine. That's a again . . that's there's there's probably always a little bit there."

"They're gonna be both . equal forces because . when you pull on the spring ... or band with . your two hands . one . the rubber band makes up for . the more stiffness of the spring ... by stretching more."

> therefore if you take the . equation which we've been using f = ma . a and m are both gonna be bigger for . for the . girl than the force has to be bigger . the elephant or the girl say . take the elephant first . if its the elephant . for the elephant . the mass will be bigger but the acceleration would be smaller . . so you're really . use this expression for . both . both things.

"so are food and energy the same thing"

Past Experience

One finds the conception to be consistent with past experience. Similar to "other knowledge" category, but the source of the knowledge is from personal experience in this case. This category is reserved for occasions when the learner recalls a particular event which may be a vicarious experience. The learner may use recall of a past experience to corroborate a personal theory.

> That's like the dude who wanted to ski down a mountain . and he thought he'd slow himself down with a parachute. And like when he was on the top there was not . very much air and he opened up the parachute and bit it. He couldn't slow down that way .... so maybe that's like the same thing."

"Probably like movies I've seen about like a . nuclear power plant stuff. You know like . they had like uranium or something that has a really long half-life. And . you know that kind of thing."

Epistemology

The conception is consistent with one's epistemological commitments. An example in this category may arise through a demonstration of a need for similar phenomena to have similar explanations or a statement expressing a belief in the significance of experimentation. Epistemological commitments, along with metaphysical commitments, make up one's fundamental assumptions.

"We could figure it out by taking one of those funny scales and putting it . where every arrow is (back to back) and then measuring them all.."

Example of a teacher explaining that similar phenomena should have similar explanations:

> now .. the physicist wanting to come up with a logical sort of definition that makes rational sense as you go across different situations says . look . I see something in common in these situations . [referring to two force-on-book diagrams that the teacher placed on the board] this book is . at rest . and this book . is at rest . so I want to say . that here the book is at rest and what keeps it at rest is a down force exerted by the earth and an up force exerted by the hand . and those two balance each other. Then the physicist says . shoot I guess that means that I'd better think of force . as something that the table can do as well . but I wanna think of that . as sort of a passive support that the table does . rather that something really active muscular-wise . but logically if I wanna be logical about it ten I want the same kind of explanation here as what I have over here.
>
> Yes um once you get down to, I think we discussed this the last time [referring to pre-interview] and I felt you probably never would actually get down to the end. But, ... once you get down to. the last atom . in there . . it's either gonna decay or not. You can't go any farther in in the half-life. Er, I can't I can't cut the thing in

half. Oh, well, I guess they can nowadays, but I I'm not cutting the thing in half. So, once that last atom . . kicks out the the proton, . or the neutron, it decays, it's over. . . So, yes, it it does finally make it to the end. I guess we discussed it the last time. Theoretically, under mathematical terms, I guess you'd never get to zero. If you're always taking a half, you can get down to . . um . . sub-one numbers. But, in physical . properties . no you can't. I mean, I've got one atom left, it decays, that's it. End of story.

Metaphysical (ontological)

The conception is consistent with one's metaphysical beliefs. Metaphysical beliefs, along with epistemological commitments, make up one's fundamental assumptions. An ontological category may arise from embryonic theory (formed from very commonplace experiences) at a deeper level. Past experience, other knowledge, embryonic theory, and ontological categories overlap to some extent and cannot be distinguished without a reasonable extended exchange and a well-ordered context. If interviewer noticed that the learner used the same explanation in a wide variety of situations, and thus demonstrating repeated and unyielding assertions that some fundamental conception applied, then this would support placing comments in this category versus the embryonic theory or past experience categories.

"it's just there, and keeping it from falling down"

"and the table can't lift anything"

OK? Now Newton suggested that those forces . were equal . that those forces were equal . but the effects . may be very different. His jaw may break. My hand might come through with a little owie. The effects may be very different . but the forces Newton suggested would be the same.

Analogy

A student's statements concerning an analogy can be categorized within the plausibility condition as well as intelligibility. For a statement about an analogy to demonstrate plausibility or implausibility, it must be analogous to some other conception

with which the learner is already familiar. That is, the learner must have independent representations of both the analog and the target.

> So it like the river. The book is pushing down, say with um, it's a little far fetched, but with the velocity of the engines, it's pushing down, and the table's pushing up, with velocity of the current. If you take the current away, then the engine, if you take the force of the table pushing up, away, then the book would just fall down.
>
> The one analogy was the . . dripping ice, the melting . . ice into water. . . Um . . and that was to be analogous to . . ah . the decay of radioactive materials. . In that, over a certain amount of time, it goes from the parent to progeny. Ice to water.

Authority

This category refers to the use of authority that is based on information received from text books, teachers, or peers. One finds the conception to be consistent with past learnings. However, unlike statements in the other knowledge category, no attempt is made at a reasoned consistency with this other knowledge. Like neotheory, this category represents statements that implicitly rather that explicitly indicate that a connection exists with the learner's conceptual ecology.

Statements in this category differ from internal authority statements that come from a having a concept personally make sense. They also differ from the authority given to scientific outcomes that is derived from the methods and values developed by the scientific community to produce and validate scientific knowledge (Hewson, Beeth, Thorley, in press). This category is intermediate between these two. Statements in this category relate to plausibility because they represent the intrinsic authority that the knowledge has for a learner based on intermediate-level external information.

"I think I learned this in high school"

"Because that's how . I learned it. I read it in a book. Um hu. I don't remember any specific thing. But . that's the theory."

Transient Sub-group

The following three plausibility categories (lab experience, thought experiment, and hypothesis) are considered to be transient in that they are less durable that the features of the conceptual ecology. However, they do express a relationship between conceptions and experience, real, potential, or imagined. Also, at they time they are being entertained, they are as significant as the other, more permanent, categories such as past experience or epistemological commitments.

Laboratory Experience

Discussion of a laboratory experience or a teacher's demonstration in conjunction with a discussion of a concept.

(after evacuating air from around a weight on a scale) "It didn't go to zero? OK . awfully hard to detect any difference if there's any difference at all."

"I have a chunk of radioactive material. And I know you said . in your talk the other day, that . eventually you would get down to . . having no radioactive material . left."

Thought Experiment

A thought experiment involves imagined experience at the same time as discussing a conception. Closely related to hypothesis, but the question must be resolved conceptually in that there is no easy way to resort to real experience. May involve extrapolating to a situation which is not testable, extrapolation to an ideal case, or extrapolation to an experiment which is feasible but is impractical.

extrapolation to non-testable situation -

> Say you're up at the Space Needle and had three balls (different weights). Then would it start to be a factor the weight and stuff? Do those come into a factor when you drop them off the space needles coz you had more time to . for them to pick up .

velocity or whatever?"

Extrapolation to ideal situation -

(student comments concerning the force that a table exerts on a book that is placed on it) ".. if the table is perfectly rigid, does not move at all, then I don't see how - then I don't see how it could be pushing up . on the book. I don't see how it pushes on the book."

Extrapolation to an experiment which is feasible but is impractical

(teacher discussing demonstrating the concept of force by hitting a student on the chin) "Now, how about this? Luke, take your hand away from your chin, OK? Now just . lift your chin up. Yeah, that's right . remove your glasses."

"say you start with ten grams of this radioactive material, you know the life time of this radioactive material, you can actually calculate at anytime how much left.

Hypothesis

Entertainment of a hypotheses about anticipated laboratory experience at the same time as discussing a conception. Can be a result of a prediction from theory, or a result of a prediction from experience. Closely related to thought experiment category, but one can resort to real experience to test the hypothesis.

(student comment about two objects being dropped) "Now I think that the lighter one will hit first"

Additional Factor

Direct

One makes a direct statement concerning their strength of commitment to the believe

that their understanding of a conception represents how that phenomenon actually occurs in nature.

"After a hundred percent radioac active decay, . . you have . . it is different. Because it's not decaying anymore. So I'm a hundred percent sure of that.

Learner response after the researcher asked if she believed her column one information was true. She responded "Oh well I wouldn't stake my life on it or anything."

Anomaly

One finds the conception capable of solving problems of which one is aware. This category accentuates the resolution of anomalies, not just the acknowledgement of the existence of an anomaly.

Fruitfulness

To be fruitful, a new conception should do more than the prior conception without sacrificing any of the prior conception's benefit, or must provide sufficient incentives for any required sacrifice. A new conception will appear fruitful to the extent that students are aware of, can generate, or can understand novel practical applications or experiments which the new conception suggests. The categories are as follows:

Direct

A learner directly states that a concept is useful.

A learner's response after being asked if he found his understanding of a concept to be useful: "Oh ya, probably".

Power

Conception has wide applicability.

The key point here folks, and I'm glad all these examples are coming out . because its true no matter where you go in the universe . if something is not accelerating, then there are no unbalanced forces acting on it . pure and simple.

> Well like I said. The . . they can probably predict . when the sun's gonna burn out. . For medicine. For a generating electricity. You have to know how long that core's gonna last. So they . whoop, there it's gone. nobody has any power anymore. For medicine. You gotta know how long it's gonna last so that they aren't having it running around or disposed of improperly. . and it's hot. Cause if it does happen to get into the food, . . they certainly have to know how long it's gonna last.

Promise

Looking forward to the potential benefits of a new conception.

"The whole key here folks . and this is a biggie . and you're gonna be using it . for the rest of the year ... if something is accelerating . then there's an unbalanced force acting on it ..."

When Fred was asked if he found his understanding of column two of the work sheet to be useful, he replied "Ya. Absolutely. Ah-um . . in giving . . someone a . . an understanding of the level of radioactivity . . in that area."

Competition

The merits of two competing conceptions are explicitly compared. This category bears more on conceptual exchange that on conceptual capture.

benefit of regarding table's supporting action as a force rather than an obstruction

Extrinsic

Recognition of conception as important in discipline or associated with some expert. For example, Newton's fame as an incentive to understand his laws.

> Well, it would certainly be useful here for anybody here who tends to work . with radioactive material. Obviously, the labs must do it. I don't think there's anybody in our lab. But um I'm sure you must somewhere or we wouldn't have our radio . we wouldn't have you teaching us."

"Now Newton suggested that those forces would be equal ..."

" . down toward the bottom of the page . there's a nice little square there . all outlined . what does that it mean that its all outlined like that important .. its a definition right .. scientific definition for . food .right ok"

Appendix E

Lesson Overhead Transparencies

RADIOACTIVE MATERIAL DECAY

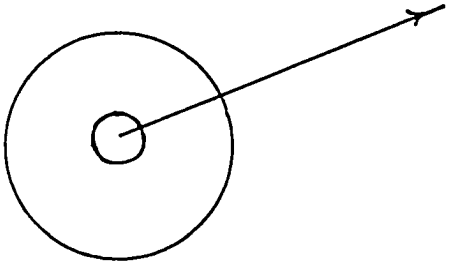
SOME MATERIALS ARE RADIOACTIVE

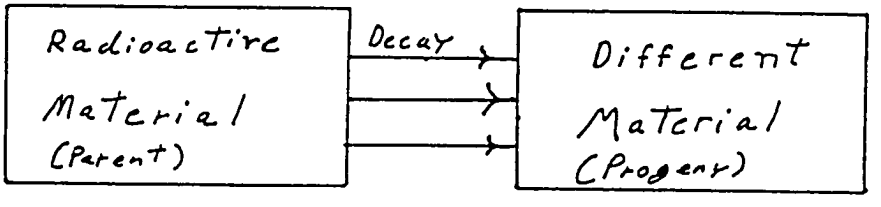
RADIATION IS EMITTED FROM THE NUCLEUS OF A RADIOACTIVE MATERIAL

PARENT MATERIAL DECAYS INTO PROGENY MATERIAL

A PARENT DECAYS INTO ITS PROGENY UNTIL THE CHANGE IS ENTIRELY COMPLETED

FOR A GIVEN RADIOACTIVE MATERIAL, ALL NUCLEI HAVE AN EQUAL PROBABILITY OF DECAYING





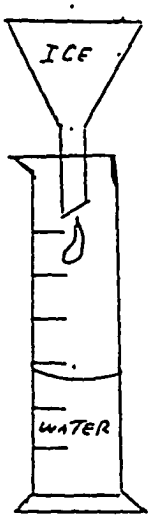
MELTING-ICE ANALOGY

CONSIDER THAT YOU HAVE 1,000 GRAMS OF ICE CUBES IN A FUNNEL AND THEY ARE ALLOWED TO MELT.

THE MELT-WATER IS COLLECTED IN A GRADUATE CYLINDER

COMPARE THE ICE TO A RADIOACTIVE MATERIAL

COMPARE THE MELTING OF THE ICE TO RADIOACTIVE MATERIAL DECAY



CORRESPONDENCES -

ICE - PARENT

MELTING - DECAY

WATER - PROGENY

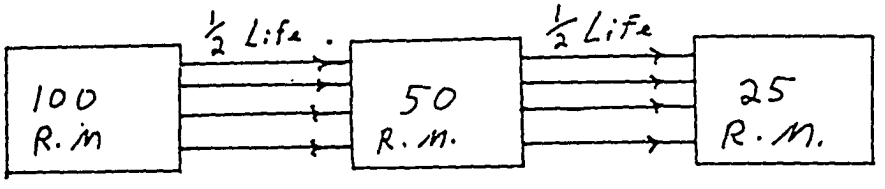
MELTING PROCEEDS UNTIL ALL ICE BECOMES MELT-WATER

- DECAY PROCEEDS UNTIL PARENT IS ENTIRELY CHANGED INTO ITS PROGENY

RADIOACTIVE MATERIAL HALF-LIFE

THE TIME REQUIRED FOR 1/2 OF THE PARENT MATERIAL TO DECAY INTO ITS PROGENY MATERIAL

HALF LIFE IS A CONSTANT FOR A GIVEN RADIOACTIVE MATERIAL

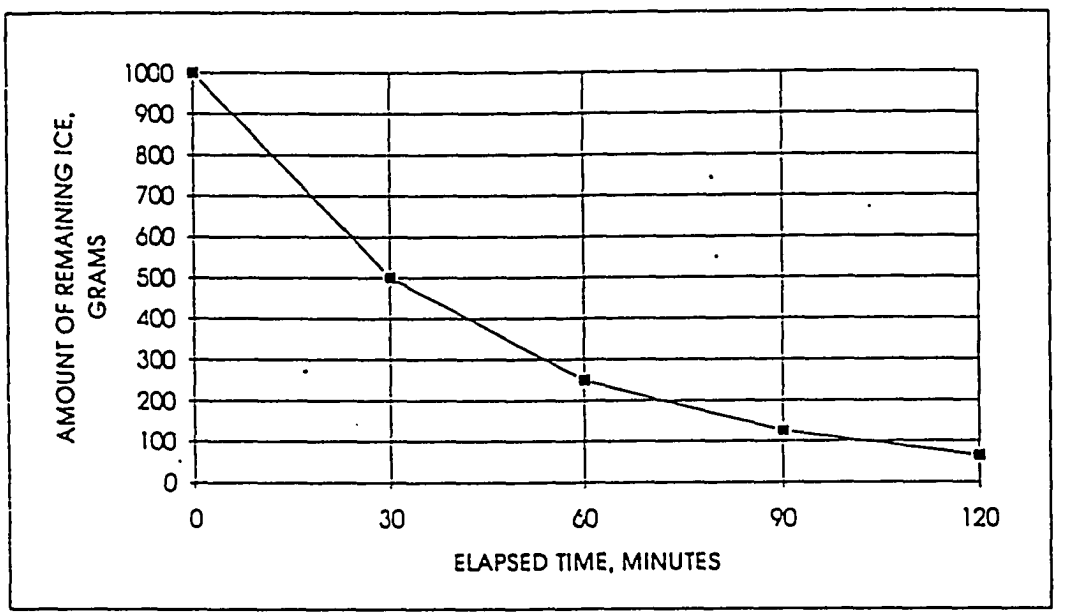


RECORD THE AMOUNT OF REMAINING ICE AND THE AMOUNT OF MELT-WATER PRODUCED VERSUS TIME AND COMPARE THIS TO HALF LIFE:

TIME, MINUTES	REMAINING ICE, GRAMS	MELT-WATER, GRAMS
0	1000	0
30	500	500
60	250	750
90	125	875
120	62.5	937.5

MELTING-ICE: HALF-LIFE PLOT

TIME, MINUTES	AMOUNT OF REMAINING ICE, GRAMS	TOTAL AMOUNT OF MELT-WATER, GRAMS
0	1000	0
30	500	500
60	250	750
90	125	875
120	62.5	937.5



CORRESPONDENCES -

AMOUNT OF TIME REQUIRED FOR 1/2 ICE TO MELT	-	HALFLIFE
AMOUNT OF TIME REQUIRED FOR 1/2 ICE TO MELT IS THE SAME REGARDLESS AMOUNT OF ICE REMAINING	-	HALFLIFE IS A CONSTANT

RADIOACTIVE MATERIAL ACTIVITY

ACTIVITY IS THE NUMBER OF NUCLEI THAT DECAY PER UNIT TIME

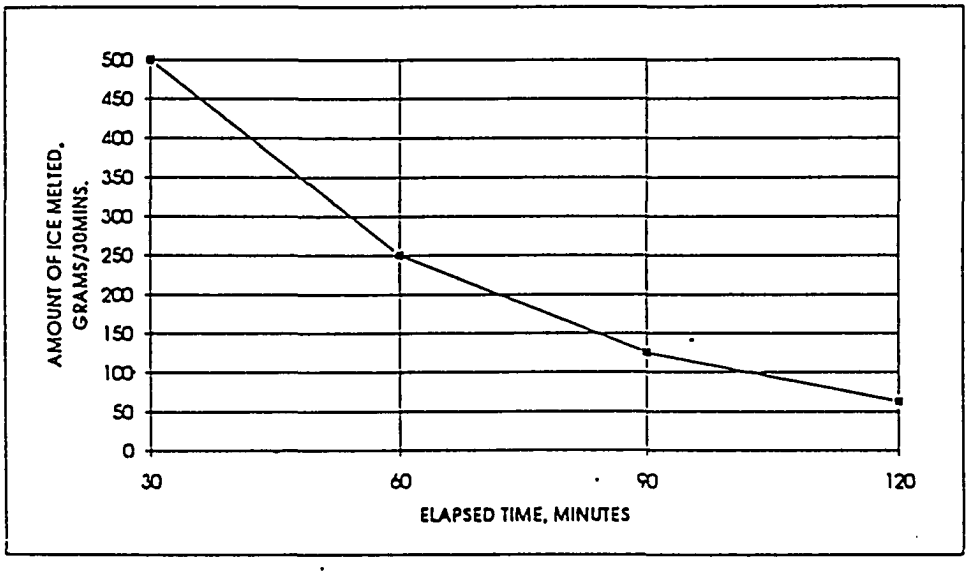
ACTIVITY IS DIFFERENT FOR EACH PARTICULAR RADIOACTIVE MATERIAL BEING CONSIDERED

FOR A GIVEN RADIOACTIVE MATERIAL, ACTIVITY IS DEPENDENT ON THE AMOUNT OF MATERIAL THAT IS PRESENT

FOR A GIVEN RADIOACTIVE MATERIAL, ACTIVITY DECREASES WITH DECAY (FOR A SINGLE STEP DECAY).

MELTING-ICE: ACTIVITY PLOT

TIME, MINUTES	AMOUNT OF ICE MELTED, GRAMS/30 MINS.	REMAINING ICE, GRAMS	TOTAL MELT-WATER, GRAMS
0	0	1000	0
30	500	500	500
60	250	250	750
90	125	125	875
120	62.5	62.5	937.5



CORRESPONDENCES -

AMOUNT OF WATER PRODUCED EVERY 30 MINUTES - ACTIVITY

AMOUNT OF WATER PRODUCED EVERY 30 MINUTES DECREASES AS MELTING PROCEEDS - ACTIVITY DECREASES AS DECAY PROCEEDS

NON-CORRESPONDENCES

MELTING-ICE	RADIOACTIVE MATERIAL
ICE AND WATER ARE CHEMICALLY THE SAME SUBSTANCE	PARENT AND PROGENY ARE DIFFERENT SUBSTANCES
SURFACE ICE MELTS BEFORE INTERNAL ICE	ALL PARENT NUCLEI HAVE AN EQUAL PROBABILITY OF DECAYING
MELTIING PROCESS IS REVERSIBLE	DECAY PROCESS IS NOT REVERSIBLE
MELTING PROCESS IS TEMPERATURE DEPENDENT	DECAY PROCESS IS NOT TEMPERATURE DEPENDENT

FALLING TACKS ANALOGY

DROP A GROUP OF TACKS ONTO A SURFACE

COMPARE THE TACKS TO A RADIOACTIVE MATERIAL

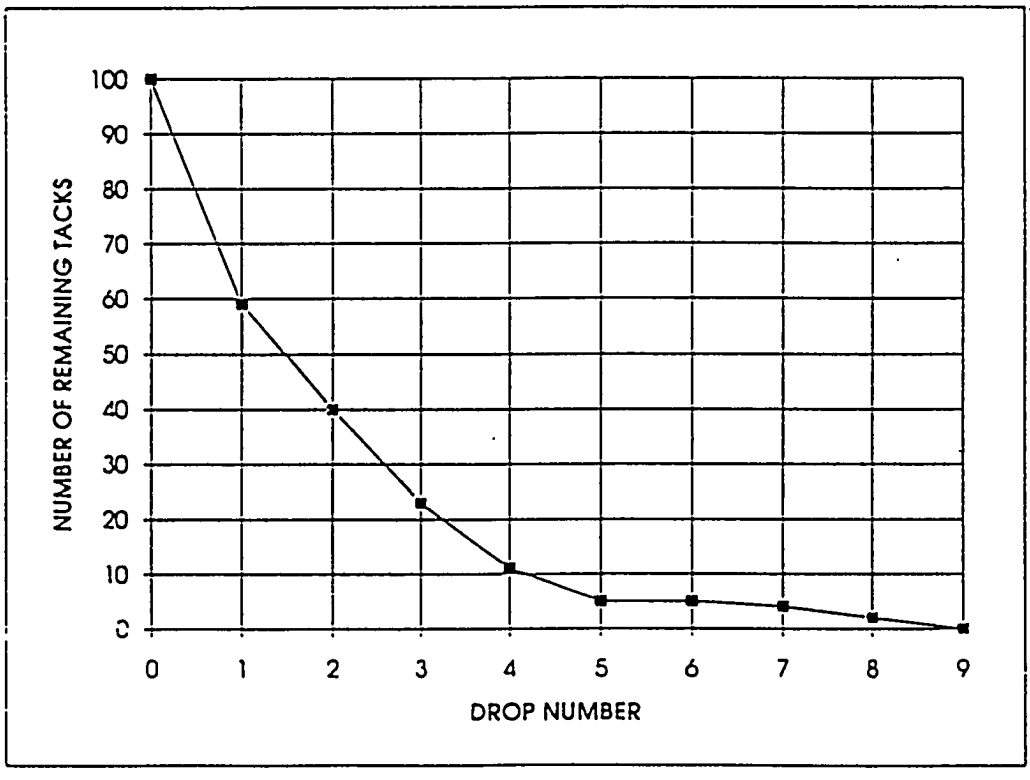
COMPARE THE DROPPING OF THE TACKS TO THE DECAY OF A RADIOACTIVE MATERIAL

CORRESPONDENCES -

TACKS IN HAND	-	PARENT
DROPPING TACKS	-	DECAY
TACKS ON SIDE	-	PROGENY
DROPPING TACKS PROCEEDS UNTIL ALL TACKS ARE ON THEIR SIDES	-	DECAY CONTINUES UNTIL PARENT IS ENTIRELY CHANGED INTO ITS PROGENY

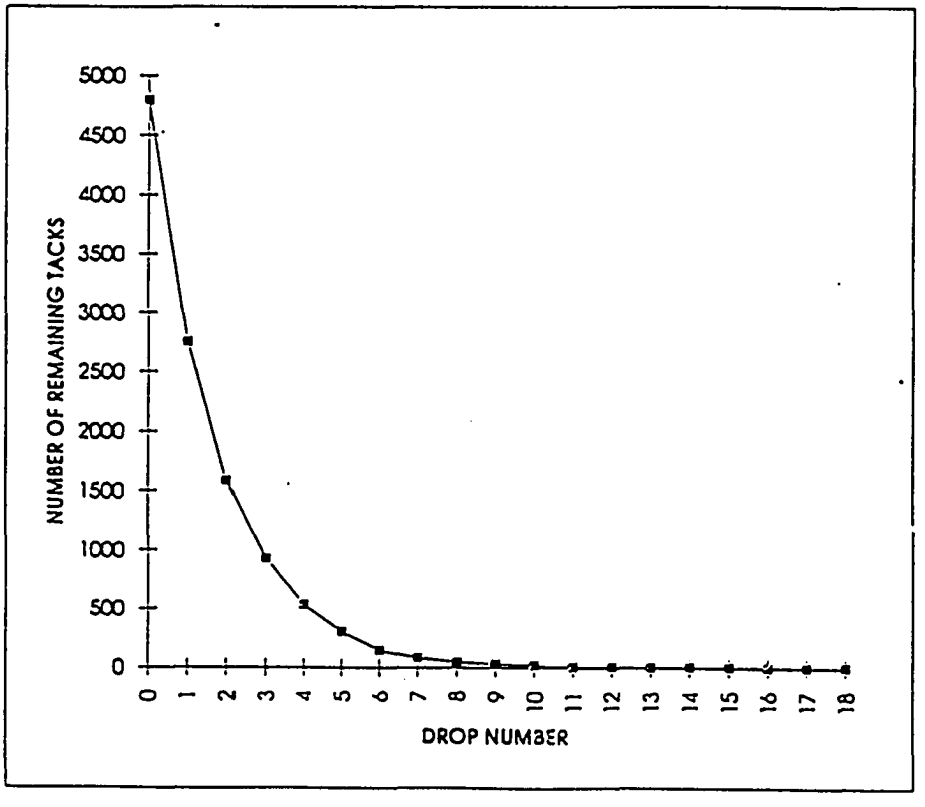
FALLING TACKS: HALF-LIFE PLOT, PARTICIPANT #1

DROP NUMBER	NUMBER OF REMAINING TACKS	NUMBER OF TACKS ON THEIR SIDES PER DROP	CUMULATIVE NUMBER OF TACKS ON THEIR SIDES
0	100	0	0
1	59	41	41
2	40	19	60
3	23	17	77
4	11	12	89
5	5	6	95
6	5	0	95
7	4	1	96
8	2	2	98
9	0	2	100



FALLING TACKS: HALF-LIFE PLOT, SUMMED DATA

DROP NUMBER	NUMBER OF REMAINING TACKS	NUMBER OF TACKS ON THEIR SIDES PER DROP	CUMULATIVE NUMBER OF TACKS ON THEIR SIDES
0	4800	0	0
1	2750	2050	2050
2	1584	1166	3216
3	922	662	3878
4	529	393	4271
5	300	229	4500
6	146	154	4654
7	81	65	4719
8	48	33	4752
9	29	19	4771
10	21	8	4779
11	11	10	4789
12	7	4	4793
13	6	1	4794
14	5	1	4795
15	2	3	4798
16	1	1	4799
17	1	0	4799
18	0	1	4800



FALLING TACKS: HALF-LIFE PLOT, SUMMED DATA

DROP NUMBER	NUMBER OF REMAINING TACKS	NUMBER OF TACKS ON THEIR SIDES PER DROP	CUMULATIVE NUMBER OF TACKS ON THEIR SIDES
0	4800	0	0
1	2750	2050	2050
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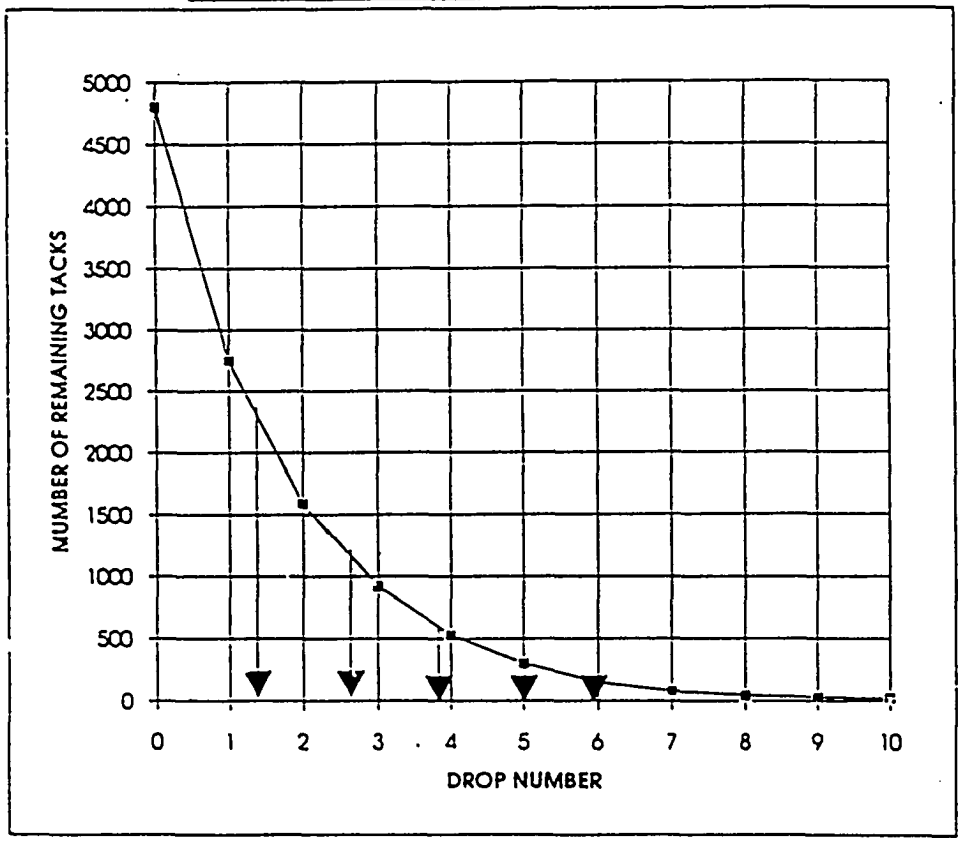
3	922	662	3878
4	529	393	4271
5	300	229	4500
6	146	154	4654
7	81	65	4719
8	48	33	4752
9	29	19	4771
10	21	8	4779

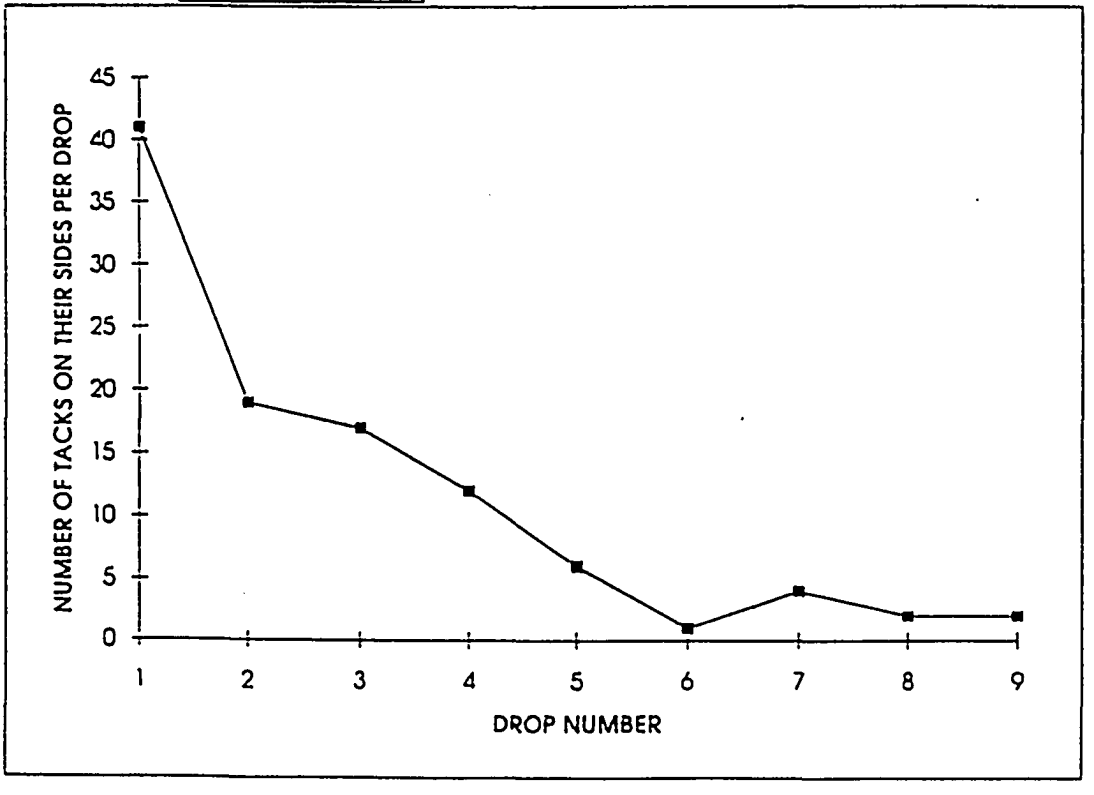


CORRESPONDENCES -

AMOUNT OF TIME REQUIRED FOR 1/2 TACKS TO FALL ON THEIR SIDES	-	HALFLIFE
AMOUNT OF TIME REQUIRED FOR 1/2 TACKS TO FALL ON THEIR SIDES SIDES IF THE SAME REGARDLESS OF THE NUMBER OF TACKS THAT HAVE ALREADY BEEN DROPPED		HALFLIFE IS A CONSTANT

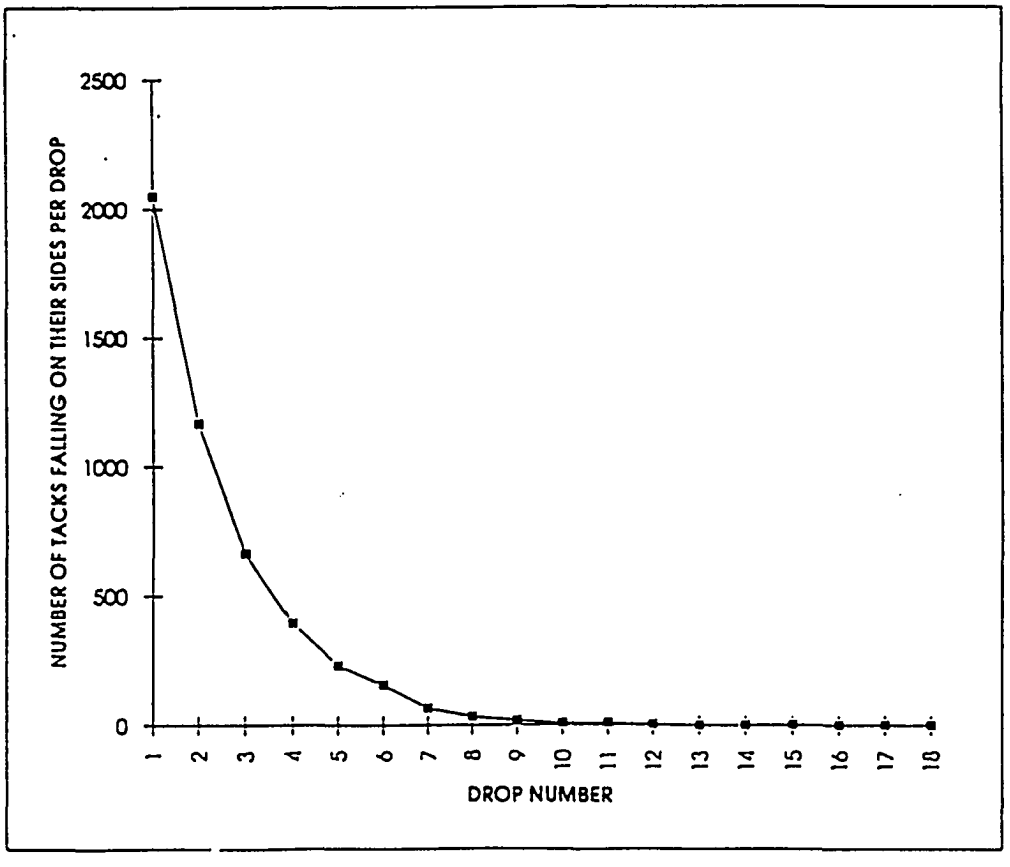
FALLING TACKS: ACTIVITY PLOT, PARTICIPANT #1

DROP NUMBER	NUMBER OF TACKS ON THEIR SIDES PER DROP	NUMBER OF REMAINING TACKS	CUMULATIVE NUMBER OF TACKS ON THEIR SIDES
0	0	100	0
1	41	59	41
2	19	40	60
3	17	23	77
4	12	11	89
5	6	5	95
6	1	5	95
7	4	4	96
8	2	2	98
9	2	0	100



FALLING TACKS:ACTIVITY PLOT, SUMMED DATA

DROP NUMBER	NUMBER OF TACKS ON THEIR SIDES PER DROP	NUMBER OF REMAINING TACKS	CUMULATIVE NUMBER OF TACKS ON THEIR SIDES
0	0	4800	0
1	2050	2750	2050
2	1166	1584	3216
3	662	922	3878
4	393	529	4271
5	229	300	4500
6	154	146	4654
7	65	81	4719
8	33	48	4752
9	19	29	4771
10	8	21	4779
11	10	11	4789
12	4	7	4793
13	1	6	4794
14	1	5	4795
15	3	2	4798
16	1	1	4799
17	0	1	4799
18	1	0	4800



CORRESPONDENCES -

NUMBER OF TACKS FALLING ON THEIR SIDES PER DROP	-	ACTIVITY
NUMBER OF TACKS FALLING ON THEIR SIDES PER DROP DECREASES WITH SUBSEQUENT DROPS	-	ACTIVITY DECREASES AS DECAY PROCEEDS FOR A SINGLE STEP DECAY

NON-CORRESPONDENCES

FALLING TACKS	RADIOACTIVE MATERIAL
TACKS ARE ALWAYS THE SAME SUBSTANCE	PARENT AND PROGENY ARE DIFFERENT MATERIALS

CORRESPONDENCES

MELTING-ICE	FALLING TACKS	RADIOACTIVE MATERIAL
ICE	TACKS IN HAND	PARENT MATERIAL
MELTING	DROPPING TACKS	DECAY
MELT-WATER	TACKS ON SIDES	PROGENY MATERIAL
MELTING CONTINUES UNTIL ALL ICE BECOMES MELTWATER	DROPPING CONTINUES UNTIL ALL TACKS ARE ON THEIR SIDES	DECAY CONTINUES UNTIL PARENT IS ENTIRELY CHANGED INTO ITS PROGENY
	ALL TACKS HAVE AN EQUAL PROBABILITY OF FALLING ON THEIR SIDES	ALL PARENT NUCLEI HAVE AN EQUAL PROBABILITY OF DECAYING
AMOUNT OF TIME REQUIRED FOR 1/2 ICE TO MELT	AMOUNT OF TIME REQUIRED FOR 1/2 OF THE TACKS TO FALL ON THEIR SIDES	HALF-LIFE
AMOUNT OF TIME REQUIRED FOR 1/2 OF REMAINING ICE TO MELT IS THE SAME REGARDLESS OF THE EXTENT OF MELTING	AMOUNT OF TIME REQUIRED FOR 1/2 OF THE TACKS TO FALL ON THEIR SIDES IS THE SAME REGARDLESS OF THE NUMBER OF TACKS THAT HAVE ALREADY BEEN DROPPED	HALF-LIFE IS A CONSTANT
AMOUNT OF MELT-WATER PRODUCED EVERY 30 MINUTES	NUMBER OF TACKS FALLING ON THEIR SIDES PER DROP	ACTIVITY
AMOUNT OF MELT-WATER PRODUCED EVERY 30 MINUTES DECREASES AS MELTING PROCEEDS	NUMBER OF TACKS FALLING ON THEIR SIDES PER DROP DECREASES WITH SUBSEQUENT DROPS	ACTIVITY DECREASES AS DECAY PROCEEDS(FOR A SINGLE STEP DECAY)
THE MORE ICE PRESENT, THE GREATER THE AMOUNT OF MELT-WATER PRODUCED	THE MORE TACKS REMAINING, THE GREATER THE NUMBER OF TACKS FALLING ON THEIR SIDES DURING THAT DROP	THE MORE PARENT MATERIAL PRESENT, THE GREATER THE ACTIVITY

Appendix F

Pre- and Post-Interview Interpretations

Interview Interpretation Codes:
R - Researcher
L - Learner
. . . - pause, one . per second
(??) - unintelligible
[ ] - researcher comments enclosed in brackets

Nucleus-one Concept:

Felix's interviews (Nucleus-one Concept)

Felix's pre-interview: (Nucleus-one Concept)

During the pre-interview, Felix expressed intelligibility for this concept when he made the statements "Decomposition at the atomic . . of the material" (I-t) and "It probably comes from the core" (I-t) when answering a question about the origin of radiation. Felix made no plausibility or fruitfulness statements for this concept.

Thus, prior to the lesson, Felix possessed intelligibility for this concept. His plausibility and fruitfulness were unknown.

Felix's post-interview: (Nucleus-one Concept)

During the post-interview, Felix spontaneously made the statement "And . the energy . . is de caused by the decomposition of the material due to nuclei or whatever flying around in there. Splitting the atoms apart." (I-t,P-r) Later in the interview, when asked to describe the process of radioactive material decay, he said "mass have been hit by particles and changed to a different material. To a different element. Because you've changed the atomic structure of it." (I-t,P-r) These statements revealed that although Felix had an understanding of radioactive material decay that was an alternative to the accepted scientific conception, he still understood that decay was a nuclear event. Thus, he possessed intelligibility for the Nucleus-one concept.

Along with the above statements, which also fit into the real mechanism plausibility category, when describing how radioactive decay occurs, Felix stated that "Ok. So it's

dependent on being hit by something given off by another atom." (P-r) Thus, Felix possessed plausibility for the Nucleus-one concept.

During the post-interview, no fruitfulness condition statements were made. Thus, the fruitfulness was unknown.

Felix's status changes: (Nucleus-one Concept)

The pre-interview status for this concept was I, unknown P, and unknown F. During the post-interview, Felix demonstrated the status of I, P and unknown F. Thus, no change in status between the pre- and post-interviews was detected.

Mark's interviews: (Nucleus-one Concept)

Mark's pre-interview: (Nucleus-one Concept)

In the pre-interview when Mark was asked where radiation came from, he replied "Um . . . . well those are, they're part of the . . the basic struc the atomic structure of the material." (I-t) He was then asked by the researcher where in the atomic structure radiation came from. He replied "Well, electrons would be like in the outer shell. And and it's, I guess some of them give off neutrons. I'm not sure if that's alpha radiation or what. But in the in the center, the middle." (I-t) These statements revealed that Mark understood that during radioactive material decay, neutron radiation is emitted from the "the center, the middle" of the atom. But he thought that electron radiation was emitted from the electronic layers of the atom. Because Mark had an internal representation of radiation being emitted from the nucleus, he demonstrated intelligibility for the Nucleus-one concept. When explaining where he thought neutrons originated from in the atomic structure, Mark commented "Besides I'm not sure . . if the new . discoveries of all the particles now-a-days, and quarks, and all those sorts of things, and I'm sure they all (??)

(??)." (P-o) Through this statement and the above statement concerning electron (Beta) radiation, Mark demonstrated that he was not totally convinced of the nuclear origin of radioactive material decay. Thus, he exhibited developing plausibility for this concept.

No statements were made concerning the usefulness of knowledge concerning the Nuclear-1 concept. Thus, Mark's pre-interview fruitfulness for this concept was unknown.

Mark's post-interview: (Nucleus-one Concept)

While filling out his post-interview work sheet, Mark stated "To indicated that I've changed from . one material to another. . . ah because I've . . changed the actual structure of the nucleus of that material." (I-t;P-r) A little later in the interview, the researcher asked why the learner believed his understanding of radioactive material decay. During Mark's response, he stated "I guess because of the definition of . a an an element . . has to do with the content of the nucleus of an atom. And the emitting material from the nucleus of an atom." (I-t;P-o,r) These statements revealed that Mark possessed intelligibility and plausibility for concept Nucleus-one. Since no other post-interview statements were made concerning this concept, his fruitfulness is unknown.

Mark's status changes: (Nucleus-one Concept)

Marks pre-interview status for this concept was I, developing P, and unknown F. His post-interview status was I, P and unknown F. Thus, Mark's status increased because he gained confidence in his understanding that radioactive material decay involves nuclear changes. Mark's believability in the concept that radioactive material decay is a nuclear event increased.

Edgar's interviews: (Nucleus-one Concept)

Edgar's pre-interview: (Nucleus-one Concept)

Edgar made no statements concerning the fact that radioactive material decay is a nuclear event. Thus his intelligibility, plausibility, and fruitfulness are unknown.

Edgar's post-interview: (Nucleus-one Concept)

During the interview, the researcher asked Edgar if the alpha, beta, and gamma radiation that he had mentioned came from any particular portion of the source. In response, the learner said "No." (I-d) This indicated that Edgar did not have an understanding of the concept N-1. Since no other statements concerning this concept were made, Edgar's plausibility and fruitfulness are unknown.

Edgar's status change: (Nucleus-one Concept)

Edgar's pre-interview status was unknown. His post interview status was no I, unknown P, and unknown F. Thus, his change in status is unknown.

Fred's interviews: (Nucleus-one Concept)

Fred's pre-interview: (Nucleus-one Concept)

When filling out the work sheet, Fred commented

> For uranium 235 . .it's part of the . um the nucleus that's coming out, I think. Gosh, it's been a long time. And the actual physical . . size of the chunk of of metal . wouldn't change . as far as I understand. I mean, I still have the same size. I may be actually changing its. atomic number. (I-e,t;P-r)

A little later in this process, the learner, when talking about the nature of radioactivity, commented "It's gotta be . actually probably either a proton or neutron coming out of from the nucleus." (I-t;P-r) A little later in the interview, the researcher asked Fred to describe the process of radioactive material decay. During his answer, the learner commented:

> I I think it's from the the ah the nucleus. Ya . . a part of itself actually. Cause if if I'm dropping atomic mass, my electrons are not . . heavy enough to significantly affect that. So it's gotta be a neutron or a proton coming out of the mass, out of the nucleus . nuclear material. So, it's an emission of . one of those . . from the nucleus . nuclear material. (I-t;P-r,o)

These statements revealed that Fred had intelligibility and plausibility for the Nucleus-one concept. Since no other comments concerning this concept were made by Fred, his fruitfulness is unknown.

Fred's post-interview: (Nucleus-one Concept)

While filling out column one of the work sheet, Fred commented "Um if I'm losing a proton or a neutron out of the nucleus . . I'm changing the mass." (I-t;P-r) When the researcher asked Fred to describe the meaning of the term radiation, the learner responded "Radiation is the . um . emitting of . . a particle . from the the center of the nucleus." (I-t;P-r) A little later in the interview, Fred was asked the meaning of the term activity. During his answer, the learner commented "The decay is um . . . . the loss of . . a . . part of the nucleus . when it is emitted." (I-t;P-r) These statements revealed that Fred had intelligibility and plausibility for the Nucleus-one concept.

Since no other statements pertaining to this concept were made, Fred's fruitfulness is unknown.

Fred's status change: (Nucleus-one Concept)

During the pre-interview and post-interview, Fred possessed the status of I, P, and unknown F for the Nucleus-one concept. Thus, no change in status was detected.

Wilbur's interviews: (Nucleus-one Concept)

Wilbur's pre-interview: (Nucleus-one Concept)

When Wilbur was asked where radiation came from, he responded "From the atom." (I-t) When then asked if it came from any particular part of the atom, he responded ". . . . I would say the atom in general. I I I guess I don't know, don't know that much about the ah atomic ah ah (??). I I .. I've lost that." (I-d) These statements indicated that Wilbur did not understand that radioactive material decay is a nuclear process. He thought it to be a process that possibly involves the atom in general. Thus, he demonstrated no intelligibility for the Nuclear-1 concept. Since no other pertinent statements were made by Fred, his plausibility and fruitfulness for this concept are unknown.

Wilbur's post-interview: (Nucleus-one Concept)

While filling out the work sheet, Wilbur commented "Well the the ah . . the radiation that comes out in the . . alpha . beta . gamma . radiation that comes out. So the the ah I guess the nucleus is changed a little bit." (I-t) A little later in the interview, Wilbur was asked what the product was for the emission of alpha particles. He responded "Well you you ya . you'd wind up with different substances if it you're losing the ah . . part of the core. Ah the ah protons from the core." (I-t,P-r) A little later, the researcher asked Wilbur from where the radiation was emitted. The learner responded "From the the nucleus that . . going from unstable to ah . . I guess the lower energy level." (I-t) These statements revealed that Wilbur understood that radiation was emitted from the nucleus. The plausibility feature also indicated that he believed his understanding to be true. Thus, he possessed intelligibility and plausibility for the Nucleus-one concept.

Wilbur made no statements concerning the usefulness of his understanding of the Nucleus-one concept. Thus, his fruitfulness is unknown.

Wilbur's status change: (Nucleus-one Concept)

During the pre-interview, Wilbur exhibited the status of no I, unknown P, and unknown F. His post-interview status was I, P, and unknown F. Thus his status increased. The increase occurred because Wilbur exchanged (conceptual exchange) the information that radioactive material decay involved the emission of radiation from the nucleus rather that from the atom in general.

Jennifer's interviews: (Nucleus-one Concept)

Jennifer's pre-interview: (Nucleus-one Concept)

Jennifer made no statements that related to the Nucleus-one concept. Thus, her status was unknown I, unknown P, and unknown F.

Jennifer's post-interview: (Nucleus-one Concept)

During the interview, Jennifer mentioned that the exposure that one gets from a radioactive material is composed of "whatever particles the substance is giving off . that are radioactive". (I-t) When the researcher asked Jennifer where the particles came from, she responded "I I don't know precisely to be honest." (I-d) This statement revealed that Jennifer did not have an understanding that radiation was emitted form the nucleus of the atom. Thus, she possessed no intelligibility for the Nucleus-one concept. Since no other pertinent comments were spoken, her plausibility and fruitfulness are unknown.

Jennifer's status change: (Nucleus-one Concept)

Jennifer's pre-interview status was unknown I, unknown P, and unknown F. Her post-interview status was no I, unknown P, and unknown F. Since here pre-interview intelligibility is unknown, no change in the intelligibility condition could be detected. Since her pre- and post-interview plausibility and fruitfulness conditions are unknown, no

change in these conditions could be detected. Thus, her change in status is unknown.

Florence's interviews: (Nucleus-one Concept)

Florence's pre-interview: (Nucleus-one Concept)

During the pre-interview, Florence made no comments concerning the Nucleus-one concept. Thus, her status for this concept is unknown.

Florence's post-interview: (Nucleus-one Concept)

The learner made no comments relating to the Nucleus-one concept. Thus her status is unknown.

Florence's status change: (Nucleus-one Concept)

During the pre- and post-interviews, Florence's status were unknown. Thus, no change in status was detected.

Ralph's interviews: (Nucleus-one Concept)

Ralph's pre-interview: (Nucleus-one Concept)

During the interview, the researcher asked Ralph why the radioactive material was disappearing. During his response, Ralph commented "Um . they're . emitted from the nucleus of the atom." (I-t) And ". have the . you have a beta emission. Which is . an electron is ejected from the . nucleus . of an atom." (I-t;P-r) A little later, Ralph was asked from where the particles that came off during radioactive material decay originated. Ralph replied "Ok. Um . . well there is . . . . . the the particles . . they always come from . the nucleus . of the atom." (I-t) These statements revealed that Ralph had the understanding that radioactive material decay was a nuclear event. Therefore, he

demonstrated intelligibility for the Nucleus-one concept. He also demonstrated plausibility by the use of a statement within the real mechanism category. Since no other pertinent comments were made, Ralph's fruitfulness is unknown.

Ralph's post-interview: (Nucleus-one Concept)

When filling out the work sheet, Ralph commented "Ya the . . (clears throat) . ah the substance decays. It changes into . some other element . or a couple of different . or . not even a couple, but different kinds of elements, by emitting particles . from it's nucleus." (I-t;P-r) This statement revealed that Ralph understood and believed that radioactive decay was a nuclear event. Thus, he demonstrated intelligibility and plausibility for this concept.

Ralph made no fruitfulness comments relating to this concept. Thus, his fruitfulness is unknown.

Ralph's status change: (Nucleus-one Concept)

Ralph's pre-interview status was I, P, and unknown F. His post-interview status was I, P, and unknown F. Thus, no status change was detected.

Decay-one Concept:

Margaret's interviews (Decay-one Concept)

Margaret's pre-interview: (Decay-one Concept)

During the pre-interview, Margaret demonstrated no intelligibility for this concept. She made a comment that "I'll say it disintegrates. It gets smaller." (I-t) When asked if she knew the meaning of the terms parent and progeny material, Margaret made the direct category comment "No." (I-d) Thus, Margaret demonstrated that she had no mental representation that the parent material changed into some other material. She also had no

understanding of the meanings of the terms parent and progeny.

Margaret made several comments indicating that she did not find her understanding of this concept to be plausible. She frequently made comments such as "Because I have no idea" (P-d) and " I really can't, no idea." (P-d) When asked if she thought that her idea that the material disintegrates had the potential to be true, Margaret made this comment.

> Probably not. Because I real, I'm just guessing at the ah it's either gonna get bigger, stay the same, or it's or it's get smaller. And I just picked that one out. I really . I'm just waiting for your course. (P-d)

Thus, she did not have plausibility for her understanding of the concept.

When asked if she could see any usefulness to knowing how a radioactive material would change over time, Margaret made this comment.

> Well, it would certainly be useful here for anybody here who tends to work . with radioactive material. Obviously, the labs must do it. I don't think there's anybody in our lab. But um I'm sure you must somewhere or we wouldn't have our radio . we wouldn't have you teaching us. (F-e)

Thus she saw that the concept was associated with the researcher, whom she recognized as an expert in radiation science. However, she did not give any specific examples of the usefulness of the concept, she just recognized that if one had an understanding of this concept, that knowledge would be useful. Thus, she demonstrated no fruitfulness.

Margaret's post-interview: (Decay-one Concept)

During the post-interview, Margaret demonstrated that she understood that during radioactive material decay, one substance changes into another substance and that this process is referred to as decay. She also spontaneously used the terms parent and progeny correctly. These assertions are illustrated by these two statements: "Um it would

decay and most likely it would . transform into another element when it when it during the decaying process." (I-t) and "it would go from the parent to the progeny and this would be the result of the . . this would be the the progeny." (I-t) Thus, she demonstrated intelligibility for concept Decay-one.

The learner also demonstrated plausibility for this concept. This is illustrated by putting four closely spaced and related sections of her dialogue together: "Ok I'm going to use the same concept you used in the safety meeting. This [referring to start position of column one] will be a block of ice", "And . ah . . let's say it's . . . it's it's decayed. . . I'm . my parent my parent material is now down in half.", "I assume my progeny . . . would escape down melting and decaying . the the progeny would be . . . sitting around the dish I guess.", and "it would have decayed into another form which would be the water that would have been left." (P-a)

Margaret made a statement with both extrinsic and power category components, to demonstrate that she had acquired initial fruitfulness for her conception of radioactive material decay.

> I guess the main thing would be working you know in the . the lab. The lab and like you do um . . there's obviously must be materials that you work with that you'd have to be very careful. That they could possibly be decaying into something that might be harmful to you, for one thing. Both the, both, both . things . could be harmful I guess. If this was full of radioactive material. (F-e,p)

This statement revealed that the learner had developing fruitfulness because she gave an example of the usefulness of her knowledge.

Margaret's status changes: (Decay-one Concept)

The comparison of the pre- and post-interviews revealed that Margaret's status changed from no I, no P, no F to a status of I, P and developing F. Therefore two conditions of Margaret's status increased for this concept after she attended the analogy-

based lesson. In undergoing this status change, Margaret experienced conceptual capture. This is because she added additional information to her understanding of concept Decay-one, but she did not have to become dissatisfied with or reject any of her previous knowledge.

Mark's interviews: (Decay-one concept)

Mark's pre-interview: (Decay-one concept)

While Mark was completing his pre-interview work sheet, he commented "But I don't think it would change in terms of the size ah . . of the material. ah . but I guess it would change in terms of the nature of the material that's there." (I-t) A little later, still in this same response, he stated "as the . . radioactive material decays, then it's getting smaller . . . . . and it's also changing . in nature to a different material." (I-t) A little later in the interview, Mark was asked by the researcher to clarify where the initial substance was when the decay process was completed. He replied "Um . . that is ah because . . you've given up, (clears throat) you've given off the radiation, um, it's kind of changed into another material." (I-t;P-r) These statements revealed that Mark understood that a radioactive material changes into a different material during the decay process. When asked if he thought his understanding of how a radioactive material changes was true, Mark responded

> After a hundred percent radioac active decay, . . you have . . it is different. Because it's not decaying anymore. So I'm a hundred percent sure of that. If it was the same as it was before, it'd be ra radiation. And it's no longer radiating." (P-d,o)

This statement, along with the plausibility feature of a preceding statement, revealed that Mark found his understanding that a radioactive material changes into a different material to be believable.

When asked to define the words parent and progeny, Mark replied

> Um-ah . . . . . possibly the parent material, that's just the material you're starting with . ah I'm not real . . . . I suppose the various . . . ah . . . . the progeny might be the radioactivity itself. But I I've really never heard those terms. I've never heard those terms in relation to radioactivity. (I-d,t)

This statement revealed that Mark understood what parent was, but he did not understand the term progeny. Also, his believability in his understandings was low.

Mark understood that radioactive material decay involved a change from one substance into another substance. He also understood the meaning of the term parent. However, he did not understand the meaning of the term progeny. Therefore, he demonstrated developing intelligibility for concept Decay-one. Mark had believability in his idea that a radioactive material changes into a different material. But, he had low believability in his understanding of the terms parent and progeny. Thus, he demonstrated developing plausibility for this concept.

When the researcher asked Mark if he found his knowledge about how a radioactive material changes to be useful, he replied

> . . . . . Ya in in all sorts of senses. I mean . . however it's being used or applied or . . um . . ya have to know that it's not . . not constant. And they're all sorts of practical implications to that. If it's being used . . if it's being used for a particular purpose, then you have to know that it's not a forever thing. If it's a waste product, then you know, you have to know that . it's not gonna stay the same. (F-p,r)

This statement revealed that the learner thought that an understanding of the concept had "all sorts of practical implications", and he was able to state one. Thus, he demonstrated developing fruitfulness for this concept.

Mark's post-interview: (Decay-one Concept)

During the post-interview, while filling out the work sheet, Mark commented "And just gonna draw . a red . mass of material. . . and . all the way down at the bottom . . I will draw a a blue mass. About the same size. . . . . To indicate that I've changed from . one material to another." (I-i,t) When asked to describe the process of radioactive material decay, the learner responded "That's the emission of . either alpha, beta, or gamma rays . from a material. It . um . results in a change that material to another material. Parent to the progeny." (I-t;P-r) These statements revealed that Mark possessed intelligibility for concept Decay-one.

When Mark was talking about the correspondences between the melting-ice analogy and radioactive material decay, the researcher asked him what had changed about his knowledge as a result of the lesson. He commented "But . . and I guess I wasn't totally sure . that . . you were going from one element to another element. You know that you were actually changing materials. Um when we were decaying. Um . so . . . so those are two two areas then." (P-d) The plausibility features of Mark's statements revealed that he possessed plausibility for the Decay-one concept.

Mark gave no comments concerning the usefulness of his understanding of concept Decay-one. Thus, he possessed unknown fruitfulness.

Mark's status changes: (Decay-one Concept)

During the pre-interview, Mark exhibited a status of developing I, developing P, and developing F. During the post-interview, Mark demonstrated a status of I, P, and unknown F. Thus, he experienced an increase in status, at least for the first two conditions. The reason for the increase was that he developed understanding of the term progeny and a believability in his understanding. This was an example of conceptual

capture. This is because additional information was added to his conceptual ecology relative to concept Decay-one. No dissatisfaction with and replacement of prior knowledge was necessary.

Edgar's interviews: (Decay-one concept)

Edgar's pre-interview: (Decay-one Concept)

While filling out the work sheet, Edgar commented "Ok . . . . . now, ah, radium decays . . into . . . . . radon . . . . . which is a gas." (I-e,t) A little later, while still filling out the work sheet, he said "Um hu . radon then decays into . . think it decays, it goes into thorium . . . and then finally it goes into . . bismuth." (I-e,t) A little later in the interview, the researcher asked Edgar to explain the meaning of the term radiation. In his response, Edgar commented "Ok a . radioactive material, such as ah uranium . starts out with a certain amount of . natural radioactivity . . over a course of time ah . . that is lost and the material changes its form. It's chemistry . . to where uranium eventually becomes . lead." (I-e,t) When asked the meaning of the term parent, the learner responded ". . . Um . . . . I have and . . a little foggy, but I believe that is what is used to . . a parent. A . a parent material . is used to make another form of radioactive material. . . Such as uranium . . being processed into plutonium." (I-e,t) When asked the meaning of the term progeny, Edgar responded "Progeny?" He also indicated with his body language that he did not know the meaning of this term. These statements revealed that Edgar understood that a radioactive material changes into a different material. He also understood the meaning of the term parent, but he did not understand the meaning of the term progeny. Thus, he demonstrated developing intelligibility for the Decay-one concept.

When the researcher asked Edgar if he believed that his ideas about radioactive material decay were true, he responded "Ah yes a . . radioactive material would form at

the beginning of . when the earth was formed . . and over a period of time radioactive radioactive material loses its radioactivity. . Uranium becomes lead, . . radium becomes bismuth, . so on and so forth." (P-d,o) A little later in the interview, Edgar was asked if he found his column two work-sheet response to be true. During his response, he commented "Um . . . as the . . material changes . and becomes something else . . ah, it slowly loses its radioactivity" (P-o) These statements revealed that Edgar believed his ideas about radioactive material changes were true. However, because he only possessed developing intelligibility for this concept, his plausibility is also developing.

When asked if he found his ideas about radioactive material decay to be useful, Edgar responded

> Well yes because um . as you know radon is a ah big issue in ah . in this area . because of a . the . a . a belt of . radioactive material . that is under a lot of housing developments. So, knowing where the . . ah . . radioactive belts are, you might be able to predict where radon would occur . and hence, either ah (laughs) move or monitor your house . to check for radon. (F-p)

Edgar could give an example of the usefulness of his understanding of radioactive material decay. Thus, he possessed developing fruitfulness for this concept.

Edgar's post-interview: (Decay-one Concept)

While completing the work sheet, Edgar commented "Well, one of the decay, one of the decay . materials. for example radium decays into radon." (I-e) Later in the interview, when asked to describe the process of radioactive material decay, Edgar responded "It is the . . . is is what happens to a radioactive material over a period of thousands of years . in that it changes its . . . level of radioactivity . and in true fact changes its physical form also. (I-t;P-o) Later in the interview Edgar was asked if he remembered any of the correspondences between the melting-ice analogy and radioactive material decay. In response, Edgar commented ". . Um . . yes that is . ice melts . . ah, it changes form . . um .

as radioactive materials do." (I-a,t;P-l,a) When asked the meaning of the term parent, Edgar responded "Parent material is the original material." When asked the meaning of the term progeny, Edgar responded "The progeny is, ah, . the material . left at the end of the process of radioactive decay." These statements revealed that Edgar possessed intelligibility and plausibility for the Decay-one concept.

When asked if his understanding of radioactive material decay was useful information to have, Edgar responded

> Um (??) curiosity, that's about it. It's also interesting in that ah in the area that we all live in, ah, radon gas is become a um, rather interesting um part of where we live, where some of us live. And I think it's good to have some basic knowledge of . what that means . . to you personally. And um . and how it got there. (F-p)

This statement indicated that Edgar could give an example of a situation where his knowledge of radioactive material decay would be useful. Thus, he possessed developing fruitfulness for concept Decay-one.

Edgar's status change: (Decay-one Concept)

During the pre-interview, Edgar's status was developing I, developing P, and developing F. During the post-interview, his status was I, P, developing F. Thus his status for this concept increased. The increase in status was due to Edgar gaining (conceptual capture) understanding for and plausibility in his understanding of the term progeny.

Fred's interviews: (Decay-one concept)

Fred's pre-interview: (Decay-one Concept)

While filling out the work sheet, Fred made the comment "I may be actually changing its . atomic number. . Now I forget, is it . uranium ah 237 goes to 235." (I-t,e;P-r) When

filling out the "end of process" position of this work sheet, the learner commented "I have zero percent of . U 237. And at this point the whole thing would be ah . . . like I had said it we're calling it U 235 . you know ah um . would be one-hundred percent." (I-e) Later in the interview, the researcher asked Fred if he believed his column one work-sheet information was true. During his response, Fred said "Um . . . I'm not sure that I have the atomic mass numbers correct . here. As far as . . does it change atomic mass like I'm saying it does, ya, I'm pretty sure it does." (P-d) These statement demonstrated that Fred understood that during the radioactive decay process, the original material changes into a different material. He also demonstrated that he believed this understanding to be true.

At one point during the interview Fred was asked if he was aware of the term parent. He replied

> "Um . . . not really. I would assume parent would be like the 237 would be the parent of the 235. Ah what the starting material would be the parent, and probably your daughter material would be the 235, what you're left off with." (I-e;P-d)

The learner was then asked if he had heard the term progeny. Fred responded "Well ah I'm assuming it it's the material that you, after, that's left after the radioactive decay." (I-t;P-n) These statements revealed that Fred had an understanding for the terms parent and progeny, but his believability in his understanding was not strong.

The above statements indicated that Fred could mentally represent the idea that a parent material changes into a progeny material during radioactive material decay. Thus he possessed intelligibility for this concept. Because he demonstrated a degree of uncertainty in his understanding of the terms parent and progeny, he possessed developing plausibility.

Fred made no fruitfulness statements that concerned this concept. Thus, his fruitfulness is unknown.

Fred's post-interview: (Decay-one Concept)

While filling out column one of the work sheet Fred commented

> you start off with . again I still don't know which one. I didn't look it up. Either U 2 234 or U 237. And it would change to some other isotope . of uranium. I guess it doesn't necessarily have to be. Um if I'm losing a proton or a neutron out of the nucleus . . I'm changing the mass. So I could a different, I would have a different element. There is potential for that. (I-e,t;P-r)

A little later in the interview, the researcher asked Fred what happened to the original radioactive mass. Fred responded "Again, the radioactive material . degrades, it decomposes . . amidst the radioactivity. Once it's not gone, certain isotopes . . once it emits the radioactive material, it's changed to another . . . isotope." (I-t;P-r) Near the end of the interview, Fred was asked if he remembered the two analogies that were used during the lesson presentation. During Fred's response, he commented

> The one analogy was the . . dripping ice, the melting . . ice into water. . . Um . . and that was to be analogous to . . ah . the decay of radioactive materials. . In that, over a certain amount of time, it goes from the parent to progeny. Ice to water. (I-a;P-a)

When the researcher asked Fred the meaning of the term parent, he replied "Parent is the initial radioactive material". When asked the meaning of the term progeny, Fred replied "Progeny . would be the . daughter . material or what it changes into. What it decomposes or degrades to." (I-t) These statements revealed that Fred understood that the original radioactive material changed into a different material and he understood the terms parent and progeny. He also expressed plausibility for his understanding. Thus, he possessed intelligibility and plausibility for this concept.

Fred did not make any statements indicating if he found his knowledge of concept Decay-one to be useful. Thus, his fruitfulness is unknown.

Fred's status change: (Decay-one Concept)

During the pre-interview Fred's status was I, developing P, and unknown F. His post-interview status was I, P, and unknown F. Thus, his status increased. This change in status was due to an increase in the plausibility that Fred had for his understanding of the terms parent and progeny.

Wilbur's interviews: (Decay-one Concept)

Wilbur's pre-interview: (Decay-one Concept)

When the researcher asked Wilbur what the material on the dish would look like after all changes were completed, the learner responded:

> Well ah for ah for all intensive purposes, once it gets down to a certain level and it's ah giving us noise, it's still krypton. It may be oth other ah other . . isotopes, or whatever, ah ah . ah that that ah bah evolve . in in the ah . disintegration of the radioactive . phase. So that ah . . ah . I don't think it would change completely to the next . next lower ah ah element. Well it ah . still most mostly ah krypton. Minus some ah ah . I don't know what it ah ah . an electron, or what whatever is is in the molecule. (I-e,t;P-o,r)

A little later in the interview, the researcher again asked what the material on the dish would look like at the end of the process. In response, Wilbur said "I don't know. . I don't know if if it's gonna be end . you know the end of time, or a million years, or in some cases it may ah . may be pretty quick to change into ah . another element." (I-t) Later in the interview, Fred was asked to describe the process of radioactive material decay. He responded:

> Well ah ah ah I know a mat goes through ah . . stages I think of decay. ah I think where where it gives, takes, . gives off a certain . . electron. Or something gets it reaches another state. Which maybe still ah . ah active. In which another . some other change happens. So . you might have different . tah . stages. And ah different rates to get to each case. (I-t;P-r)

These statements revealed that Wilbur understood that during radioactive material decay, the original material changes into something else, another isotope or a different element. At one point, he did mention that the change may be to a different "state" of the original substance. However, this does not diminish the fact that he could mentally represent the idea of a change to a different substance during the decay process. When asked the meaning of the term parent, Wilbur responded "No I don't think I've heard that that term." (I-d) When asked the meaning of the term progeny, Wilbur responded "Progeny. No I haven't heard that term either." (I-d). These statements indicated that Wilbur understood that the original material changes into something else, but he did not have an understanding of the terms parent and progeny. Thus, he exhibited developing intelligibility for the Decay-one concept.

When asked if he believed his column one information to be true, Wilbur responded "Ya I believe that that's true." (P-d) The researcher then asked why and Wilbur responded: .

> Well just from from ah my past education. And just from reading ah . . um . you know like ah . . things related to radioactivity. Whether it's news or magazine articles. Ah . . the on the only . the only thing . . . . . oh I I even there I I kind of doubt it. I thought there might be some cases where something would . . would change . state . . from ah but I can't see it. Radon is a is a is supposed to be a gas, right? And it still stays a gas. I think even . . so ah . I I think I could, I still stand by what I said before. (P-u,o)

This statement indicated that Wilbur believed his understanding that the original radioactive material changes into something else, but he was not sure what it changes into. However, he did display plausibility for his understanding that the decay process involves a change into something different. Because this constitutes plausibility for only a portion of the Decay-one concept, it equates into a developing plausibility for the entire concept.

Wilbur made no statements concerning the usefulness of the Decay-one concept

information. Thus, he demonstrated unknown fruitfulness for this concept.

Wilbur's post-interview: (Decay-one Concept)

When filling out the work sheet, Wilbur commented "I and a (??) like I said if an alpha particle comes out, then the . the atomic number changes a little bit." (I-t;P-r) and "Well it's changing. Ah er as you might see, you go from . parent to progeny. But I guess that the progeny . the proportion of the progeny is increasing. And ah the proportion of the . . parent is decreasing." (I-t) When the researcher asked Wilbur what would be the product when the radioactive material gave of alpha particles, Wilbur responded "Well you you ya . you'd wind up with different substances if it you're losing the ah . . part of the core. Ah the ah protons from the core." (I-t;P-r) A little later in the interview, Wilbur was asked to explain the meanings of the terms parent and progeny. He replied "Oh in in this case, the parent is the original radioactive material. And the progeny . is what happens to it after it goes through at least one stage of ah . disintegration . or coming to a a stable . ah state." (I-t) These statements indicated that Wilbur had understanding for the terms parent and progeny. He also had understanding for the parent to progeny relationship, and the fact that the progeny was a different substance that the parent. Thus, he demonstrated intelligibility for this concept. The plausibility features of the statements also showed that he had plausibility for the Decay-one concept.

Near the end of the interview, the researcher asked Wilbur if he remembered any of the correspondences between the melting-ice analogy and the radioactive material decay process. The learner responded "Ya well ya the ice is the ah parent. The water is the . the progeny." (I-a;P-a) [Plausibility inferred because his intelligibility for the Decay-one concept had already been established] The learner was also asked if he remembered what the tacks corresponded to in the falling-tacks analogy. He responded "I guess it's the

original number of of ah . of tacks . . and then ah . . ah the the ah . the position of the tacks. . . The ah . the ones on the sides were . the ones that . that kicked over. . . Those were removed." The researcher then asked what the tacks on their sides corresponded to. Wilbur replied "Well then that's that they can . you can consider that's that's the progeny. That's that's the one that . you could consider the other way to if you wanted to." (I-a;P-a) These statements are consistent with the above classification of I and P for Wilbur concerning the Decay-one concept. These statements indicated that Wilbur understood, and believed in his understanding, that the parent material changed into the progeny.

When the researcher asked Wilbur if he found the fact that a radioactive material changes into something else to be useful, he replied:

> Well for . ah only only . I suppose a lot lot of things. But to to me it's most ah . . most practical thing is a is a . dating. . . Of course it's use for . to a large extent . to date ah ah archeological digs or or ah . maybe date ah . ah . some . . geologic geological . ah . strata or something like that. Ah to find out maybe when when it ah . . originated. . . . That kind of thing. Which which I I guess could be of value to ah . . geologists maybe oil oil chemists or something. Oil oil drillers or . that sort of thing. (F-e,p)

This indicated that Wilbur thought that the products remaining in a sample could be used to determine the age of the sample by calculating the time required to go through the required parent to progeny change. Since this application required an appreciation for the Decay-one concept, he possessed developing fruitfulness for this concept.

Wilbur's status change: (Decay-one Concept)

During the pre-interview, Wilbur possessed the status of developing I, developing P, and unknown F. During the post-interview, he possessed the status of I, P, and developing F. Thus, his status increased. This change in the condition of intelligibility was due to a conceptual capture of the understanding of the meanings of the terms parent

and progeny. The change in the plausibility condition occurred because Wilbur expressed belief in his full understanding of the Decay-one concept. Because his understanding increased to the level of full intelligibility, his belief in this understanding represented full plausibility.

Jennifer's interviews: (Decay-one concept)

Jennifer's pre-interview: (Decay-one Concept)

While completing the work sheet, Jennifer made the following three comments: "I and this is what the radioactive material looks like [referring to the first intermediate position] . the same." (I-t) and

> and this is another intermediate time [referring to second intermediate position] and and I think the material stays the same. I really have no idea. But . I honestly don't know what happens to the material over time. Although I know I mean the radioactive . part decays over like . a long time (I-t;P-d)

and "Two years [referring to second intermediate position] . . . so um. I don't know. It's probably gone down some. I really don't know how it decays. . . So let's put it like less. . . This is the end. I don't know. I think it's still looks the same." (I-e,t;P-d) A little later in the interview, the researcher asked Jennifer to explain the process of radioactive material decay. She responded "Radioactive material decay. I I don't know how it works . to be honest. But it has to do with the half-life stuff. And over a period of time it decays and it's not harmful anymore." (I-t;P-d) At one point in the interview, the researcher asked Jennifer if she believed her column one information was true. She responded "Oh well I wouldn't stake my life on it or anything." (P-d) These statements revealed that Jennifer had the understanding that the radioactive material on the dish went through a decay process, a change, which eventually rendered it not harmful anymore. So she did understand that something was occurring to the material to render it innocuous.

When the researcher asked her if she knew the meaning of the terms parent and progeny, she responded "No." (I-d) Thus, Jennifer had only developing intelligibility for the Decay-one concept because she did not understand the meanings of the terms parent and progeny and she did not understand that the original material became a different material. Also, she did not have a belief that her understanding was true. Thus, she possessed no plausibility for the Decay-one concept.

Jennifer made no statements pertaining to the usefulness of her understanding of the Decay-one concept. Thus her fruitfulness was unknown.

Jennifer's post-interview: (Decay-one Concept)

When discussing Jennifer's conception that the meter dial reading decreased as the radioactive material decayed, the learner commented "It goes down I think so. Depending upon what . what's left at the end. I mean if it changes into something else that's . still radioactive" (I-t;P-o) When the researcher asked her the meaning of the term parent, she responded "That's the starting . radioactive material." When asked the meaning of the term progeny, she responded "That's what it . becomes when it's done."

During the interview, the researcher produced the correctly completed comparison work sheet for comparison with Jennifer's work sheet. While doing the column one comparison, the researcher asked which sheet Jennifer thought was more correct. Jennifer replied "Oh probably the parent and progeny one [referring to the comparison work sheet]." The researcher then asked why. To this, the learner responded "I guess cause it just shows that it goes from parent to progeny. And mine doesn't really." (I-t) Near the end of the interview, the researcher asked Jennifer what the correspondences were between the melting-ice analogy and the decay of a radioactive material. She responded "Well the . . one thing changing into another. You know the difference between the parent

and the progeny." (I-t;P-a) These statements indicated that Jennifer possessed intelligibility and plausibility for the scientifically accepted version of the Decay-one concept. These statements indicated that the learner understood the meanings of the terms parent and progeny and that she had a mental representation for the concept that radioactive material decay involves a change from one material into a different material. Thus, she possessed intelligibility for the Decay-one concept. The plausibility features of two of her statements revealed that she had plausibility for this concept. Jennifer gave no statements indicating that she recognized any usefulness to the Decay-one concept. Thus, her fruitfulness was unknown.

Jennifer's status change: (Decay-one Concept)

During the pre-interview, Jennifer possessed the status of developing I, no P, and unknown F. Her post-interview status was I, P, and unknown F. Thus, Jennifer experienced an increase in status. This change was due to the fact the learner gained an understanding of the meanings of the terms parent and progeny and plausibility for her understandings of the Decay-one concept. This change represented a conceptual capture because no concept had to be rejected.

Florence's interviews: (Decay-one Concept)

Florence's pre-interview: (Decay-one Concept)

While filling out the work sheet, Florence commented "In the year time . part of the radioactive material will be gone." (I-t) A little later in the interview, the learner was asked to verbally explain the process of radioactive material decay. Florence responded:

> . . . Decay means it's going . through a . . a loss process. And in the process this material becomes something else. And therefore release energy. . . Ya the material's gone . and ah it's . um . . . . . it becomes another like say a radioactive

element. . . . . It's some ah radioactive element. (??) three days and (??) it gives off energy and becomes a lighter . atomic number element. (I-e,t;P-r)

When asked if she know the meaning of the terms parent and progeny, Florence replied "No." (I-d) These statements revealed that Florence had an understanding that during the process of radioactive material decay, the original material changes into a different material. But, she did not have an understanding of the meaning of the terms parent and progeny. Therefore, she possessed developing intelligibility for this concept.

When asked if she believed her column one information to be true, Florence responded ". . Um . . in some situations, yes . Like . um . . yes I would say it . that's . I believe that's . actually what happens." (P-d) When then asked why she believed it to be true, she responded "I think I learned this in high school." (P-u) The learner believed that her understanding was true. Hence, she possessed developing plausibility for the Decay-one concept.

When asked if she found her column one information, that a radioactive material completely changes to a different material, to be useful, Florence responded . . . . Ah . . . I'll say it's probably useful if you know the radioactive material actually . if you got exposed to a radio . um . to the radiation, you might get harmed by that." (F-p) Since Florence was aware of an application of her column one information, she expressed developing fruitfulness for the Decay-one concept.

Florence's post-interview: (Decay-one Concept)

While filling out the work sheet, Florence made the comments "At first intermediate time ah . some of the radioactive material ah converted into ah . something else." (I-t) and "In second intermediate time will be . more material lost." (I-t) When asked to explain the meaning of the term radiation, Florence responded "Radiation is when a radioactive

material . um . going through a process. It it tells converts to something else." (I-t) When asked the meaning of the term parent, the learner responded "That would be the original . material." When asked the meaning of the term progeny, Florence replied ". The thing it become after the radiation decay." At the end of the interview, the researcher asked Florence if she remembered any of the correspondences between the falling-tacks analogy and the decay of a radioactive material. She answered "It's changing from the parent material . to something else." (I-t) These statements revealed that Florence had an understanding of the terms parent and progeny, and she understood that during radioactive material decay, the parent changed into the progeny. Thus, she demonstrated intelligibility for the Decay-one concept.

When asked if she believed her column one information to be true, Florence responded "Yes I do." (P-d) When the researcher asked her why she thought her understanding was true, she responded "Because that's how . I learned it. I read it in a book. Um hu. I don't remember any specific thing. But . that's the theory." (P-u) These statements revealed that the learner believed that her understanding was true. Therefore she had plausibility for the Decay-one concept.

When the researcher asked if she found her column two information to be useful, the learner made a reply that indicated her usefulness for this concept. She replied:

> I think that's useful. Ah . because . people know you have less amount of radioactive material, the activity will be less. I think that's useful information. As far as like personal safety concerns. Like if you . get exposed to a large amount of a radioactive material, . and you know you got exposed to like a . large quantity of activity, radioactivity. And that's more dangerous than just a . a small . . amount of radioactivity. (F-d,p)

When the researcher asked Florence if she found her column three information to be useful, she made a statement which was applicable to the Decay-one concept; "So it is . not as dangerous as it was before." (F-p) These statements showed that Florence knew of

two applications where her understanding that a radioactive material changes into a different material, which may be non-radioactive, was useful. Thus, she expressed developing fruitfulness for this concept.

Florence's status change: (Decay-one Concept)

During the pre-interview, Florence had the status of developing I, developing P, and developing F. Her post-interview status was I, P, and developing F. Hence, her status increased. The change was due to the fact that the learner experienced a conceptual capture by gaining an understanding the meanings of the terms parent and progeny.

Ralph's interviews: (Decay-one Concept)

Ralph's pre-interview: (Decay-one Concept)

While completing the work sheet, Ralph commented:

> So I guess I'll just draw a . . a rang a a rectangle of . . supposedly to represent . some material. And . . say that it starts out with . a a unit quantity of one. and . . . I will . start out by assuming that . it's going to . decay (I-e)

Subsequent to this, the researcher asked Ralph to explain how the decrease in the amount of original radioactive material on the dish related to the fact that the nucleus was emitting particles. During his response, the learner stated "And . make it clear that . the matter . the radioactive matter that was there . what you called it um . is actually changing into something else . in the process of this decay." (I-t) When asked the meaning of the term parent, Ralph responded ". . Um . I'm not familiar with that term." (I-d) When asked how the term progeny related to radioactive material decay, Ralph responded "Not related to this." (I-d) These statements revealed that Ralph understood that the original radioactive material changes into something else. However, he did not have a mental

representation for the term parent and progeny, at least not as they related to the radioactive material decay process. Thus, Ralph demonstrated developing intelligibility for this concept.

When asked if he found his column one information to be true, the learner responded "So . um . . . I think . it represents . . ah . most radioactive materials." (P-d) When the researcher then asked why, Ralph responded "Well actually . because I was mostly taught that. I've never really measured it. Ah . so . my . the information I have is . ah . what I've learned . from others who I can ah . only assume had the . ah ah proper empirical evidence." (P-u) These statements indicated that Ralph believed his understanding of the Decay-one concept to be true. Thus, he demonstrated developing plausibility.

When asked if he found his column-one work-sheet information to be useful, Ralph responded "I . I think to some people . ah . . a lot many great many people who work ah with ah . the material. Then . for society in general it's certainly useful information." (F-e) When then asked if he was aware of any specific uses of the information, Ralph responded:

> for instance we have . here at the Tech Center some radioactive materials . . that ah may very quickly . and with some of our inst in in some of our instruments. Then if they decay to the point where they are no longer useful, then we would like to know. We would like to know when to expect when that would happen. And ah by the same token, if we . if there were any hazards . ah associated with the . material. With handling that. We could also know when it was safe to handle. (F-p)

These statements revealed that Ralph thought that his understanding of the Decay-one concept was useful, and he could site two examples of its usefulness. Therefore, he possessed developing fruitfulness for this concept.

Ralph's post-interview: (Decay-one Concept)

While filling out his work sheet, Ralph commented:

> Ya the . . (clears throat) . ah the substance decays. It changes into . some other element . or a couple of different . or . not even a couple, but different kinds of elements, by emitting particles . from it's nucleus. Um . . . and such as an alpha particle, . . um . which . . the helium . nucleus . and . it loses it it decays. and it and the process of decay is in that . in that process rather it . would . um . transform into a lighter . element. (I-t;P-r)

When asked the meaning of the term parent, Ralph responded "Ok that's . what you start with when you . . ah . . . say ah ah . what you what you start out looking at". When asked the meaning of the term progeny, Ralph responded "That's simply . . um what it changes, what the parent changes into . through the process of the decay." When the learner was asked if he thought his column one information was true, he commented "Um hu." (P-d) When asked why, he said "So I basically I just . made that assumption. that it changes into a completely different substance." (P-n) These statements revealed that Ralph understood that the parent material changes into the progeny. He also believed his understanding to be true. Therefore, he demonstrated intelligibility and plausibility for this concept.

No statements were made that indicated the learner's usefulness for his understanding. Thus, his fruitfulness is unknown.

Ralph's status change: (Decay-one Concept)

During the pre-interview, Ralph possessed the status of developing I, developing P, and developing F. His post-interview status was I, P, and unknown F. Thus, Ralph experienced a status increase through the process of conceptual capture. His knowledge increased because he acquired an understanding of the meanings of the terms parent and progeny.

Decay-two Concept:

Margaret's interviews (Decay-two Concept)

Margaret's pre-interview: (Decay-two Concept)

While discussing her work sheet, Margaret stated that "by the end, by by the end of this period of time, . which is two, four, six hours, they would have to be zero."(I-e,t) By this statement, she demonstrated that she could mentally represent the process ending with none of the original material left. Thus, she demonstrated intelligibility for the Decay-two concept.

During the interview, she also made other statements that pertained to concept Decay-two. For example: "it would be minute" (I-t), and "there would be something there" (I-t) This vacillation of ideas about the end result of the radioactive material decay process, along with the direct category statement that "Once again, not really knowing, I assume that as time goes on it would just . . evaporate." (I-d,t) revealed that Margaret did not have belief in any of her mental representations concerning the end of the radioactive material decay process. When asked how much faith she had in her idea that after a period of time, there'd be nothing left on the dish, she made the statements "Not much." (P-d) and "Probably it grows, but I'm not sure." (P-d) These statements reinforced the assertion that she did not posses plausibility for the Decay-two concept.

When margaret was asked if she could see any usefulness to the knowledge of how a radioactive material changed over time, she made the extrinsic category statement indicated under the Decay-one pre-interview section. Thus, she demonstrated no fruitfulness for concept Decay-two.

Margaret's post-interview: (Decay-two Concept)

During the post-interview, Margaret stated that she understood that "the end process

would be my . parent material would be all gone and it would all be into progeny and it would have decayed into another form which would be the water that would have been left." (I-t,a) This statement demonstrated her intelligibility for concept Decay-two. When asked if she believed the idea that after a certain amount of time, the original material in the dish was all gone was a true representation of what happened to a radioactive material, Margaret made the statement "Well I think it's the concept. . . . If I were relating it to what you said in our . our um . . talk. Um . . I would say that that is the concept." (P-d,l) In addition, later in the interview she sated that "I've taken your little class and learned that . that it does decay and and go down to nothing or to another . . not necessarily nothing always but . to perhaps another element." (P-l) This dialogue indicated that Margaret had intelligibility and plausibility for concept Decay-two. At another point in the interview, the learner made the statement that "well I guess it would be the same thing as a piece of ice. If you wanted to use that concept. Just decaying in that dish. And eventually it would be all water." (I-a;P-a) This again demonstrated that the learner exhibited intelligibility and plausibility for the concept.

When the researcher asked if Margaret found her understanding of how radioactive materials decay to be useful in any way, she did not relay any thoughts concerning the fact that the parent material is eventually completely changed into progeny material. Thus, her fruitfulness for her understanding of concept Decay-two is unknown.

Margaret's status changes: (Decay-two Concept)

A comparison of the pre- and post-interviews revealed that Margaret's status for concept Decay-two changed from I, no P, no F to I, P and unknown F. Thus her status increased because she developed plausibility for her understanding that during the radioactive material decay process, the parent entirely changes into the progeny. This

represented a conceptual capture process because no dissatisfaction and replacement of a prior understanding had to occur.

Felix's interviews (Decay-two Concept)

Felix's pre-interview: (Decay-two Concept)

Prior to the lesson presentation, Felix thought that a radioactive material completely decayed. This was demonstrated by the statement "Eventually it's gonna all become . it's just gonna decompose to nothing because it's all released as energy." (I-t;P-r) In addition, at another point in the interview, he stated "A hunk of uranium. You'd probably have nothing left. It would break down into its atomic particles, or whatever." (I-e,t;P-r). These statements revealed that Felix had pre-interview intelligibility for concept Decay-two.

Through their real mechanism properties, the above statements also exhibited that Felix had plausibility for this concept.

When asked if he found his knowledge of radioactive material decay to be useful, Felix responded "The . . they can probably predict . when the sun's gonna burn out." (F-e,p), and for medicine. For a generating electricity. You have to know how long that core's gonna last. So they . whoop, there it's gone. Nobody has any power anymore." (F-p), and

> Cause if it does happens to get into the food, . . they certainly have to know how long it's gonna last. So they can . ban it or whatever . I don't like to use the term ban. But, to prevent people from using that particular . material . for so long . then it becomes . quote unquote . safe. (F-e,p)

These statements indicated that Felix could see usefulness to the idea that a radioactive material decays completely over time. Thus, he demonstrated developing fruitfulness.

Felix's post-interview: (Decay-two Concept)

After the lesson presentation, Felix stated "And all the particles hit. You would have no more radioactive mass left." (I-t;P-r) When then asked by the researcher "Ok. But what would be left? Nothing?", he responded "No there'd be a lump of something. I think a different at, a different material. But it would not be radioactive. It would not necessarily be radioactive." (I-t) Later in the interview, in response to a question concerning half-life, Felix stated "Eventually it does. Keep dividing by half till it gets to zero." (I-t;P-o) When the researcher asked Felix if there were any correspondences between the falling-tacks analogy and a radioactive material, he responded "Eventually they're all ah . . . be . you gonna have none left . eventually." (I-t) These statements revealed that Felix possessed intelligibility and plausibility for this concept.

When asked if he felt that his knowledge concerning the decay of radioactive materials was useful, Felix replied "Oh ya, probably. I think for generating . nuclear power . . they have to know . . about how much . how long . there core material will last." (F-d,p) Thus, Felix demonstrated developing fruitfulness for this concept.

Felix's status changes: (Decay-two Concept)

During the pre-interview, Felix possessed the status I, P, and developing F. During the post-interview, he possessed status I, P, and developing F. Thus, no change in status occurred for this concept.

Mark's interviews: (Decay-two concept)

Mark's pre-interview: (Decay-two concept)

When the researcher asked the learner if he thought his understanding of the changes that a radioactive material undergoes was true, he replied "After a hundred percent

radioac active decay, . . you have . . it is different. Because it's not decaying anymore. So I'm a hundred percent sure of that." (I-t;P-d,o) This statement revealed that Mark understood that "a hundred percent" of a radioactive material decays and that he was "a hundred percent sure of that". Thus, he demonstrated an understanding of concept Decay-two, that decay goes to completion. It also appears that he demonstrated belief in his understanding. However, later in the interview, the learner was asked if he thought his work-sheet-meter dial changes were true. He replied:

> I'm not totally sure that it would go down to zero. And the only reason . . I think it's one of those . . . . . asymptotic things. And I'm not sure why. Never quite reach zero. ya. Because I don't I don't I don't base that on any . knowledge. Other than the fact that . radioac longevity of radioactivity is always defined in terms of half-life. And it's . it's easily . fairly easily defined . what the half-life of the material is. But . . to define what the . the time in which it's completely . decayed . is always . been a problem for some reason. (I-t;P-d,o)

Even though this answer was directed at the concept of activity, it also related to the Decay-two concept. What is apparent is that Mark had some doubts that a radioactive material would decay completely. Thus, his plausibility for concept Decay-two was developing. However, initially, he did express the idea that a radioactive material decayed to completion. Therefore he demonstrated that he had the capacity to understand this concept. Thus, he had intelligibility for concept Decay-one.

When asked if he found his understanding of radioactive material change to be useful, Mark replied:

> . . . . . Ya in in all sorts of senses. I mean . . however it's being used or applied or . . um . . ya have to know that it's not . . not constant. And they're all sorts of practical implications to that. If it's being used . . if it's being used for particular purpose, then you have to know that it's not a forever thing. (F-r)

Although Mark said his understanding had "all sorts of practical implications", he did not give any examples of the usefulness of his version of concept Decay-two. Thus, his

fruitfulness is unknown.

Mark's post-interview: (Decay-two Concept)

When asked by the researcher "What is the degree of change from the red [parent] to the blue [progeny], Mark responded "Eventually, I mean . it's complete. After an infinite period of time." (I-t) The researcher then asked Mark to further explain his answer. He replied "I think it's um (clears throat) . . I think it's a ah . . . kind of an asymptotic . relationship. It never quite reaches zero." (I-t,P-o) These statements indicated that Mark's understanding of concept Decay-two was different than the scientifically accepted version. During the interview, Mark was asked if he remembered any correspondences between the melting-ice analogy and radioactive material decay. He responded

> Um . . . . only that the ah . all that you were changing from one material to another. Um . . the . . the rate didn't quite work out. . . ah . wasn't a good analogy. . . Um because it . . it wasn't a ah . . . um . an asymptotic relationship to a radioactive decay. (P-a)

When Mark was asked if there was anything else about the analogies that he wanted to mention, he said

> Well they still . . I I guess there's there's still some confusion in my . my own mind about the fact that . . material is not totally, it never totally . decays. Um because it's not really . it wasn't . . it couldn't be illustrated by either of the ah . demonstrations, the analogies. Because eventually all of the ice would turn into liquid water. And eventually all of the tacks would end up on their side. And so they didn't, certainly didn't serve to clarify that issue.In fact they kind of confused the issue. Well I mean if you, if you assume that those were good analogies, then you'd say that over a period of time . then a hundred, over a finite period of time, then a hundred percent . you know you'd have a hundred percent decay. You'd have no more radioactive. And um . . and I guess my understanding is that's not the case. (P-a)

These statements illustrated the Mark held an alternative understanding of concept Decay-two. But, he also understood the accepted version of the concept. Thus, he

possessed intelligibility for the Decay-two concept. But he demonstrated that he did not have believability in the scientifically accepted version of concept Decay-two. Thus he demonstrated no plausibility for this concept.

When asked if he found any usefulness to his understanding that a radioactive material never completely changes to its progeny Mark responded "Ya I think in terms of ah . . . . . um . . . possibly . . . safety, for safety reasons. It it'd be good to know that . it's never really . . a hundred percent non-radioactive." (F-d,p) This statement indicated that Mark found usefulness in his understanding of this concept. Thus he exhibited developing fruitfulness for his ideas. However, since he possessed an alternative idea to the scientifically accepted version of this concept, this translates into no fruitfulness for concept Decay-two.

Mark's Status Change: (Decay-two Concept)

During the pre-interview, Mark possessed the status of I, developing P, and unknown F. During the post-interview, Mark possessed the status of I, no P, and no F. Thus, his status for concept Decay-two decreased. The decrease in status was due to his increased satisfaction with his implausibility for the accepted version of concept Decay-two.

Edgar's interviews: (Decay-two Concept)

Edgar's pre-interview (Decay-two Concept)

During his explanation of the meaning of the term radioactive, Edgar commented "But it it is ah natural to, a radioactive material to become non-radioactive over time." (I-t) Near the end of the session, the researcher asked the learner how far the radium to bismuth change would go. Edgar responded "An . . . over a period of time, I would guess, if we're talking about just one chunk, I would guess all of it. Given enough time."

(I-e,t;P-n) These statements revealed that Edgar found the Decay-two concept to be intelligible and plausible.

No other statements relating to this concept were made. Thus, the learner's fruitfulness is unknown.

Edgar's post-interview: (Decay-two concept)

At one point in the interview, the researcher asked Edgar where the meter dial's needle would be at the end of the process. During his reply, the learner commented "Um, would go down to low or . the original product, the original solid might go down to . zero." (I-t) This statement revealed that Edgar could mentally represent the scientifically accepted version of the Decay-two concept. Thus, he demonstrated intelligibility for this concept.

Later in the interview, Edgar commented

> Ah, in thinking about it, I realize that there probably is going to be . no matter how many, how many . thousands of years have gone by, there's probably going to be a a measurable amount of radiation left. From the original material, or from its, a or from its progeny. (I-t;P-y)

A little later in the interview, Edgar was asked why be believed his work sheet was more accurate that the comparison work sheet. He responded "Um . . . basically because of the long period of time it takes for something to decay completely. . . And I think you're always going to have . . . some amounts of radioactivity . remaining." (P-o) These statements revealed that Edgar did not find the idea that a parent decays completely to be plausible.

During the post-interview, Edgar made no comments relating to the fruitfulness of concept Decay-two. Thus his fruitfulness is unknown.

Edgar's status change: (Decay-two Concept)

During the pre-interview, Edgar possessed the status of I, P, and unknown F. During the post-interview, his status was I, no P, and unknown F. Thus, his status decreased. The change in status occurred because after the analogy-based lesson presentation, Edgar no longer found the idea that the parent material completely changed to something else to be plausible. Thus, he experienced a conceptual exchange because he had to become dissatisfied with the idea that the parent eventually all changed into progeny and replace this with the idea that the parent is never completely changed. Having only developing plausibility for this concept during the pre-interview indicated that Edgar was ripe for this conceptual exchange to occur.

Wilbur's interviews: (Decay-two Concept)

Wilbur's pre-interview: (Decay-two Concept)

When asked what the material on the dish would look like at the end of the process, Wilbur commented "I don't think it would change completely to the next . next lower ah ah element. Well it ah . still most mostly ah krypton." (I-e,t) A little later in the interview, Wilbur was asked to explain the meaning of the term half-life. During his response, he commented "So just a a matter of of ah . . of going from half to half to half and d ah . . never quite reaching zero. Although you know you can say for all practical purposes you have zero." (I-t,P-o) These statements indicated that Wilbur's understanding was alternative because he thought that a radioactive material never completely changes into a different material. Since the scientifically accepted version of this concept is not compatible with Wilbur's alternative view, he did not have intelligibility for concept Decay-two.

When asked if he believed his column one work-sheet information to be a true

representation of how a radioactive material decays, Wilbur responded "Ya I believe that that's true." (P-d) This statement, along with the plausibility features of the above statement, revealed that Wilbur had plausibility for his alternative concept that a radioactive material never completely changes into its progeny. Since Wilbur's view and the scientifically accepted version of this concept are not compatible, he had no plausibility for concept Decay-two.

During the interview, Wilbur made three comments that indicated that he found his conception that a radioactive material does not completely decay to be useful. The first statement was

> Um . . . but ah . I imagine that the the stuff is still ah . would have some radioactivity. And . you would have to ah take proper pre precautions on on disposing of it. I don't know what they do now. I ah I . maybe they just gather it together and bury it someplace and ah . . um . . isolate it somehow from from ah human contact. (F-p)

The second statement was:

> Probably still have some. But the . . low sensitivity end. And maybe still potentially dangerous for . say say for prolonged contact. If it were in a . . it somehow got in the paint, for example, and you were constantly in the room, ah you'd have maybe a low lever. But still some exposure to . something like that.(F-p)

The third statement was in response to the researcher's question concerning what usefulness Wilbur found to his column one information. To this question, the learner responded

> Because I I think that it's ah ah it's still potentially dangerous. Ah even though it's maybe low levels. And maybe ev even undetectable. If you know that it was . krypton to begin with . I think you'd have a healthy respect for it and and and ah . try to bury it or dispose of it or keep away from it somehow. (F-p)

These statements showed that Wilbur found his understanding that a radioactive

material never completely decays to be useful. Thus he had fruitfulness for his alternative conception. However, since the scientifically accepted version of concept Decay-two is not compatible with this alternative conception, Wilbur demonstrated no fruitfulness for concept Decay-two.

Wilbur's post-interview: (Decay-two Concept)

While filling out the work sheet, Wilbur commented "But the radioactivity ah to we're assuming we'll stop when a radioactive material goes down to ah . ah . one stable state." (I-t) During this process of completing the work sheet, the researcher asked Wilbur what the material on the dish went "down to". Wilbur responded "Ah . . not measurable. Well . eventually zero. End of ya eventually." (I-t) These statements revealed that Wilbur understood that the radioactive material decay process went to completion. He thus possessed intelligibility for the Decay-two concept.

The researcher asked Wilbur if his column two information was true. During his response, Wilbur made the following comment which related to the Decay-two concept: "That's that that other thing is um , you know, half and half and half and . keep going till . down to practical zero." (I-t;P-o) The researcher then asked if it ever went to zero, or just to practically zero. Wilbur responded "Well I I guess it [the reading of the meter dial] when the when the final molecule ah final atom . does go . then it's then zero." (P-r) These statements revealed that Wilbur had believability for his understanding that the radioactive material decay process went to completion. Thus, he possessed plausibility for the Decay-two concept.

Wilbur made no comments concerning the usefulness of his understanding of the Decay-two concept. Thus, his fruitfulness was unknown.

Wilbur's status change: (Decay-two Concept)

During the pre-interview, Wilbur exhibited the status of no I, no P, and no F. His post-interview status was I, P, and unknown F. Therefore, his status for the Decay-two concept increased. This status change represented a conceptual exchange of the idea that the decay process goes to completion for the idea that the process is never complete. Wilbur had to become dissatisfied with his alternative pre-interview understanding and replace it with the scientifically accepted post-interview understanding. His plausibility for his alternative conception also had to replaced with plausibility for the scientifically accepted version of the Decay-two concept.

It is apparent when reading Wilbur's statements that between the pre- and post-interviews, he had acquired and connected the ideas that the radioactive material diminishes in half-life steps with the idea that this halving process does not go on indefinitely because the atom can not be divided, but is either present in parent form, or it has decayed. This post-interview understanding represents a full understanding of the Decay-two concept.

Jennifer's interviews: (Decay-two Concept)

Jennifer's pre-interview: (Decay-two Concept)

Most of the comments presented under Jennifer's pre-interview discussion for the Decay-one concept are applicable in this section. For example, while completing the work sheet, Jennifer made the following three comments: "I and this is what the radioactive material looks like [referring to the first intermediate position] . the same." (I-t) and "and this is another intermediate time [referring to second intermediate position] and and I think the material stays the same. I really have no idea. But . I honestly don't know what happens to the material over time." (I-t;P-d) and

> Two years [referring to second intermediate position] . . . so um. I don't know. It's probably gone down some. I really don't know how it decays. . . So let's put it like less. . . This is the end. I don't know. I think it's still looks the same." (I-e,t;P-d)

Also, a comment that Jennifer made a little later in the interview applies to this concept. When asked to describe the process of radioactive material decay, she responded "Radioactive material decay. I I don't know how it works . to be honest. But it has to do with the half-life stuff. And over a period of time it decays and it's not harmful anymore." (I-t;P-o) The comment made at one point in the interview when the researcher asked Jennifer if she believed her column one information was true also applies here. To this inquiry, she responded "Oh well I wouldn't stake my life on it or anything." (P-d) These statements revealed that Jennifer had the understanding that the radioactive material on the dish did not change, but she did understand that the decay process eventually rendered the parent material harmless. However, she made no statement about the change being complete, with no parent material remaining at the end of the process. Thus, Jennifer did not have a mental representation for this concept, so she had no intelligibility for this concept. Jennifer's plausibility category comments revealed that she also had no plausibility for the scientifically accepted view of this concept. Jennifer made no statements pertaining to the usefulness of her understanding of the Decay-two concept. Thus her fruitfulness was unknown.

Jennifer's Post-interview: (Decay-two Concept)

During the interview the researcher and Jennifer were talking about her falling asleep during the lesson. During this discourse the learner commented

> I wasn't paying attention. You started out and you would talk about . you know . if it if it was so many years and then it would be (laughs) if it was still going. Then it would be like half of those years. And then half again, and then . until it all decayed. (I-l,t;P-o)

This statement indicated that Jennifer could mentally represent the concept that the original material was all gone at the end of the process. Thus, she possessed intelligibility for the Decay-two concept.

When the researcher asked Jennifer if the radioactive material completely decayed, she responded "Well . this part I'm not totally . . " (P-d) Also, when the interview centered around a discussion of the falling-tacks analogy, Jennifer commented "But that was an argument too, about not and not getting down to absolutely zero. Because you can't keep dividing and dividing and still get . there's no such thing as absolute zero." (I-t;P-o) These statements indicated that Jennifer did not totally believe that the initial radioactive material completely decayed. One reason for this was that she had not reconciled the idea of the asymptotic approach to zero dictated by the halving steps with the fact that the last nuclei to decay can not be divided in half. Thus, Jennifer displayed developing plausibility for the Decay-two concept.

No statements were made concerning the usefulness of Jennifer's understanding of the Decay-two concept. Thus, her fruitfulness is unknown.

Jennifer's status change: (Decay-two Concept)

Jennifer's pre-interview status was no I, no P, and unknown F. Her post-interview status was I, developing P, and unknown F. Thus, she experienced an increase in status. This increase occurred because at the time of the post-interview, Jennifer was able to represent the understanding that the initial radioactive material completely decayed. She had no mental representation of this idea at the time of the pre-interview. Also, her plausibility condition increased because she remembered by rote that the initial material completely decayed, even though she could not reconcile this with her understanding of the infinite divisibility of a quantity by two. This is in comparison with her pre-interview

lack of any understanding about the possibility of a complete parent to progeny change. This increase in status represented a conceptual capture. This is because Jennifer did not become dissatisfied with, and reject, an understanding about the completeness of the decay process. She only captured the understanding that complete decay could occur.

Florence's interviews: (Decay-two Concept)

Florence's pre-interview: (Decay-two Concept)

While filling out the work sheet, Florence commented "Ok. at the end of process there'll be nothing left. (I-t) A little later, while still filling out the work sheet, the learner remarked:

> Ya just say after . a number of years . um . . everything is gone. It's . more than ten years. Because everything has a certain and all the radioactive material has a certain life time. And then so . after a number of years . there will be nothing left. (I-e,t;P-o)

These statements revealed that Florence understood that the decay process eventually goes to completion. That is, she expressed intelligibility for this concept.

The researcher asked Florence if she found her column one information, the fact that the original material becomes something else and that this change goes to completion, to be true. Florence responded ". . Um . . in some situations, yes. Like . um . . yes I would say it . that's . I believe that's actually what happens. (P-d) When then asked why she believed her information to be true, she responded "I think I learned this in high school" (P-u) These statements, along with the plausibility features of the second statement in the previous paragraph, revealed that Florence believed her conception of concept Decay-two. Thus, she possessed plausibility for this concept.

When asked if she found her column one information to be useful, Florence did not contribute any statements pertinent to this concept. Thus, her fruitfulness is unknown.

Florence's post-interview: (Decay-two Concept)

While filling out the work sheet, Florence commented ". and at the end . there'll be no ah detectable . radioactive material left. That's not to say . it's all gone. It's it's not zero. It's just below detection limits." (I-t) This statement revealed that the learner had the understanding that a radioactive material did not decay completely, but that a small, undetectable, quantity always remained. However, her comment that "that's not to say . it's all gone" indicated that she also had intelligibility for the scientifically accepted view that the parent material eventually all decays into its progeny. Therefore, she possessed intelligibility for the Decay-two concept.

When the researcher asked the learner if she found her column one information to be true, she responded "Yes I do." (P-d) When the researcher then asked the learner why she found her column one information to be true, she responded "Because that's how . I learned it. I read it in a book. I don't remember any specific thing. But . that's the theory." (P-u) Later in the interview, the learner was shown a correctly filled in work sheet for comparison with her work sheet. While comparing these two work sheets, the learner commented "Do you actually go down to the very end. And and I think . . in philosophy, no. You always have something. It's a . below your detection limits." (P-o) When the researcher asked the learner why she thought that there was always some of the parent material left, she responded:

> Cause they they . you take forever. In this process, that's ah . . . . you reduce half. You have another half left. So you always have half of where you started. This half won't be zero. It could be very very close to zero. But . . it's still this material. (I-t;P-o)

These statements revealed that Florence found her understanding that a radioactive material never completely decays to be believable. Thus, she had plausibility for her alternative conception. Since her conception and the scientifically conception are not

compatible, this translates into no plausibility for the Decay-two concept.

Florence made no fruitfulness statements relating to this concept. Thus, her fruitfulness is unknown.

Florence's status change: (Decay-two Concept)

Florence's pre-interview status was I, P, and unknown F. Her post-interview status was I, no P, and unknown F. Thus, her status decreased. This decrease in status occurred because Florence became aware of the connection between the infinite nature of mathematically dividing a given quantity in half. In this process, one keeps producing smaller fractions, but never reaches zero. One only approaches zero. Therefore she thought that the parent material was never completely depleted. During the pre-interview, she was not aware of this mathematical relationship. At that time, she recognized that the parent material went to zero because she had not needed to reconcile this idea with the mathematical infinity of dividing by two. This change represented a conceptual exchange because her pre-interview idea had to be rejected and replaced with the post-interview conception that a radioactive material never completely decays.

Ralph's interviews: (Decay-two Concept)

Ralph's pre-interview: (Decay-two Concept)

While filling out the work sheet, the following exchange of dialogue occurred.

> Ralph: Ok. Well I can arbitrarily decide that the end of the process is on eight. But ta it sounds like what you're looking for is . um . for . . the end of the process to be . a zero quantity.
> Researcher: No. What I'm looking for is what you
> Ralph: I have no objection to that. (I-t)

This discourse revealed that Ralph could mentally represent that at the end of the

process of radioactive material decay, no parent material remains. Thus, he possessed intelligibility for the Decay-two concept.

The exchange above indicated that the learner had "no objection" to the idea that the end of the decay process was reached when no parent material remained. However, a little later in the interview, when being questioned about the amount of parent material remaining at the end of the process Ralph said "And . you know you might still have a large number of them [parent atoms] left. Course after many years, we would improve technologically to the point that we might be able to . detect such a small quantity." (I-t) This statement indicated that Ralph did not believe that all parent material was gone at the end of the process. He thought that the amount remaining was just undetectable with modern methods of analysis. Thus, he expressed no plausibility for this concept.

Ralph made no fruitfulness comments for this statement. Thus, his fruitfulness is unknown.

Ralph's post-interview: (Decay-two Concept)

While filling out the work sheet, Ralph made the comments "So . . ya . . not before present but . sometime before present it would decay to nothing." (I-t) and "the only thing you'd have left is what it's decayed into . and that's . . progeny." (I-t) These statements revealed that Ralph could mentally represent the idea that at the end of the radioactive material decay process, no parent material remained. Thus, he demonstrated intelligibility for this concept.

When the researcher asked Ralph to clarify the end of the process in terms of the initial radioactive material, he stated "I would think . after . . . certainly after ah . . . eight half-lives, . . it will . you know be almost undetectable." (I-t;P-y) and "The way you split it up into . half . each time. . . . Get ah . I mean you get down to a quarter, then an eight,

and then a sixteenth, . then a thirty second." (I-t;P-o) When the researcher then asked how long the process would continue, Ralph responded "Ya it should eventually reach a point it won't change anymore." (I-t) The researcher then asked "What will that point be?" and Ralph responded "I don't know." (P-d) These statements revealed that Ralph did not have a strong belief in his understanding that the end of the process is represented by zero parent material left. This lack of belief occurred because Ralph understood the infinite nature of dividing a real number by two. Thus, he possessed developing plausibility for this concept.

Ralph gave no statements indicating usefulness for the Decay-two concept. Thus, his fruitfulness was unknown.

Ralph's status change: (Decay-two Concept)

Ralph's pre-interview status was I, no P, and unknown F. His post-interview status was I, developing P, and unknown F. Thus, his status increased. This occurred because Ralph acquired an understanding that the mass of initial radioactive material decayed in half-life steps and this process, theoretically, could continue indefinitely because of the infinite ability to divide a real number by two. This process represented a conceptual capture because additional information was added to his conceptual ecology. An initial move toward satisfaction with his understanding of this concept was developing, but had no fully expressed itself at the time of the post-interview.

Decay-three Concept:

Margaret's interviews (Decay-three Concept)

Margaret's pre-interview: (Decay-three Concept)

During the pre-interview, Margaret did not spontaneously mention anything about the

Decay-three concept. In response to a question by the researcher concerning how probability related to radioactive material decay, the learner made the direct intelligibility category comment that "I I really don't know." Since no other statements concerning the Decay-three concept were made, Margaret's status for this concept is unknown.

Margaret's post-interview: (Decay-three Concept)

During the post interview, Margaret, in a manner similar to her pre-interview, did not spontaneously make any statement concerning this concept. When asked how probability related to radioactive material decay, she made the direct intelligibility category response that "Gosh, I remember you talking about that. But I can't think of what um . . . . . sorry I can't think of that." Thus, Margaret's status for this concept was unknown.

Margaret's status change: (Decay-three Concept)

Comparing Margaret's pre- and post-interview responses, it is apparent that no change in status was detected for concept Decay-three due to the analogy-based lesson.

Felix's interviews (Decay-three Concept)

During the pre-interview, Felix was asked a question about probability and it's relation to radioactive material decay. In response, he replied "The more dense it is, the more radioactive material there is, the more likely it is for those collisions to occur. You have a higher probability of the collisions occurring. Releasing energy." (I-t;P-r) This statement was not directed at the issue of concept Decay-three, that each nuclei of a radioactive material has the same probability of decaying. It is directed at the kinetics concept concerning reaction rate versus concentration. Since no other statements were made related to the Decay-three concept, Felix demonstrated unknown intelligibility and

plausibility. In addition, he did not make any pertinent fruitfulness statements. Thus, this condition is also unknown.

Felix's post-interview: (Decay-three Concept)

During the post-interview, when asked what probability had to do with radioactive material decay, Felix responded "I think it was stated you all have the same probability . of contacting another atom so that the decay rate is constant." (I-l,t) He further went on to say "The radioactive . mass would all have . . if one atom . . . I guess knocked a particle off of it . hit another atom . . (coughs) equally, you'd all be equal. I mean the chances of being hit are equal." (I-t;P-r) These statements demonstrated that Felix had incorporated the analogy-presented concept of equal atomic-level probability into his alternative Decay-one concept (see Decay-one discussion section). Although his concept of natural radioactive material decay was somewhat alternative, Felix thought that each atom had the same probability of decaying. Thus, he demonstrated intelligibility for this concept, albeit in terms of atoms rather than nuclei. However, this still represented intelligibility for the Decay-three concept. In addition, he also demonstrated plausibility for his understanding of this concept because he had an idea of the cause or mechanism of the process.

No statements were made by Felix pertaining to the usefulness of his concept about Decay-three. Thus, his fruitfulness was unknown.

Felix' status change: (Decay-three Concept)

During the pre-interview, Felix demonstrated unknown status. During the post-interview, he demonstrated the status of I, P, and unknown F. Thus, the change in his status for the Decay-three concept, following the analogy-based lesson presentation, was unknown.

Edgar's interviews: (Decay-three Concept)

Edgar's pre-interview: (Decay-three Concept)

When asked how the term probability related to radioactive material decay, Edgar responded "Probability as as ah (??) being able to predict . the decay . . and that was you're . . . . ". The researcher then asked him to give an example. Edgar responded ". . If . if you are given a radioactive material then . by some kind of formula you can predict . the . . ah . . the life or half-life of the of of the material, is that what you mean by probability? . . . Ya I would guess you could." (I-t;P-o) These statements revealed that Edgar had intelligibility and plausibility for his idea that a formula can be used to determine the half-life of a radioactive material. However, these statements do not relate to concept Decay-three, that each nuclei has an equal probability of decaying. Thus, his intelligibility, plausibility, and fruitfulness for this concept are unknown.

Edgar's post-interview: (Decay-three Concept)

When asked how the term probability related to radioactive material decay, Edgar responded "Um, I guess probability would come into effect in order to predict the half-life and its ah its radioactive levels after a period of time." (I-t) This statement revealed that Edgar understood that probability was involved in the process of determining a radioactive material's half-life. However, his comment did not relate to the Decay-three concept, that all nuclei have an equal probability of decaying. Thus, his intelligibility, plausibility, and fruitfulness for this concept are unknown.

Edgar's status change: (Decay-three Concept)

During the pre-interview and post-interview, Edgar possessed the status of unknown I, unknown P, and unknown F for concept Decay-three. Thus any changes in the status for

this concept went undetected.

Fred's interviews: (Decay-three Concept)

Fred's pre-interview: (Decay-three Concept)

When the researcher asked Fred how the term probability related to the process of radioactive material decay, the learner responded "I . . I'm not sure . that I understand, ah, probability in terms of um . . what's the probability of . the decay happening or it's ah being there, or what's the probability of . um a certain exposure." A little later in this same response he commented "As far as I remember, these things do decay and will change . . their atomic mass, so . I'm not sure about it's probability, it . . um . . ah I don't know how to answer that." (I-t) These statements did not relate to the Decay-three concept. Since no other pertinent statements were made, his status for this concept is unknown.

Fred's post-interview: (Decay-three Concept)

When the researcher asked Fred to explain how probability related to radioactive material decay, the learner commented "Ah the probability is that um . . each radioactive . . atom has the same probability of undergoing decay . . as any other atom within that mass, within that radioactive mass." (I-t) Later in the interview, Fred was asked to compare his work sheet with a correctly completed comparison work sheet. During the comparison of column one of the two work sheet, Fred commented "Um as you had said, . . every atom within the radioactive material has the potential . . to decompose, to degrade. To emit the radioactive." (I-l,t) These statements revealed that Fred had intelligibility for the Decay-three concept.

Fred made no comments concerning the believability or usefulness of his understanding of concept Decay-three. Thus, his plausibility and fruitfulness are unknown.

Fred's status change: (Decay-three Concept)

During the pre-interview, Fred' status was unknown. During the post-interview, his status was I, unknown P, and unknown F. Thus, it is unknown if he underwent a status change.

Wilbur's interviews: (Decay-three Concept)

Wilbur's pre-interview: (Decay-three Concept)

When the researcher asked Wilbur how probability related to the process of a radioactive material going through its changes, the learner responded "Well I think ah in each phase I I think there is ah in each phase I think the radiation is is probably pretty steady. But as far as you you knowing . where . you are . . I think it's difficult." (I-t) This statement indicated that Wilbur associated probability with an understanding that radioactive material decay involved several stages, and there was a probability associated with what stage the material was in at a given point. However, this statement did not relate to concept Decay-three, that all nuclei have an equal probability of decaying. Thus, his status for this concept is unknown.

Wilbur's post-interview: (Decay-three Concept)

When the researcher asked Wilbur to explain how probability related to a radioactive material's changes over time, the learner responded:

> Probability is re is related to it in that tah as as . . . . . what you can say is that if if

> you have ah . you're talking about half-life ah . you can say . . . all the ah . the probability of any one . . . . one . . atom changing . . is is probably one-half over over over the half-life. (I-t;P-o)

The researcher then asked if some atoms had a higher probability of decaying than others. To this, Wilbur responded "No I don't think so." (I-d) The learner was then asked why he didn't think so. He responded ". . . . . Well . . the fact that it in a half-life, half go and half don't go." (I-t, P-o) These statements indicated that Wilbur understood that all of the atoms in a sample of a radioactive material have the same probability of decaying. Thus, he demonstrated intelligibility for the Decay-three concept. The plausibility features of his statements revealed that he possessed plausibility for this concept also.

Since no other statements were made that related to this concept, his fruitfulness is unknown.

Wilbur's status change: (Decay-three Concept)

During the pre-interview, Wilbur exhibited unknown status. During the post-interview, he exhibited the status of I, P, and unknown F. Thus, his status change is unknown.

Jennifer's interviews: (Decay-three Concept)

Jennifer's pre-interview: (Decay-three Concept)

When asked how probability would relate to the process of radioactive material decay, Jennifer responded:

> Not really. . . . . I don't know. I mean . I know what the word means. . But in terms of relating to . . the probability of what? Of you coming in contact with the material? . The probability that you're gonna get exposed? . The probability of a . nuclear reaction? Like the probability of what?

This statement did not relate to the Decay-three concept which concerns the probability of nuclei to undergo natural decay. Thus, her status is unknown.

Jennifer's post-interview: (Decay-three Concept)

When Jennifer was asked if probability had anything to do with the process of radioactive material decay, she responded ". . Um . . . . I guess ya it does. But I'm not exactly sure how. Again you know you did the little tacks thing. And you you really didn't explain to much about probability." (I-d) This statement did not relate to the Decay-three concept which concerns the probability of nuclei to undergo natural decay. Thus, her status is unknown.

Jennifer's status change: (Decay-three Concept)

Jennifer's pre-interview status was unknown I, unknown P, and unknown F. Her post-interview status was unknown I, unknown P, and unknown F. Thus, no status change was detected.

Florence's interviews: (Decay-three Concept)

Florence's pre-interview: (Decay-three Concept)

When Florence was asked how probability related to the process of radioactive material decay, she responded:

> Probability (??) probability. . . Ok the way I I I I really don't see any connection. Because probability radioactive ah radiation but I'm thinking maybe . um . not all the radioactive material . will become active. There is a chance that . becomes active . So it's not always active. So that means there's a probability. (I-t)

This statement did not relate to concept Decay-three that relates to the probability that each nuclei of a radioactive material has an equal probability of decaying at any given

time. Since the learner made no other pertinent comments, her status for the Decay-three concept is unknown.

Florence's post-interview: (Decay-three Concept)

When the researcher asked the learner how the term probability related to the radioactive material decay process, she replied:

> Probability . . . . . you can't relate prob probability to any of this process. You can't make it a guess. With something you have prior probability that it decays. Something is . more likely to decay. Something is less likely that . the probability . I . . just my guess. (I-t,P-n)

This statement did not relate to the Decay-three concept, that each nuclei of a given radioactive material has the same probability of decaying at any given time. Also, no other statements relating to this concept were made. Thus, Florence's status for this concept is unknown.

Florence's status change: (Decay-three Concept)

The learner's pre-interview status was. Her post-interview status was also unknown. Thus, no status change was detected.

Ralph's interviews: (Decay-three Concept)

Ralph's pre-interview: (Decay-three Concept)

When talking about radioactive decay, Ralph commented:

> Um . . so . and and if you take into account . or if you accept . the concept . that . um . it's going to happen . randomly, . . in the sense that it's each molecule, . there's a certain probability . over a period of time that each molecule is going to decay. So it's not completely random. It is defined by . your interactions of strong and weak forces. (I-t,P-r)

A little later, the learner stated:

> Um . and . because there is a certain amount of randomness in the event, ah . you you never know which molecule is going to decay. But if you have a high enough . ah quantity, statistical quantity, . it actually begins to look like a fairly smooth decay. That ah . . and over a period of time, it will average out. And half of those . half of any given quantity will decay at a regular interval. (I-t;P-o)

These statements revealed that Ralph understood that "there's a certain probability . over a period of time that each molecule is going to decay" and that "you never know which molecule is going to decay". Thus, he understood all radioactive molecules have an equal probability of decaying. Therefore, he expressed intelligibility for the Decay-three concept. The plausibility features of his first statements revealed that he believed in his understanding, and therefore had plausibility for this concept.

Since Ralph made no comments about his understanding, his fruitfulness is unknown.

Ralph's post-interview: (Decay-three Concept)

Near the end of the interview, Ralph was asked if he remembered any correspondence between the falling-tacks analogy and the decay of a radioactive material. In response, the learner said:

> Well . . . I guess assuming like . um . all tacks are . . so close to . or are manufactured in a way that they are very nearly identical. . that they would respond with an equal probability of . of thrown any given one. . Of landing on it's side or not. Um . and . in that same way, um most . . many . um . . radioactive substances are assumed to be the same . and . um . . in that it would, they would have, each of its atoms would have a probability of decay. (I-a;P-l,a)

This statement revealed that Ralph understood that each atom of a radioactive material has an equal probability of decaying. Therefore, he possessed intelligibility for this concept. The plausibility features of this statement indicated that he believed his understanding to be true, thereby expressing plausibility for the Decay-three concept.

Since no other statements relating to this concept were made, his fruitfulness is unknown.

Ralph's status change: (Decay-three Concept)

Ralph's pre-interview status was I, P, and unknown F. His post-interview status was I, P, and unknown F. Thus, no status change was detected.

Half-Life-one Concept:

Felix's interviews: (Half-Life-one Concept)

Felix' pre-interview: (Half-Life-one Concept)

During the pre-interview, Felix made several statements indicating his understanding of concept H-1. For example, when asked what he thought the time interval was between the second intermediate and the end of process positions on the work sheet, he responded "It . you lose half and . . the radioactive material . . or whatever it's life span. If it were a hundred years, in fifty years it'd be half as strong . in order for there to be half as much material." (I-t,e) Later in the interview, when asked to explain the process of radioactive material decay, he replied

> It's the particles flying around and neutrons, I think it was the main one, is flying as it breaks down. Emits neutrons are likely to hit another atom. Knock that apart and it continues and after what they call a half-life, half of that material . is gone. (I-t;P-r)

These statements revealed that Felix possessed both intelligibility and plausibility for the Half-Life-one concept.

When asked if he found the information in column two of the work sheet to be useful, Felix made a statement that uncovered his fruitfulness for concept Half-Life-one. He stated

> Oh your . your your treatment of cancer. Where they put a radioactive implant into the person. That's loc . get a concentrated dose locally. . . They have to know what the strength of it is. The half-lives . and stuff. So they can give an accurate dose. (F-p)

In his response, Felix went on to make the following statement that indicated his fruitfulness for concept Half-Life-one, and concurrently concept Half-Life-two.

> Well like I said. The . . they can probably predict . when the sun's gonna burn out. . For medicine. For a generating electricity. You have to know how long that core's gonna last. So they . whoop, there it's gone. nobody has any power anymore. For medicine. You gotta know how long it's gonna last so that they aren't having it running around or disposed of improperly. . and it's hot. Cause if it does happen to get into the food, . . they certainly have to know how long it's gonna last. (F-p,e)

These statements revealed that Felix could see several areas where half-life knowledge could be useful. Thus, he exhibited developing fruitfulness of this concept.

Felix' post-interview: (Half-Life-one Concept)

During the post-interview, when asked the meaning of the term half-life, Felix responded "The time it takes for one-half of the radioactive mass to decay." (I-t) Later in the interview, in response to a question concerning what he was representing with his work-sheet column three, he responded "Ya. Well. For each, if a half-life is a year, . . for every year . half of your remaining radioactive material is gone." (I-e,t) When asked what the correspondence between the melting-ice analogy and a radioactive material was in terms of half-life, Felix responded "Isn't that in a given period of time half the ice would ah turn to water." (I-a;P-a) When asked if he believed that his ideas about half-life were true, he responded "Ya." (P-d) These statements revealed that Felix possessed intelligibility and plausibility for the Half-Life-one concept.

When asked if he found his thoughts about half-life to be useful, Felix made a

statement that revealed that he did see usefulness for concept Half-Life-one, and simultaneously concept Half-Life-two . He stated:

> I think it goes back to what I in the beginning. You have to know how much. How long your . source is going to last. If your gonna generate power. . Or use it for medical treatment. How long it's going to be at a certain . . . strength . . to efficiently do its job. (F-p)

This statement revealed that Felix knew of specific applications of half-life knowledge, indicating that he possessed developing fruitfulness for the Half-Life-one concept.

Felix's status change: (Half-Life-one Concept)

During the pre-interview and post-interview, Felix possessed the status of I, P, and developing F for this concept. Thus, his status did not change after the analogy-based lesson.

Mark's interviews: (Half-Life-one Concept)

Mark's pre-interview: (Half-Life-one Concept)

During the pre-interview, Mark was asked the meaning of the term half-life. He responded "That's ah the point at which . I guess the . . ah . . the radioactivity is half of what it was initially." (I-t) The researcher then asked Mark what units would be assigned to half-life. The learner responded ". . Ah it would be time. The time that it takes . to go . . to . . go from the original radiate radiate radioactivity to a level that's half of that." (I-t) These statements revealed that Mark understood that half-life is a time. However, he thought it was the time required to halve the amount of radioactivity rather that the mass of parent material. Thus, he demonstrated developing intelligibility for this concept.

None of Mark's statements also had plausibility features. Thus, his plausibility for this concept is unknown.

Mark did make some pre-interview statements that related to the usefulness of his understanding of the Half-Life-one concept. At one point in the interview the researcher asked Mark if he found his thoughts about the time required for a radioactive material to change to be useful. In response he stated:

> Um . . . no I I know that ta . . you know I've heard that decay periods for like the source for measurement gauges, ah on paper machines, . . and that just over the period of like several years, they have to replace sources. So they've had a significant decay over just a period of let's say six or eight years. And if that had a half-life of ah . a hundred thousand years, . then you wouldn't have to change it after . eight years. (laughs) (F-p)

He went on to say:

> Ya. Ya. Just from, again, you know, from practical . considerations of using radioactive material . for . . measurements . and also waste disposal. You know, the same sort of thing. Um . . it's good to know how long things, you know, . things are gonna be radio radioactive. (F-p)

These statements indicated that Mark thought that his understanding of the Half-Life-one concept was useful and he could site a few examples of where it would be useful. Thus, he possessed developing fruitfulness for the Half-Life-one concept.

Mark's post-interview: (Half-Life-one Concept)

When asked to explain the meaning of the term half-life, Mark responded:

> Half-life is . the . amount of time it takes . for . . half of . the . material . to . . um . . degrade . and . um . . to (??) the parent . to the . um . I'm trying to think what the term is, the . . . the um . . not offspring, but the . original material to the . ah decayed material. (I-t)

This statement demonstrated that Mark had post-interview intelligibility for this concept. Later in the interview, Mark was asked if anything in the falling-tacks analogy related to radioactive material decay. he responded:

> . . . Ya you could . . um . . if you chart out . the number of tosses versus the number of tacks on their side, . . you could . . um . . find . a point at which half of the tacks . . were on their side . and . . identify the number of throws that it . would take to have half the tacks on their side. And that would be . the half-life of the material. (P-l,a)

A little later in the response, he stated:

> . . Oh well . . . um . . because . . as you . . . . . as . . . the radioactive material . . as each atoms decays . . . . it takes it out of the . um . . it's no longer radioactive. So it's just like the tack being on its side. You . you're pulling it out of the pile. So there's less material there to be radioactive. (P-l,a)

These statements revealed that Mark found concept Half-Life-one to be plausible.

No information was given that pertained to the usefulness of this concept. Thus, Mark's fruitfulness for this concept is unknown.

Mark's status changes: (Half-Life-one Concept)

During the pre-interview, Mark exhibited the status of developing I, unknown P, and developing F. During the post-interview, he exhibited the status of I, P, and unknown F. Thus, his status increased, at least for the I condition. This increase in status was due to Mark acquiring an understanding that half-life related to the loss of an amount of radioactive material, not radioactivity. This represented a conceptual change because Mark's understanding that half-life related to a decrease in the level of radioactivity had to be replaced with the understanding that it related to the loss of the mass of the parent material.

Edgar's pre-interview: (Half-Life-one Concept)

When asked the meaning of the term half-life, Edgar responded:

> Ok. ah, as I understand half-life, it is the . . it is basically what is, as the name

> implies, . it is one-half of the . . ah . . life expectancy of that . material ah . . before it would . lose its radia radioactivity. . . For example, something with a half-life of, say, five years, . then in ten years . it would be non-radioactive. (I-t,e)

This statement indicated that Edgar's understanding of half-life was that it was half of the time required for a radioactive material to change into another material. This is not the same as the scientific understanding of the term, which is the time required for half of a radioactive material to change to another material. However, Edgar did understand that half-life related to the time involved for a change in some property of a radioactive material. Thus, he demonstrated developing intelligibility for the Half-Life-one concept. Edgar made no plausibility comments about this concept. Thus, his plausibility is unknown.

When asked if he found his understanding of his work-sheet's third column to be useful, Edgar replied:

> . . . . Um . um . . . . it would be useful from I guess a a . a geological viewpoint. If you're finding . ah . for example . . ah . . layers of bismuth . then you can . . . think backwards . and realizing that these this was at at one point a radioactive material. (F-p)

Thus, he expressed developing fruitfulness for his idea about half-life. Also, this fruitfulness assignment is based on the fact that the example that Edgar gave was, in fact, a legitimate application of the half-life concept. Even though Edgar did not understand the exact relationship between time and the amount of radioactive material decayed, he did understand that half-life involved the relationship between time and half of some radioactive material's property to change.

Edgar's post-interview: (Half-Life-one Concept)

When Edgar was asked to explain the meaning of the term half-life, he responded:

> That is the . ah . half-life basically says, says what it is. It is the . half of the radioactive life expectancy . of a radioactive material. For example, (??) has a half-life of five years . then in ten years it would be not radioactive. (I-t,e)

Later in the interview, Edgar was asked to compare his work sheet with a correctly filled out comparison work sheet. One difference between the two work sheets was the fact that the comparison sheet indicated that the change from one fourth of the radioactive material to zero remaining radioactive material took a very long time compared with the time required to go from the original amount of material to one fourth of the original amount of radioactive material. Edgar was asked if this made sense to him. He responded:

> Well if we use the term half-life then then the radioactive material . should have . decayed half in . . half of the time indicated. . . . . I would think. Yet yet he's that it's (??) a small period of time has passed . and half the radiation is gone. I don't think that that for half the radio radioactivity to remain . would be . . the half way period between the time . . the material began . to the time when it became . . ah non-radioactive. (I-t;P-m)

These statements revealed that Edgar had an alternative understanding of the term half-life, and that he believed this alternative understanding to be true. He understood half-life to mean half of the time required for a radioactive material to become non-radioactive rather that the time required for half of a given amount of a radioactive material to decay. However, he did understand that half-life was related to the time involved for of some property of a radioactive material to change. Thus, he had demonstrated developing intelligibility and developing plausibility for this concept.

When asked if he found any usefulness to his understanding of the time involved for radioactive materials to change, Edgar responded:

> Um . ok . . um . well if I were in the business of ah . disposing of radioactive material, it would be useful to me. Um, that includes materi hospital waste, ah, fuel from spent nuclear, ah, reactors. Um . . but personally, like like I said, it . . should be aware of radioactive radioactivity and try to avoid it . . when possible.

(??) personal safety. (F-p)

Edgar mentioned two areas where his knowledge of the time required for a radioactive material to change would be useful. Thus, he expressed developing fruitfulness for this concept.

Edgar's status change: (Half-Life-one Concept)

During the pre-interview, Edgar possessed the status of developing I, unknown P, and developing F. During the post-interview, he demonstrated the status of developing I, developing P, and developing F. Thus, a change in status was not detected.

Fred's interviews: (Half-Life-one Concept)

Fred's pre-interview: (Half-Life-one Concept)

While filling out the work sheet, Fred volunteered the statement:

> That's the first intermediate. Ah one half-life. Um . . . my understanding of a half-life, if I remember correctly, is it's . the amount of time it takes . to lose half of the, I'll call it potential, half of the . . radioactive material. (I-t)

A little later in the process of filling out the work sheet, Fred commented "Alright. . um . . . at the end of the half-life . it would be . half of it would be . U 237. And I'm assuming it's losing some, so . half of that would be, we'll call it U 235." (I-t;P-n) When the researcher asked Fred the meaning of the term half-life, he responded "A half a half-life is a term that is used for the amount of time, whatever time frame it may be, whether it's in years, seconds, milliseconds, hours, that you lose . . half of the . . . again, radioactive material." (I-e,t) When Fred was asked if he believed his representation of the work-sheet's column number three was true, he responded "Um . as far as . . do radioactive materials have half-lives, yes." (P-d) However, he made no statements concerning whether

he believed his representation of half-life was true. Thus, these statements revealed that Fred had intelligibility for the Half-Life-one concept. However, his plausibility is unknown.

When Fred was asked if his column three information was useful, he responded:

> It can give you, a again, like a carbon 13 type of dating . system. Um it can tell you . . . . um . . . yes, I I I think there there is a significant . to knowing that that there are half-lives to these. Um . . you know, and and how quick. A as far as can I name them all? No. (F-p)

This statement indicated that Fred could see that his understanding of the Half-Life-one concept was useful and he could give one example of its usefulness. Thus, he demonstrated developing fruitfulness for this concept.

Fred's post-interview: (Half-Life-one Concept)

When filling out the work sheet, Fred commented "Ok. I I understand, I think I understood what you were saying [referring to researcher's analogy-based lesson presentation] . is the radioactive material would be half-left after one half-life." (I-l,t) When the researcher asked Fred the meaning of the term half-life, the learner responded "A half-life is the amount of time it would take for the radioactive material to lose half of its radioactive mass . . in . within that time frame." (I-t) These statements revealed that Fred understood that the half-life was a time required to lose half of the original radioactive material's mass. Thus, he expressed intelligibility for the Half-Life-one concept. Since no plausibility statements were made, this condition is unknown.

When asked if he found his understanding of half-life to be useful, Fred responded "Well ya cause, again, talking about storage of . waste radioactive material. And ya have to have some . idea of how long it's gonna have to be stored." (F-p) This statement shows that Fred though his understanding was useful, and he gave an example of its

usefulness. He thus expressed developing fruitfulness for the concept.

Fred's status change: (Half-Life-one Concept)

During the pre-interview, Fred's status was I, unknown P, developing F. During the post-interview, his status was I, unknown P, and developing F. Thus, no change in the status for this concept was detected.

Wilbur's interviews: (Half-Life-one Concept)

Wilbur's pre-interview: (Half-Life-one Concept)

When filling out the work sheet, Wilbur spontaneously stated "Well the krypton ah . I think has a half-life of of . ahh . four years, or something like that." (I-e,t) Later on in this process he stated "In four years it'd be half of what it was initially." (I-e,t) When the researcher asked Wilbur to explain the meaning of the term half-life, the learner responded "Half-life to me means that ah . whatever the level is at one point . . at some point, another point, it's what it'd be half the ah ah . the strength that it was initially." (I-t) These statements revealed that Wilbur understood that half-life referred to the time required for a radioactive material to exhibit half of the initial quantity of some property. However, he thought this property was "strength" rather that mass. Thus, he exhibited developing intelligibility for this concept.

When asked if he thought that his column three information was true, Wilbur stated "I believe that's ah . you know I believe in ah . the facts about half-life." (P-d) Thus, Wilbur demonstrated believability in his understanding of the Half-Life-one concept. Thus his understanding fit the category of developing intelligibility and his believability is categorized as developing plausibility for the Half-Life-one concept.

During his response to being questioned about the meaning of the term half-life,

Wilbur said "I think some of those things are used for dating dating purposes. Um . so you can maybe trace back to ah you know prehistoric times, or something like that." (F-p) This statement revealed that Wilbur found usefulness in his understanding of the Half-Life-one concept. Thus, he exhibited developing fruitfulness for this concept.

Wilbur's post-interview: (Half-Life-one Concept)

While filling out the work sheet, Wilbur spontaneously commented "I guess the half-life is . three hours" (I-e,t) A little later in the interview, the researcher asked Wilbur to explain the meaning of the term half-life. The learner responded "The half-life is ah . . a period in which there's there the activity . . goes down . to half it's orig initial ah activity." (I-t) These statements that Wilbur understood that half-life related to the time involved to lose half the quantity of some property of a radioactive material. However, he thought the property was "activity", not mass. Thus, he exhibited developing intelligibility for the Half-Life-one concept.

Since no plausibility statements were made, Wilbur exhibited unknown plausibility.

Since no other statements were made concerning this concept, his fruitfulness is unknown.

Wilbur's status change: (Half-Life-one Concept)

Wilbur's pre-interview status for this concept was developing I, developing P, and developing F. His post-interview status was developing I, unknown P, and unknown F. Thus, no change in status was detected. It is interesting that in the pre-interview, Wilbur thought of half-life in terms of decreasing "strength" and in the post-interview as decreasing "activity". This indicated that he captured the term activity and used it correctly. This is because the activity of the radioactive material is cut in half over one

half-life interval. This is true, even though it is not acceptable as the definition for the term half-life.

Jennifer's interviews: (Half-Life-one Concept)

Jennifer's pre-interview: (Half-Life-one Concept)

When the researcher asked Jennifer the meaning of the term half-life, she responded:

> Ah no. Actually I don't. I don't. I don't know. . I mean I only know . I know very little. And I only know that . radioactive stuff have half-lives. You know and like . . if you like get something inside your body or whatever, it's gonna like, or get exposed to something you know . like . some nuclear you know power plant explosion, you you get exposed to it. I mean it's . it's gonna stay around with you for like a long time. Depends on what the half-life is. So like if it has a half-life of a certain amount, then that means in so many years . or whatever, that it's gonna take to decay. (I-t;P-d)

A little later in this interview, the researcher asked Jennifer to clarify a statement she had made earlier that the life times of different radioactive material could vary. In response, the learner stated "Like, you know, if it's got a longer half-life, then it's gonna be around a longer time. It's gonna be . . not around. It's it's gonna be around, but it's gonna be radioactive for a longer period of time." (I-t) These statements disclosed that the learner had the understanding that the half-life of a radioactive material involved time, and the longer the half-life, the longer that material would be around, or would be radioactive, since she had the understanding that it would not change form (see Jennifer's pre-interview Decay-one discussion). Thus, the learner had a mental representation for part of the Half-Life-one concept in that she understood that half-life was a quantity of time. However, she did not understand that half-life was also related to the mass of the material. Thus, she demonstrated developing intelligibility for this concept.

When the researcher asked Jennifer if she believed her information in column three to be true, she responded "Ya. I think this almost. But then again like I can't say that I

know more than maybe a couple . and that's about it. Cause like . . not really read up on a lot of it . radioactive stuff." (P-d) The researcher then asked Jennifer why she believed her understanding to be true. In response she stated "Probably like movies I've seen about like a . nuclear power plant stuff. You know like . they had like uranium or something that has a really long half-life. And . you know that kind of thing." (P-p) These statements revealed that Jennifer believed in her understanding that half-life was a time. Thus, she possessed developing plausibility for this concept.

At one point in the interview, Jennifer made the comment:

> And I only know that . radioactive stuff have half-lives. You know and like . . if you like . get something inside your body or whatever, it's gonna like, or get exposed to something you know. Like . some nuclear you know power plant explosion, you you get exposed to it. I mean it's . it's gonna stay around with you for like a long time. (F-p)

This statement revealed that Jennifer could see that her understanding of the time involvement of the Half-Life-one concept was useful. Thus, she expressed developing fruitfulness for this concept.

Jennifer's post-interview: (Half-Life-one Concept)

When Jennifer was asked to explain the meaning of the term half-life, she responded:

> . Ah . half-life is . . the amount of time that it takes . the radiate the radioactive material . . did it the amount of . ah . I know I'm not going to say this right, . but . . . . it's the time that it takes . . . it . I'm not exactly sure to be honest. But I I think it's the time that it takes . um . . . . . half of the ma material to . decay. . . I'm I'm not positive, to be honest Chuck. (I-t;P-d)

A short time after this statement, the learner commented "Isn't it the time that it takes the substance to decay?" (I-t) These statements indicated that Jennifer could mentally represent the Half-Life-one concept; that half life was the time required for half the mass

of a radioactive material to decay into it's progeny. Thus, she possessed intelligibility for the Half-Life-one concept. However, her believability in this mental representation was not strong. This was revealed by her vacillation of understanding of the meaning of half-life and the fact that she frequently made plausibility statements that indicated this weakness of belief (e.g. "I'm not exactly sure to be honest" and "I'm I'm not positive, to be honest, Chuck", (P-d)). Thus, she demonstrated developing plausibility.

When asked if she found her understanding of her work sheet's column three to be useful, she commented:

> . . Well . if you have something that has a . um . extremely long half-life. And you get exposed to it. Then you have to worry about the effects that that'll have. Let's say you got it, somehow got something into your system, or whatever, I don't know. You know and . you'd have to worry about the effects that they . I I mean considering most of em are . are longer than anyone's lifetime, I suppose the damage is done. It doesn't make that big a difference. But if you're talking about wanting to . assess personal damage. If you're talking about wanting to um . what was that . material . that radioactive [referring to a radioactive material that I recently disposed of in my capacity as the radiation safety officer]. Ya. Then you would have to consider that half-life. Because ten thousand years would be . it's gonna be . . active where ever you're gonna put it for an awfully long time. (F-p)

This statement revealed that Jennifer could think of two areas where her understanding that half-lives may be long, and that a half-life relates to the longevity of a radioactive material, would be useful. Thus, she possessed developing fruitfulness for the Half-Life-one concept.

Jennifer's status change: (Half-Life-one Concept)

Jennifer's pre-interview status was developing I, developing P, and developing F. Her post-interview status was I, developing P, and developing F. Thus, she experienced an increase in status for this concept. This change was due to the fact that during the post-interview Jennifer understood that half-life relates to the time required for the mass of the

initial radioactive material to decay. During the pre-interview, she only understood that half-life relates to an amount of time. Thus, she went through a conceptual capture process because she only added information to her understanding of the meaning of the half-life, term. No information was rejected or replaced.

Florence's interviews: (Half-Life-one Concept)

Florence's pre-interview: (Half-Life-one Concept)

When the researcher asked her the meaning of the term half-life, Florence responded:

> Half-life means . um . for all radioactive material . how long it takes . for half of this . this whole material . to ah . to . go through the radiation. Specifically . . . it's like a evaporation. You know it's it's . it's going . . ah . half . . . ok the material is lost . through that radiation process. . Ok half of the material. . . The time it takes . to . lose half of the material. That's called a half-life. (I-t,a)

At one point, Florence was asked why she believed her column three information was true. She responded:

> If there's like this material radioactive material. Half-time . life time is . how many years . you you have a certain amount of material after a number of years. Ok. That's the way I remember doing home work. You know those questions. That's why I I put down years. (I-t,P-u)

These statements indicated that Florence had the understanding that half-life refers to the time required for half of a mass of a radioactive material to become something else. Her plausibility statement indicated that she had plausibility for the Half-Life-one concept.

When asked if she found her column three information to be useful, the learner responded ". . Um . I don't know." Thus, she exhibited no fruitfulness for the Half-Life-one concept

Florence's post-interview: (Half-Life-one Concept)

When the researcher asked Florence the meaning of the term half-life, she responded "Half life means . ah when half of the radio material . . radioactive material . . ah converts or converted to something else. The time it takes . to lose half of the radio material." (I-t) This statement revealed that the learner had the understanding that half-life involves the time required for one-half of a given mass of a radioactive material to convert into its progeny. She this possessed intelligibility for this concept.

When the researcher asked her if she believed her column three information to be true, that the time change was six hours for half of the material to be converted to its progeny, the learner responded "That could be true. I'm just think (??) the half-times for different radioactive material . different . . so . . in . in some case, . . ah . it could be true." (P-d) This statement revealed that Florence believed in the concept of half-life as she understood it, and that she recognized that different materials have different half-life values. Thus, she possessed plausibility for the Half-Life-one concept.

Florence made no fruitfulness statements relating to this concept. Thus, her fruitfulness is unknown.

Florence's status change: (Half-Life-one Concept)

Florence's pre-interview status was I, P, and no F. Her post-interview status was I, P, and unknown F. Therefore, no change in status was detected.

Ralph's interviews: (Half-Life-one Concept)

Ralph's pre-interview: (Half-Life-one Concept)

While filling out the work sheet, Ralph commented:

> Ok Um so . . alright, I've . just , I've decided that I would have as a start . a unit quantity of matter. Of radioactive matter. And . the first intermediate time . ah .

> period will end with one-half of that . matter . left. And the second intermediate time period will end with one quarter . of that period. And . . (clears throat) that period will . . um . . I suppose it's . . . . it doesn't matter if I say that it doesn't matter at this point if I state that's the half-life. (I-t)

When the researcher asked Ralph to explain the meaning of the term half-life, the learner responded "Ok the . half-life . is . really the time that it takes for . half of a . say defined and isolated quantity of mass, quantity of mass, to decay . to half it's present . half your initial amount." (I-t) These statements revealed that Ralph understood the Half-Life-one concept. Thus, he had intelligibility for this concept.

When the researcher asked Ralph if he believed his clock information to be true, he responded:

> That's the model of behavior that I have . . set up for this material . that . I believe I am emulating . what I have been taught. is that . what I've read in books. That is my interpretation of what I think I was taught. (P-u)

This statement revealed that the learner believed his understanding of the concept to be true. Thus, he exhibited plausibility for the Half-Life-one concept.

When the researcher asked if he found his column three information to be useful, Ralph replied "You could then make prediction . of how much of that material would be left. . . . . At at what period of time. . . And . depending on your situation, determine . what to do with it." (F-p) This statement revealed that Ralph could think of an example of where his understanding would be useful. He therefore expressed developing fruitfulness for this concept.

Ralph's post-interview: (Half-Life-one Concept)

When the researcher asked Ralph the meaning of the term half-life, the learner responded "Ok. The half-life is . the period of time in which half of a given . hypothetical

quantity this radioactive element would decay . to half its beginning . ah . you know half the half the quantity you started with." (I-t) This statement revealed that Ralph had intelligibility for this concept.

When the researcher asked Ralph if he thought his understanding of half-life was true, he responded "Oh ya I think that's . they all pretty much follow that rule." (P-d) When then asked why he believed his understanding to be true, he replied "Cause that's what I was taught." (P-u) Near the end of the interview, Ralph was asked if he knew what the half-life correspondence was between the melting-ice analogy and the decay of a radioactive material. He replied "Well that would be . . . . where you . each time you . um . . had half the amount of material . . the amount of ice that you started with . I think I think that was . be the best way to define the half-life." (P-a) When asked the same question for the falling-tacks analogy, Ralph replied "Um . . . . that I didn't understand quite as well. Perhaps. But I would guess you'd have half the number of tacks landing on their sides. Half the number left over landing on their heads." (P-a) These statements revealed that Ralph believed that his understanding was true and thereby expressed plausibility for this concept.

When the researcher asked Ralph if he found his column three information to be useful, the learner made the following comment that related to the Half-Life-one concept: Well ya. I think for the same reasons. If you happen to be happen to be working on it. And you depend on a certain amount of this material to be there, ah . and . you know to provide power, ah . . to know how much is there." (F-p) This statement revealed that Ralph could think of an example of where his Half-Life-one concept knowledge would be useful, thereby expressing developing fruitfulness for this concept.

Ralph's status change: (Half-Life-one Concept)

Ralph's pre-interview and post-interview statuses were I, P, and developing F. Thus, no status change was detected.

Half-Life-two Concept:

Margaret's interviews: (Half-Life-two)

Margaret's Pre-interview: (Half-Life-two)

During the pre-interview, Margaret responded "no" (I-d) when asked if she had ever heard the term half-life in relation to radioactive materials. This indicated that she had no intelligibility for the scientifically accepted version of concept Half-Life-two.

On her work sheet, Margaret indicated that the size of the radioactive material in the dish decreased in size over time, showing, but not explaining, two hour clock changes between the two intermediate and the final elapsed time positions. When asked "How much faith do you have in the belief that that's the time involved?", her response was "I have no." (P-d). When further asked "Do you think it has the potential to be true?", she responded "Probably not."(P-d). When asked if she had any reason why not, she responded "No." (P-d) These statements indicated that Margaret had no plausibility for concept Half-Life-two.

When Margaret was asked if it would be useful "knowing the time involved for radioactive material to change.", she responded "it would be useful if you were working with this material. I'm had a if if what I'm saying is true, my concept. It would be very important if you were doing some special tests with this material." (F-e) This comment did fit into the extrinsic fruitfulness category. However, because she did not give any specific uses of the information, fruitfulness for the concept was not demonstrated. Thus she demonstrated no fruitfulness for the Half-Life-two concept.

Margaret's post-interview: (Half-Life-two Concept)

During the post-interview, Margaret revealed that she understood that the amount of radioactive material present decreased in increments of one-half. However, she thought that the number of half-life steps required to go to total decay was three as was demonstrated by her work sheet. In addition, during the interview, when asked to compare her work sheet with the correct version work sheet, Margaret stated:

> But if there, but I would think at the end it would be . . . really I would say that mine is more accurate. That it's more of a constant decay and . and that there's a constant . . the activity is constant with this continuous decay. So I would say mine is more. (I-t;P-m)

By these statements, Margaret demonstrated that her intelligibility for the Half-Life-two concept was developing. She is given a rating of "developing" because did not understand that the amount of material left went through several half-life steps, not just three.

During the post-interview, Margaret did not demonstrate a total belief that her understanding of this concept was correct. For example, in response to a question from the researcher concerning the step-wise decay of a radioactive material according to a half-life progression, Margaret made the statement that "I guess it would just be it would be a constant. Half-life to half-life to half-life. I guess. . . Just sort of makes sense." (P-n) and

> Well just um when you were talking to us you just said that the um . the decay is a constant. And it's going to continue. It's gonna be continuous decay . from the parent and . um . . . I would say ya, I think it makes sense . . . (P-l)

A little later in the interview, Margaret said "Well, if if I just remember what you said correctly, you were you were saying that it's a continuous process, the decay." (I-t,l;P-l) and "I I would say it's it's just continuous continuous." (I-t) These statements indicated that Margaret was relying on rote memorization of the lesson material, but that she had not given thought to the meaning or implications of the information. Thus, her plausibility for the Half-Life-two concept was developing.

During the post-interview, the researcher asked Margaret if "in terms of the time involved, it's like half-life, another half, and another half-life to be gone to nothing, do you think that is useful information for anyone in any sense?". Margaret responded that "Ya it would be useful to know how . how long it takes for the material to decompose." (F-p) When asked by the researcher why that would be useful, she replied "Well working in the lab it would be, it would ah be important to you to know . . just how much radiation you were being exposed to." (F-p) This demonstrated that Margaret could see that having an understanding of the time involved for a radioactive material to decay would be an important factor in limiting exposure to radiation. Thus, Margaret demonstrated that she could see that half-life knowledge was useful, and she could give a specific example of where that knowledge would be useful. Thus, her fruitfulness for the Half-Life-two concept was developing.

Margaret's status change: (Half-Life-two Concept)

During the pre-interview, Margaret demonstrated the status of no I, no P, and no F. During the post-interview, she possessed the status of developing I, developing P, and developing F. Thus, her status increased. This occurred because Margaret gained (conceptual capture) a partial understanding and plausibility for the Half-Life-two concept, that a radioactive material decays in half-life steps. But, she did not understand that the number of half-life steps involved was typically greater than three.

Felix's Interviews: (Half-Life-two)

Felix's pre-interview: (Half-Life-two)

Felix expressed pre-interview understanding of this concept by his comment while filling out the work sheet:

> I don't know how, I know what half-life is. It . you lose half and . . the radioactive material . . or whatever it's life span. If it were a hundred years, in fifty years it'd be half as strong . in order for there to be half as much material. In a hundred years there'd be . a quarter of the material. (I-e,t)

Later in the interview, in response to a question about the number of half-lives required for the radioactive material to be completely decayed, Felix responded "It's gonna go ah . a hundred, fifty, twenty-five, twelve, six and a quarter, three, and . whatever it comes out to . An eight. and on down. Eventually it gets down to zero." (I-e,t) Thus, Felix possessed intelligibility for this concept in that he understood that the mass of a radioactive material would be halved over successive half-life intervals. He also understood that the process continued until the material was entirely depleted. Whether he had reconciled this total depletion concept with the idea that, mathematically, dividing a number by two will never result in zero, is unknown.

When asked if he believed his half-life conception was true, he responded "I don't think I've ever observed it. Just what's been taught." (P-u) and "and they have to know what the dosage is. So . . I haven't been around radioactive materials long enough to watch it go all the way to zero. But I believe it happens." (P-d) These statements revealed that Felix possessed plausibility for the Half-Life-two concept.

As indicated in the pre-interview Half-Life-one concept discussion, Felix possessed developing fruitfulness for the Half-Life-two concept.

Felix's post-interview: (Half-Life-two)

Felix's post-interview responses disclosed his understanding of and believability in his thoughts about this concept. In response to a question concerning what he was representing with his work-sheet column three, he responded "Ya. Well. For each, if a half-life is a year, . . for every year . half of your remaining radioactive material is gone."

(I-e,t) When asked by the researcher to describe the half-life correspondence between the melting-ice analogy and a radioactive material, he responded:

> Isn't that in a given period of time, half the ice would a turn to water. Which is . I think is true. The volumes would be different because ice is bigger than water. And another equal time period later, . . half the remaining ice would be gone. And so forth. another equal time period, half of that remaining ice would be gone. And your water would increase. (I-a;P-d,a)

When asked if there were any correspondences set up between the falling-tacks analogy and a radioactive material, Felix responded:

> Eventually they're all ah . . . be . you gonna have none left . eventually. . . And all . . . the number . . of tacks goes down each time. You start with a hundred you . . it's sorta like maybe . . . thirty or forty of em . . (??) the first . throw . . . put down but usually it takes . . pretty much a certain number of tossed . . to get down to zero. Which would be . corresponding to the half-life. (I-a,e;P-a)

These statements demonstrated that Felix possessed both intelligibility and plausibility for the Half-Life-two concept.

As indicated in the post-interview Half-Life-one discussion, Felix also demonstrated developing fruitfulness for this concept.

Felix's status change: (Half-Life-two)

Felix held a status of I,P, developing F both before and after the lesson presentation. Thus, no change in status was detected.

Mark's interviews: (Half-Life-two)

Mark's pre-interview: (Half-Life-two)

While filling out the pre-interview work sheet, Mark commented

> If we chose . a hundred years . . . . for the process to end. . . . Then I'm not really

> specifying where exactly these . . the meter readings are. So . . since those are kind of indefinite, I could just call this . . . twenty five [referring to first intermediate time position] and seventy five [referring to second intermediate time position] and a hundred [referring to end of process time position]. If I were to say exactly were those were then it would depend on the half-life of the material and all that sort of thing. (I-t,e)

Although this statement alluded to half-life and its relationship to radioactive material decay, it did not indicate Mark's understanding of this relationship. Since no other statements were made concerning his understanding or plausibility for this concept, his intelligibility and plausibility are unknown.

When asked if he found his knowledge about the time involved in radioactive material change to be useful, Mark responded with the statement illustrated under the Half-Life-one concept fruitfulness discussion. This statement revealed that Mark found usefulness in his understanding of the Half-Life-two concept. However his understanding is unknown. Since in this study, the conditions relate to the scientifically accepted versions of these concepts, his fruitfulness is unknown.

Mark's post-interview: (Half-Life-two)

Mark was asked what the half-life correspondence was between the falling-tacks analogy and radioactive material decay. He responded " . . . Ya you could . . um . . if

> you chart out . the number of tosses versus the number of tacks on their side, . . you could . . . um . . find . a point at which half of the tacks . . were on their side . and . . identify the number of throws that it . would take to have half the tacks on their side. And that would be . the half-life of the material. . . and . as you go up in multiples of that amount . you were just about halving . the number of tacks . each time that were that were decaying, or turning on their side." (I-a;P-l,a)

This statement revealed that Mark possessed both post-interview intelligibility and plausibility for concept Half-Life-two.

Since no other post-interview statements concerning this concept were made by Mark,

his fruitfulness is unknown.

Mark's status change: (Half-Life-two)

During the pre-interview, Mark possessed the status of unknown I, unknown P, unknown F. During the post-interview, his status was I, P, unknown F. Thus, his change in status is unknown.

Fred's interviews: (Half-life-two)

Fred's pre-interview: (Half-Life-two)

When filling out the work sheet, Fred commented:

> So . we're at the third, or is it second intermediate [second]. . . Again um . . I'm now going to . . another half-life . gonna call it the second . half-life . . so . back to the physical . . characteristics. I've now lost a half the life, ah, I have lost . . half of the half, which would be a quarter. So I'm down to . three quarters . . . U 237. and gone. Um . . ok. Let me rephrase that. Let's put one quarter U 237 left, three quarters of it now . would be u 235. . . So God, when I get down to the next one, I'm gonna have to start doing some . real math thinking here. (I-t)

When Fred was filling out the "end of process" portion of the work sheet, he commented:

> So I've gone . . to my third . half-life, which actually . . . Would be . well . ah we'll leave it there. . . Sort of . . . half-life, and again now I've got to go with my mass. I had one quarter, so now I have . half of that would be one eight. (I-t)

These statements revealed that Fred had the understanding that a radioactive material's mass decreases by half during a half-life period and that this process is continuous. Thus, he demonstrated intelligibility for the Half-Life-two concept. No plausibility statements were made by the learner.

When the researcher asked Fred if he found his understanding of column three of the

work sheet to be useful, he responded:

> It can give you, a again, like a carbon 13 type of dating . system. Um it can tell you . . . . um . . . yes, I I I think there there is a significance . to knowing that that there are half-lives to these. Um . . you know, and and how quick. A as far as can I name them all, no. But . you know, it it can help . scientists . . determine, again, how long things have been around. (F-p)

This statement revealed that Fred thought that his knowledge of half-lives was useful, and he could site an example of its usefulness. He, thus, expressed developing fruitfulness for this concept.

Fred's post-interview: (Half-Life-two)

While filling out the work sheet, Fred commented "we'll take the first intermediate to be a first half-life. . I would lose half the amount of the radioactive material. " (I-t) and

> Ok . here . and that'd be half and half. Because half of it would be gone . the first half-life . come down to the second intermediate, which I would say is the second half-life. I'll make my clock . . . going down. . . . Um . . . . I would have . roughly a quarter of it left. . . With . . . ah three quarters of it as progeny. (I-t)

Later in the interview, Fred was asked to compare his work sheet with the correctly completed comparison work sheet. During this comparison process, Fred remarked:

> At the next half-life, which would be . by this scale which . you know it isn't the greatest, . at three quarters . . on the time . clock, forty five minutes, if we're looking at a straight . dial face, um . . let's see, a quarter, should be an eight left. . . And then again, there should be a sixteenth, and then on down. So again, I'd still be losing that half. (I-t)

These statements revealed that Fred possessed intelligibility for the Half-Life-two concept. No plausibility statements were made. thus, his plausibility is unknown.

At one point in the interview, Fred was asked if he found his column one information to be useful. He responded

> Oh sure. There's . . things that um . . . again, like we discussed last time, we have radioactive . material here. And . . things are being emitted and within their particular half-lives, half of that material would be spent. Ah . . . I guess, it would be useful . . . for scientists . to know . . what the half-lives are. So they can try and estimate what was there to start with. How old it may be. (F-p,r)

When asked if he found his column two information to be useful, he replied:

> And again, um as far . as doing any kind of studies . on it . um like we've talked about (??) carbon dating and things like that. I don't know if carbon is actually a radioactive material, but it has a decay. It has a half-life. So you can determine . . . . that. (F-p)

When asked if he found his column three information to be useful, he stated "Well ya cause, again, talking about storage of . waste radioactive material. And ya have to have some . idea of how long it's gonna have to be stored." (F-d,p) These statements revealed that Fred could site three examples of where his Half-Life-two understanding could be useful. Therefore, he demonstrated developing fruitfulness for this concept.

Fred's status change: (Half-Life-two)

During the pre-interview and post-interview, Fred expressed the status of I, unknown P, and developing F. During the post-interview, Fred expressed the status of I, unknown P, and developing F for the Half-Life-two concept. Thus, no change in status was detected.

Wilbur's interviews: (Half-Life-two)

Wilbur's pre-interview: (Half-Life-two)

During the interview, the researcher asked Wilbur to explain the meaning of the term half-life. During his response, the learner said "Half-life to me means that ah . whatever the level is at one point . . at some point, another point, it's what it'd be half the ah ah .

the strength that it was initially." (I-t) and "So just a a matter of of ah . . of going from half to half to half and and ah . . never quite reaching zero." (I-t) These statements revealed that Wilbur understood that radioactive material decay could be represented as a series of half-life steps where each step was measured in terms of a halving of the "strength" of the material. However, since he did not fill in his clock, it is not known if he understood that equal times were involved in each step change. Thus, Wilbur expressed developing intelligibility for this concept. The fact that Wilbur defined half-life in terms of "strength" rather than mass affected the intelligibility rating for the Half-Life-one concept and does not affect the intelligibility rating for this concept.

When asked if he thought that his column three information was true, Wilbur stated "I believe that's ah . you know I believe in ah . the facts about half-life." (P-d) Thus, Wilbur demonstrated believability in his understanding of the Half-Life-two concept. This believability represented developing plausibility for the Half-Life-two concept.

During his reply to being questioned about the meaning of the term half-life, Wilbur said "I think some of those things are used for dating dating purposes. Um . so you can maybe trace back to ah you know prehistoric times, or something like that." (F-p) This statement revealed that Wilbur found usefulness in his understanding of the Half-Life-two concept. Thus, he exhibited developing fruitfulness for this concept.

Wilbur's post-interview: (Half-Life-two)

When asked by the researcher to describe how he filled in the clock column of his work sheet, Wilbur responded "Ah ah this is ah six [initial clock time], ah this one this is nine [first intermediate time], . . it's nine and then ah ten thirty [second intermediate time]. And then twelve [end of process time]." (I-e) When Wilbur was asked to describe the clock changes, he commented "Well I meant to . show a half and half and half. Again . that's what I said." (I-t) The researcher then asked Wilbur if he thought his clock

information was true. He responded ". . Generally. Not not absolutely." (P-d) When asked why, the learner responded ". . . . . Well in ah . . if it took ah . six hours for half the ra radioactivity . to decide and took something else another another . half to decide . ah . it it . just . that's why I decided to make it to nine o'clock." (I-t) These statements revealed that Wilbur's understanding was that radioactive material decay could be represented as a series of half-life steps where each step was measured in terms of a halving of the "radioactivity" of the material. He also thought that time for each of the steps decreased by a multiple of two, which is alternative to the scientifically accepted understanding which maintains that the time increment for the steps is constant. Thus, he demonstrated developing intelligibility for the Half-Life-two concept. The plausibility feature of one of the statements revealed that the learner also possessed developing plausibility for this concept.

No statements that would reveal the learner's fruitfulness were made during this interview. Thus, his fruitfulness is unknown.

During the interview, Wilbur was shown the correctly completed comparison work sheet. When looking at the clock portion of his own and the comparison work sheet, he commented "will mine is to but mine mine took down to three hours . down . . . . . mine mine must be wrong then. If I went . . three hours it'd be it should should be the next . next three hours (??). now is it the if the half-life is three hours . . should a been should a gone all the way up to twelve [referring to second intermediate clock position] again I . . in three hours. Well this should be twelve then. If you if you're going just . strictly by the clock and then the the activity . if it's going down half . with each three hours . this should be this should be twelve then right?" (I-e,t;P-y) This revealed that Wilbur underwent a conceptual exchange process after viewing the correctly filled out work sheet. He had to become dissatisfied with the idea that the half-life time diminished

and replace it with the idea that the half-life time is constant. Because this exchange did not occur until the learner was confronted with the comparison work sheet, the change in understanding toward the scientifically accepted view of the Half-Life-two concept can not be credited to the lesson presentation.

Wilbur's status change: (Half-Life-two)

During the pre-interview, Wilbur possessed the status of developing I, developing P, and developing F. His post-interview status was developing I, developing P, and unknown F (prior to the comparison with the correctly filled our work sheet). Thus, no change in status was detected that could be attributed to the analogy-based lesson presentation.

Jennifer's interviews: (Half-Life-two)

Jennifer's pre-interview: (Half-Life-two)

When talking about the half-life concept area, Jennifer only made statements indicating that she had an understanding that half-life involved time. For example, during a discussion about half-life, Jennifer commented:

> So like if it's . . some are worse than others. Like, you know, if it's got a longer half-life, then it's gonna be around a longer time. It's gonna be . . not around. It's it's gonna be around, but it's gonna be radioactive for a longer period of time. (I-t)

This statement indicated that Jennifer thought that the half-life of a radioactive material related to how long it would remain radioactive. She had no mental representation of the step-wise decay sequence that resulted from an understanding of the half-life concept. Thus, Jennifer expressed no intelligibility for this concept.

Jennifer made no statements indicating her believability in he understanding of this concept, or her usefulness for her understanding. Thus her plausibility and fruitfulness

are unknown.

Jennifer's post-interview: (Half-Life-two)

While commenting on the meaning of the term half-life, Jennifer stated:

> You started out and you would talk about . you know . if it if it was so many years and then it would be (laughs) if it was still going. Then it would be like half of those years. And then half again, and then . until it all decayed. (I-l,t)

When the researcher asked Jennifer if she believed her column three information to be true, she stated "You know I mean I don't . the only way anybody could figure that out is just by calculations. Because no one's actually done that experimentally. For those things that are that long that is." (I-t;P-e) These statements revealed that Jennifer had an understanding that a radioactive material would decay in a step wise manner that was related to half-life. But, her second statement indicated that she did not understand that this meant that the amount of initial mass remaining would follow the pattern one-half, one-quarter, one-eight, one-sixteenth, etc. Thus, she possessed developing intelligibility for the Half-Life-two concept.

A little later in the interview, while equating her own work sheet with the third column of the correctly completed comparison work sheet, Jennifer commented "Ya. They know more specifically when it changed. Whatever . particular one they had in mind." When then asked by the researcher which column three was more true, the learner commented "Well there's is probably more true. I don't know why." (P-n) The researcher then asked Jennifer which column three was more of an accurate representation of the time involved, and why. She responded "It [referring to the comparison work sheet] probably does. Well because whoever figured it out probably knew what they were doing." These statements indicated that Jennifer believed that the step wise half-life decay

sequence was an accurate representation of the decay phenomenon because others, who knew how to do the calculations, had determined it to be so. If she had an understanding of the way that these step wise half-life calculations functioned, these statements would have represented full plausibility. However, since she had only a partial mental representation of this concept, she exhibited only developing plausibility for the Half-Life-two concept.

When the researcher asked Jennifer if she found her understanding of the third column of the work sheet to be useful, she commented "No (laughs). Well that's what I mean. Well useful for who? It's not useful for me." (F-d) This statement indicated that the learner did not find her knowledge to be useful. Therefore, she expressed no fruitfulness for this concept.

Jennifer's status change: (Half-Life-two)

The learner's pre-interview status was no I, unknown P, and unknown F. Her post-interview status was developing I, developing P, and no F. Thus, her status increased, at least in terms of the intelligibility condition. This was a result of the conceptual capture of the understanding of the existence of a step wise pattern of radioactive material mass decay. The fact that she did not understand the nature of this calculation prevented her from possessing full intelligibility. Nevertheless, this recognition of the existence of this pattern was not present during the pre-interview.

Florence's interviews: (Half-Life-two)

Florence's pre-interview: (Half-Life-two)

When filling out the work sheet, Florence made the comment:

> There's a equation. If you know ah ah um . the life time of a radioactive material,

> actually you can actually calculate after how long . say you start with ten grams of this radioactive material, you know the life time of this radioactive material, you can actually calculate at anytime how much left. (I-e,t;P-o)

When the researcher asked her if she remembered the equation, Florence responded "No I only remember it's a log equation." (I-t) The equation that she was trying to remember was possibly $N = N_o e^{-(lambda)(t)}$, where N_o is the original number of radioactive nuclei, N is the number of nuclei after time t, and lambda is the first order rate constant for the particular material under consideration. Florence exhibited that she did not have a mental representation of this equation, or the step wise decay sequence inherent in the half-life decay of a radioactive material that can be illustrated with the application of this equation. Thus, she demonstrated no intelligibility for the Half-Life-two concept.

The plausibility features of Florence's statements revealed that she believed that an equation that could be used to calculate the amount of a radioactive material at any given time existed. But since she did not have an understanding of the form of this equation, or the half-life learnings that result for its application, she demonstrated no plausibility for this concept.

Since no other applicable statements were made, the learner's fruitfulness is unknown.

Florence's post-interview: (Half-Life-two)

When the researcher asked Florence if she found her column three information to be true, she replied "That could be true." (P-d) When he then asked her why she thought it could be true, she replied:

> It takes six . . let's just say six years . . to reduce . the last . stuff material. Which the half of the original to half of its . its self. . So . when you reach the end of . the process, will be much longer than six. (I-t)

A little later in her response to this inquiry, Florence stated:

> Why do I think that is true? . . By the definition of half-life and you you reduce the . starting material to (??). . . . You reduce to half . then ah you're gonna have one quarter, one eight, one sixteenth. . . It's still not the end of it. So you you have to keep going. And that's already a couple of half-lives. (I-t,P-o)

These statements revealed that Florence had the understanding that the radioactive material decay process can be represented by half-life steps. The plausibility features of these statements revealed that she believed this understanding to be true. Thus, she possessed intelligibility and plausibility for the Half-Life-two concept.

Florence made no fruitfulness statements for this concept. Thus, her fruitfulness is unknown.

Florence's status change: (Half-Life-two)

Florence's pre-interview status was no I, no F, and unknown F. Her post interview status was developing I, developing P, and unknown F. Thus, her status increased. This increase occurred because Florence experienced a conceptual capture of knowledge concerning the half-life decay sequence. She did not display this understanding during the pre-interview.

Ralph's interviews: (Half-Life-two)

Ralph's pre-interview: (Half-Life-two)

While completing his work sheet, Ralph commented:

> Ok Um so . . alright, I've . just , I've decided that I would have a . a start . a unit quantity of matter. Of radioactive matter. And . the first intermediate time . ah . period will end with one-half of that . matter . left. And the second intermediate time period will end with one quarter . of that period. And . . (clears throat) that period will . . um . . I suppose it's . . . . it doesn't matter if I say that it doesn't matter at this point if I state that's the half-life. (I-t)

A little later in the interview, Ralph was being questioned about his understanding

concerning the end of the decay process. During this exchange, the learner commented "And . you would ah . . . . you would . well smaller and smaller quantities would decay . would decay . One-half would decay and one-half would decay." (I-t) These statements revealed that Ralph understood that there was a step wise decay sequence involved in radioactive material decay. Thus, he expressed intelligibility for this concept.

The plausibility and fruitfulness remarks that Ralph made under the Half-Life-one discussion are also applicable to this concept. They revealed that Ralph had plausibility and developing fruitfulness for the Half-Life-two concept.

Ralph's post-interview: (Half-Life-two)

While filling out the work sheet, Ralph commented:

> The next day . . . . we had . . some . . . substance that . . . . and it was . . . . um . . . half of it had decayed. Five . . of its unit activity. . . Now let's see. I guess I'll . make that a million years . after . the beginning. . . . . after a million years . . . ok. . So . . . . . and then after another million years . . . . . we're down to about . well we've . . . after another half-life that is . it's decayed . . . and there's only one quarter of it left. (I-e,t)

A little later in the interview, the researcher asked Ralph to explain why he indicated that it took several half-lives to get to the end of the process. Ralph responded "The way you split it up into . half . each time. . . . Get ah . I mean you get down to a quarter, then an eight, and then a sixteenth, then a thirty second, then a sixty fourth." (I-t) Near the end of the interview, the interview asked if Ralph remembered any of the correspondences between the melting-ice analogy and the decay of a radioactive material. In response, Ralph replied "I don't recall whether you said that they . follow the same mathematical model. which is a logarithmic, a natural log function" (I-t;P-o) These statements revealed that Ralph understood that a radioactive material decayed in half-life steps, and that he believed his understanding to be true. Thus, he possessed intelligibility and plausibility

for this concept.

When the researcher asked Ralph if he found his column three information to be useful, the learner commented "Well ya. I think for the same reasons. If you happen to be happen to be working on it. And you depend on a certain amount of this material to be there, ah . and . you know to provide power, ah . . to know how much is there." (F-p) This statement revealed that Ralph could think of an example of where his Half-Life-two concept knowledge would be useful, thereby expressing developing fruitfulness for this concept.

Ralph's status change: (Half-Life-two)

During the pre-interview, Ralph possessed the status of I, P, and developing F. During the post-interview, Ralph possessed the status of I, P, and developing F. Thus, no change in status was detected.

Activity-one Concept:

Margaret's Interviews: (Activity-one)

Margaret's pre-interview (Activity-one)

During the pre-interview, when asked the meaning of the term activity, Margaret replied "Activity . . . just . if you would . it would just be how radioactive the . how much activity, radioactive radioactivity, is in this . . piece of material." (I-t) This indicated that Margaret thought that activity was something possessed by a radioactive material rather than a measure of the rate of decay. Thus, she demonstrated no intelligibility for concept Activity-one.

When asked if her column two work-sheet response had the potential to be true, Margaret responded "Probably not." (P-d) Then in response to the researcher question

"And why not?", she replied "Because I don't know anything about this." (P-d) and "I I have no idea." (P-d) These statements indicated that Margaret possessed no pre-interview plausibility for Activity-one concept.

During the pre-interview, Margaret made no statements concerning her fruitfulness for the Activity-one concept. Thus her fruitfulness is unknown.

Margaret's post-interview: (Activity-one)

During the post-interview, when asked to explain the meaning of the term activity, Margaret responded "I I think that's when the ah . the nuclei are breaking down. In the the radioactive material." (I-t) When asked to explain her response more fully, she replied "Constant . . it's a constant. It's a constant um . decaying and activity of this." (I-t) Later in the interview, when asked what the correspondence was between the melting-ice analogy and a radioactive material in terms of activity, Margaret responded that "It was constantly . constantly decaying and and breaking down." (I-t;P-l,a) When asked about the activity correspondence between the falling tacks and a radioactive material, Margaret responded in a similar manner, "Well you said that it was pretty constant." (I-t,l;P-l) These statements indicated that Margaret understood that activity involved the decay of the nucleus of a radioactive material. However, she did not understand that activity referred to the rate of decay of a radioactive material. In fact, her frequent references to the activity as a constant indicated that she was confusing the half- life phenomena with the term activity. Thus, her post-interview intelligibility for concept Activity-one was developing. The plausibility features of the above statements revealed that Margaret believed that the activity involved the decay of the nucleus and that the activity was constant. Because the nuclear origin part of her beliefs about activity were correct, she demonstrated developing plausibility for the scientific version of the Activity-one concept.

During the post-interview, Margaret made no statements concerning the usefulness of the Activity-one concept. Thus, her fruitfulness is unknown.

Margaret's status change: (Activity-one)

Margaret's pre-interview status for the Activity-one concept was no I, no P, and unknown F. Her post-interview status was developing I, developing P, and unknown F. Thus, her status for concept Activity-one increased after the lesson presentation, at least for the I and P conditions. This increase occurred because Margaret began to understand that activity deals with the disintegration of parent nuclei (conceptual capture).

Felix's Interviews: (Activity-one)

Felix's pre-interview: (Activity-one)

During the pre-interview, when asked if he had ever heard the term activity, Felix replied "No. All I can do is just kind of relate it to half-life." (I-d) However, when asked later in the interview why he believed that the meter dial would decrease over time, he answered "Because it's decomposition." (I-t;P-o). A little later in this same reply, he stated "So it has decomposed. Broken down to something else. Which is not radioactive. Your mass, your mass of energy goes down." (I-t;P-o) These statements revealed Felix did not have an understanding of the meaning of the term activity. However, based on his statements, it is apparent that he did have an understanding of the activity concept in that he understood that the meter's reading was related to the "mass of energy" (radioactivity) possessed by the material. Thus, he demonstrated a developing intelligibility for this concept.

A consideration of the plausibility features of the above statements indicated that Felix based his ideas about this concept on a reasoned parallel between decreasing amount of

radioactive material and decreasing radioactivity possessed by that material. Thus, he revealed a connection between his understanding and a portion of his conceptual ecology, thereby demonstrating developing plausibility for this concept.

During the pre-interview, Felix made no statements concerning his fruitfulness for his thoughts about concept Activity-one. Thus, his fruitfulness is unknown.

Felix's post-interview: (Activity-one)

During the post-interview, when asked "what is activity . as it relates to a radioactive material?", Felix responded "It's a I think it's the rate at which the material decomposes." (I-t) The researcher then asked "Ok. What would be typical units . of ah activity? . . . If not specifically but . generically.?", he answered "The amount of . . I guess if you looked at a Geiger counter . be the amount of . . pulses per second. Or whatever it is." (I-t) These two statements indicated that Felix understood that activity relates to the number of disintegrations that occur per time. Thus, he demonstrated intelligibility for this concept.

Later in the interview, the researcher asked Felix to clarify his column-two work-sheet answer showing the meter dial going down as the radioactive material decayed. Felix responded:

> I think it would be . as the . . amount of radioactive material per unit mass decreases your . . your dial reading would be less. Your activity stays the same. . But your . . on the mass, on the equal mass basis it would be less. (I-t;P-o)

A little later in his answer to this question, he explained his thinking about the meter reading decreasing by the statement "Well as your . . area stays or mass stays, basically stays the same . . . the mass itself is absorbing some of the released energy. . So what's coming out to be picked up by a meter is less." (I-t;P-r) Felix's response to the researcher's question indicated that he possessed an alternative understanding of activity. His

response is consistent with the idea that the activity was related to the ratio of the (number of disintegrations)/(mass of remaining parent), which he stated to be constant, instead of being related to the number of disintegrations per second. This would explain why he thought that the activity would remain the same. As the amount of parent decreased, the number of disintegrations would also decrease, but the ratio would not change. Also, he thought that the reading on the meter dial was a function of the number of disintegrations and the amount of these disintegrations that were absorbed. Felix thought that the number of disintegrations went down, and the combined mass of parent + progeny remained constant. Thus, a higher proportion of the disintegrations was absorbed by the lump of material, resulting in a lower meter reading.

In addition, later in the interview, when talking about correspondences between the melting-ice analogy and a radioactive material, Felix said "The rate of melting is basically constant, which would be the activity." (I-t,a;P-a,l) When asked if there was a correspondence for activity between the falling tacks and a radioactive material, Felix responded "If there was it was . . . . . the tacks . which way they fell. . . There was sort of a constant. . . There was sort of like a certain percentage. . . As your number went down . . . "(I-t,a;P-a,l) These last two references to the analogies revealed that the learner still held the alternative understanding that the activity was related to the ratio of the (number of disintegrations) /(mass of remaining parent) rather than to the number of disintegrations per second.

The vacillation illustrated here concerning Felix's understanding of the Activity-one concept can be explained if one views his response to the researcher questions concerning the definition and units of activity as rote memorizations and his later responses as liberated convictions (Posner and Gertzog, 1982), resulting from reasoning.

In this light, these statement indicated that at the start of the interview, Felix did

understand that the activity was the number of disintegrations per second. Thus, he had the capacity to mentally represent this concept in a scientifically accepted manner, which is sufficient to say that he demonstrated intelligibility for this concept. However, when reflecting on ideas related to this concept, he thought that activity was a constant that was related to the ratio of (the number of disintegrations)/(mass of remaining parent material). The plausibility features of the statements relating to this idea indicated that he had plausibility for this alternative understanding of concept Activity-one. Thus, he did not demonstrate plausibility for the scientifically accepted version of the Activity-one concept.

When asked if he found usefulness in the knowledge that the meter dial went down over time, Felix said "Ya I think that's . . that would probably be . . . . tell you how much . radiation maybe the thing emitted from the source. A measure of it. Relative, it could be relative to (??)." (F-p) The researcher then asked "That would be useful . in . what sense?" Felix replied ". . One obvious one is . people being exposed . to the source. How much are they getting over a unit of time." (F-p). These statements revealed that Felix could think of specific examples of where knowledge of the behavior of the meter could be useful. However, since he thought that the meter dial reading was related to something different than activity, these statements do not indicate his fruitfulness for his alternative concept of activity. Thus, his fruitfulness for the Activity-one concept is unknown.

Felix's status change: (Activity-one)

During the pre-interview, Felix manifested a status of developing I, developing P, and unknown F. During the post-interview, Felix gave evidence that his status was I, no P and unknown F. Hence, his status increased for the intelligibility condition and decreased for the plausibility condition. The plausibility decrease was due to the fact that during the pre-interview, Felix understood and believed that the reading on the meter dial was

related to the "mass of energy" (radioactivity) possessed by a radioactive material. During the post-interview, Felix understood that activity was related to the rate of radioactive material decay. However, he thought and believed that the reading on the meter dial was related to the ratio of the amount of radioactivity/(combined mass of parent + progeny) and that, contrary to earlier post-interview statements, the activity stayed constant through-out the decay process because it was related to the (amount of radioactivity)/(mass of remaining parent). Thus, he went from dêveloping plausibility to no plausibility for the scientifically accepted understanding of the Activity-one concept.

Mark's interviews: (Activity-one)

Mark's pre-interview: (Activity-one)

During the pre-interview, when asked the meaning of the term activity, Mark responded "Um . . . . not spec, well I mean (??) . . . ah I mean that's part of the name. Radioactivity." This indicated that Mark did not understand the meaning of the term activity. Thus he demonstrated no intelligibility for concept Activity-one. No other statements relating to this concept were made by Mark. Therefore, he also demonstrated unknown plausibility and fruitfulness for this concept.

Mark's post-interview: (Activity-one)

When asked the meaning of the term activity, Mark responded "Activity is the . um . amount of radiation emitted . um . within a particular time." (I-t) No other statements relating to this concept were made. Thus he demonstrated intelligibility. But his plausibility and fruitfulness are unknown.

Mark's status change: (Activity-one)

During the pre-interview, Mark's status was no I, unknown P, unknown F. During the post-interview, his status was I, unknown P, unknown F. Thus, his status increased, at least in relation to the condition of intelligibility. The increase occurred because Mark acquired (conceptual capture) the knowledge that activity is the rate of radiation emission by the parent material.

Edgar's interviews: (Activity-one)

Edgar's pre-interview: (Activity-one)

When Edgar was asked the meaning of the term activity, he responded "I'm not familiar with this ah that term." (I-d) This statement indicated that Edgar had no intelligibility for this concept. Edgar gave no other statements relating to this concept. Thus, his plausibility and fruitfulness are unknown.

Edgar's post-interview: (Activity-one)

When the researcher asked Edgar to explain the term activity, he responded "Ah activity is the amount of radioactivity given off." (I-t) Later in the interview, the researcher asked Edgar to describe the correspondence between the falling-tacks analogy and a radioactive material in terms of activity. Edgar responded "Well, the activity levels were decreasing. It was the decay of the material from the progeny to the . . from the parent to the progeny." (I-t) These statements revealed that Edgar understood that activity was related to the number of disintegrations occurring, albeit not in terms of number of disintegration per time. Thus, he expressed developing intelligibility for the Activity-one concept. Since no plausibility statements were made, his plausibility is unknown.

When asked if he found any usefulness to his representation of the work-sheet's meter

dial changes, Edgar responded:

> It has some relevance into ah radon gas and other . radioactive materials that either bombarded with . radiation from television . . from ah . solar flares when their flying, and things like that. X-rays when at the doctor's office. Well, (clears throat) it certainly is good to avoid contact with radioactive material . if at all possible, and if you can not avoid it, then you should minimize the risk,or the time . or take precautions . like wearing shielded clothing, or something like that. (F-p)

This statement revealed that Edgar could think of several ways in which his understanding of the Activity-one concept could be useful. Thus, he demonstrated developing fruitfulness for this concept.

Edgar's status change: (Activity-one)

During the pre-interview, Edgar possessed the status of no intelligibility, unknown plausibility, and unknown fruitfulness. During the post-interview, he demonstrated the status of developing intelligibility, unknown plausibility, and developing fruitfulness. Thus, Edgar's status increased. This change was due to the fact that Edgar developed a partial understanding of the fact that activity is related to the amount of radiation that a radioactive material emits. Since no prior knowledge had to be rejected, this was a conceptual capture process.

Fred's interviews: (Activity-one)

Fred's pre-interview: (Activity-one)

While filling out the work sheet, Fred commented:

> So it's gotta be either a proton or neutron that is coming off and what the meter should be, I'm assuming it's reading, is the . . I'll call it a concentration. The amount of . . those photons that are are hitting . the meter. (I-t;P-r)

A little later in the interview, the researcher asked Fred the meaning of the term

activity. In response, he stated:

> activity would be . how much . . . . the the process is moving or . um . . . like activity would be a half-life for U 237 . has a half-life of um let's just two hundred years, or something off the top of my head. Where something may have a half-life of . ten minutes. I would assume that has a more . . a higher activity associated with it. When you have a less of a half-life, it it's gonna be moving a lot faster getting um . . . it it's gonna deplete itself a lot faster. (I-e,t;P-o)

These statements revealed that Fred had the cognitive representation that the meter dial responded to the emissions of the radioactive material. However, he did not describe a process associated with emitted radiation per time. Also, he did not relate this representation to the meaning of activity when giving his definition of this term. Instead, he related activity to the velocity of the radioactive decay process. Thus, he possessed developing intelligibility for the Activity-one concept. The plausibility features of his statements indicated that he believed that his understanding was correct. Therefore, he possessed developing plausibility.

When asked if he found any usefulness to his representation of how a meter dial next to a radioactive material would behave, Fred commented "Ah-um . . in giving . . someone a . . an understanding of the level of radioactivity . . in that area. Again safety." (F-p) This statement revealed that Fred could cite an example of the usefulness of his understanding about a meter dial's behavior. Thus, he possessed developing fruitfulness for this concept.

Fred's post-interview: (Activity-one)

In response to being asked the meaning of the term activity, Fred replied:

> You went over that the other day [referring to the analogy-based lesson presentation] ah-um activity is the . amount, oh gosh, now I forgot. Amount of . . um . . radiation within a given time frame, time span. The . . I guess it's probably ah to the radioactive decay within a a time frame. (I-t;P-l)

This statement revealed that Fred had intelligibility for the Activity-one concept in that he could cognitively represent the concept of amount of radiation emitted in a given time period. His statements also had plausibility category features (e.g. "oh, gosh, now I forgot" and "I guess it's probably") which indicated that Fred did not strongly believe that his understanding of the term activity was correct. Thus, he exhibited developing plausibility. Since no other statements were made that related to this concept, his fruitfulness is unknown.

Fred's status change: (Activity-one)

During the pre-interview, Fred possessed the status of developing I, developing P, and developing F. His post-interview status was I, developing P, and unknown F. Thus, his status increased, at least for the intelligibility condition. This increase in status was due to Fred gaining an understanding that activity related to radiation emitted per time as opposed to the velocity of the radioactive material decay process. This change represented a conceptual exchange process.

Jennifer's interviews: (Activity-one)

Jennifer's pre-interview: (Activity-one)

When the researcher asked Jennifer if she had ever heard the term activity, she responded "No." (I-d) At one point in the interview, Jennifer was asked what the meter dial was responding to. She responded ". It's it's measuring the amount of . um . exposure that you got to that radioactive material." (I-t) When then asked the nature of this exposure, she responded "I don't know. I don't know enough about it." (I-d) These statements revealed that the learner did not have a mental representation of the term activity. She also did not have an understanding that radioactive material decay involved

the emission of radiation, as revealed by her second statement. Thus, she exhibited no intelligibility for the Activity-one concept.

Jennifer made no statements about the plausibility or fruitfulness of the Activity-one concept. Thus, her plausibility and fruitfulness are unknown.

Jennifer's post-interview: (Activity-one)

When the researcher asked Jennifer the meaning of the term activity, she responded ". That's the ah . . . . um . this is why I'm not a teacher. (laughs) It it's the amount of ah . radioactive . um . how should I say this. It's the amount radioactivity that the substance has . like . . . It's the amount of ah . . exposure that you get from a radioactive material." (I-t) Jennifer was then asked to describe the nature of this "exposure". She replied ". . I guess you get bombarded by whatever particles the substance is giving off . that are radioactive." (I-t;P-r) These statements indicated that the learner had the understanding that activity involved the amount of radiation emitted by a radioactive material. But, she did not understand that the concept also involved the amount emitted per time. Thus, she expressed developing intelligibility for this concept.

The plausibility feature of the second statement indicated that Jennifer "guessed" that the exposure from a radioactive material was a result of emitted particles. Thus, her plausibility was developing.

Jennifer made no statements concerning the usefulness of her understanding of the meaning of the term activity. Thus, her fruitfulness is unknown.

Jennifer's status change: (Activity-one)

Jennifer's pre-interview status was no I, unknown P, and unknown F. Her post-interview status was developing I, developing P, and unknown F. Accordingly, she experienced a status increase. This increase resulted for her conceptual capture of the knowledge that activity related to the amount of radiation emitted by a radioactive

material.

Florence's interviews: (Activity-one)

Florence's pre-interview: (Activity-one)

When asked the meaning of the term activity, Florence responded:

> Activity. . . Activity means when this radioac . radioactive material is active. It's doing in the radiation ah ah . emits radiation. Activity, the way I understand it is . it's . . . activity actually what is activity? Um . . . . . I'm thinking what is activity. Ah if I know what is activity. Oh . I'm just throwing out something actually. I think I don't know what is activity. (I-t,d)

This statement revealed that the learner had no intelligibility for the Activity-one concept.

Since no other pertinent remarks were made by the learner, her plausibility and fruitfulness for this concept are unknown.

Florence's post-interview: (Activity-one)

When asked to define the term activity, Florence responded "Um . . activity. What that means. . . The amount of radiation that how I understand. It'll be the amount of radiation." (I-t) A little later in the interview, Florence was asked why her post-interview meter went down over time and her pre-interview meter went up over time. She responded "Because I think I understood . I understood what you were looking for. If this meter actually just measures . the current radiation. Current amount of radiation." (I-t) These statements indicated that Florence had the understanding that activity related to the amount of radiation emitted by a radioactive material. But, she did not understand that it also involved time. Thus, she demonstrated developing intelligibility for the Activity-one concept. Since no plausibility statements were made, he plausibility is unknown.

When the researcher asked if she found her column two information to be useful, the learner replied:

> I think that's useful. Ah . because . people know you have less amount of radioactive material, the activity will be less. I think that's useful information. As far as like personal safety concerns. Like if you . get exposed to a large amount of a radioactive material, . and you know you got exposed to like a . large quantity of activity, radioactivity. And that's more dangerous than just a . a small . . amount of radioactivity. (F-p)

This statement revealed that Florence recognized an application of her knowledge of the Activity-one understanding. Thus, she expressed developing fruitfulness for this concept.

Florence's status change: (Activity-one)

Florence's pre-interview status was no I, unknown P, and unknown F. Her post-interview status was developing I, unknown P, and developing F. Thus her status increased. This increase occurred because Florence captured the knowledge that activity related to the amount of radiation emitted by a material.

Ralph's interviews: (Activity-one)

Ralph's pre-interview: (Activity-one)

When filling out the work sheet, Ralph commented "Let's see . . (clears throat) . . and . we'll . . . . . we'll say that it starts out at one-hundred units. One-hundred events per . . . one-hundred events . . events per . . um . . . um . . . . (clears throat) . . . ya we'll call that events per second" (I-e,t) In response to being asked what his term "events" meant, Ralph responded:

> Radioactive decay. I . I . . with the ah . . . I recall that your would have per each . each time on ah . you detect a . ah . particle that spins out of the nucleus. Whatever it is. An alpha particle or a beta particle. Ah whatever that is that's spit

> out, it would ah . hit you detector unit and it would register . on your oscilloscope. And you would count those. And that would be an event. (I-t;P-r)

These statements revealed that Ralph understood that activity related to the amount of radiation being emitted per time. Thus, he possessed intelligibility for this concept.

When the researcher asked if he believed his column two information that depicted the meter dial as decreasing with radioactive material decay, Ralph responded:

> Well I'm not sure of that. I'm . base that on the . . ah . my belief that . there is . . a rate of decay that is exactly proportion to the amount of radioactive material present. If that's . remains . (clears throat) if it doesn't change into any other kind of radioactive material in the process. (P-o)

This statement, along with the above real mechanism statement, revealed that Ralph believed that his understanding that the meter dial responded to events per second was true. Thus, he expressed plausibility for the Activity-one concept.

When the researcher asked if he found his column two information to be useful, Ralph answered:

> Oh ya I think a irrespective of what type of material you're using, to know what kind of . to know how much . um . how many . say . um . um . high energy particles are going through . ah any . through ah ah . a measured area, or known area of space, in a certain location, that may be very useful information. Especially . ah safe to determine the safety of that particular place. And . especially to, . with respect to . . ah . safety to human beings in the area. animal . ah life forms. (F-p)

This statement revealed that Ralph thought that his understanding was useful, and he could give an example of its usefulness. Therefore, he possessed developing fruitfulness for this concept.

Ralph's post-interview: (Activity-one)

When asked to define the term activity, Ralph replied "Um . . ya I it would be . um . . .

. . ah it would be the rate at which um . a . . substance, given a particular quantity, would decay . to . um . um . . well to half its present amount." (I-t) When then asked what the units of activity were, Ralph responded "Um . . events . per unit time." (I-t) Later in the interview, when describing his column two, Ralph commented "Activity which is . say one . one event per . unit time." (I-t) These statements revealed that Ralph understood that activity related to the amount of radioactive decay, or events, that occurred per time. Thus, he demonstrated intelligibility for this concept.

When the researcher asked Ralph if he thought his column two information was true, he responded "Ya I think that's accurate." (P-d) When then asked why, the learner responded "Mostly what I was taught. . . . After it undergoes certain . after every half-life, . the amount that is there will be exactly half and . its activity will be exactly half." (P-o) These statements revealed that Ralph believed his understanding of this concept to be true. Thus, he possessed plausibility for this concept.

When Ralph was asked if he found his column two information to be useful, he responded "Um ya um . . . . . I suppose . it would be useful to some. But the direct measurement of the radioactivity does . um . ah . indicate . how dangerous or safe that mass is." (F-e,p) and "Well I suppose it's useful for a lot of things I just . can't really . be to specific about that." (F-r) These statements revealed that Ralph thought that his knowledge of activity was useful, and he could think of an example of its usefulness. Thus, he demonstrated developing fruitfulness for this concept.

Ralph's status change: (Activity-one)

During the pre-interview and post-interview, Ralph possessed the status of I, P, and developing F. Therefore, no change in status was detected.

Activity-two Concept:

Margaret's Interviews: (Activity-two)

Margaret's pre-interview: (Activity-two)

While completing column two of the work sheet during the pre-interview, Margaret indicated that the start meter dial reading was 80 units, the first intermediate position was 50 units, the second intermediate position was 25 units, and the end of process position was zero units. (I-e,t) By itself, this indicated that Margaret had the ability to mentally represent the amount of radiation that the radioactive material emitted (the activity, albeit not explicitly defined as such) decreasing with decay. Thus, she exhibited intelligibility for this concept.

When asked by the researcher why she chose those numbers, Margaret stated "No I just, I just picking arbitrary numbers and trying to rationalize them as as the smaller it [the radioactive material in the dish] gets the less radiation." (I-t, P-o) Later in the interview, when she was asked her believability for the Activity-two concept; "if you had a a meter that was next to a radioactive material that the needle would . . would behave that way? Start out high and go low?". Her response to this question was "Once again, I was trying to . . . . trying ta make sense of what I did in column one." (P-o) This would seem to indicate that Margaret had plausibility for concept Activity-two. But, when further asked if she thought that her ideas about column one had the potential to be true, she responded "probably not." (P-d). When asked why not, she responded "Because I don't know anything about this. I I have no idea." (P-d) Thus, Margaret based her ideas about how the meter behaved on her knowledge of how a radioactive material decays, assuming that the less material present, the lower the reading on the meter. But since she did not exhibit plausibility for how a radioactive material decays (concept Decay-one), she also could not have exhibited plausibility for concept Activity-two.

During the pre-interview the researcher asked Margaret if she found the information in column two to be useful. She responded "Well it would be useful to someone if they were working in a lab. If this was true, they would know how much radioactive material was . present. And whatever precautions they would have to take to." (F-e,p) This statement demonstrated that Margaret could perceive that someone with an understanding of how much radiation was emitted could use this information to take the proper safety measures to protect themselves from the harmful effects of exposure to radiation. However, since she did not possess this information herself, it did not represent a personal use of the information. Thus, she exhibited no fruitfulness for concept Activity-two.

Margaret's post-interview: (Activity-two)

During the post-interview, Margaret filled out her work-sheet column two indicating that the meter dial reading went from 20 to thirteen, to seven, to one. (I-e,t) Later in the interview, Margaret was asked to compare her pre-interview and post-interview work sheets. During this process, she commented "When you start with the . . you know, as it decomposed that the radiation, the amount of radiation would go down." (I-t;P-o)

Later in the interview, the researcher asked her if she thought that her column two information was true. She responded "Well I would think so. Because as the material was getting smaller, your dial would be going down." (I-t;P-o) These statements revealed that Margaret understood that the reading on the meter dial, which is a measure of activity, would decrease with decay. Thus, she demonstrated intelligibility for concept Activity-two.

Later in the interview, in response to a question concerning why a decrease in the meter dial reading would tell he how much radioactivity one would be exposed to, she responded "Well the higher the meter the more radioactive material was present." (P-o)

This comment, along with the plausibility features of the above comments, indicated that Margaret believed her thoughts about the meter dials behavior. Thus, she demonstrated plausibility for the concept.

When the researcher asked Margaret if she found her column information to be useful, she replied "I would think so. If if you if you were interested in how much, ah, radioactive , ah, material you would be exposed to." (F-d,p) This comment demonstrated that Margaret found her understanding of the Activity-two concept to be useful. Thus, she exhibited developing fruitfulness for the concept.

Margaret's status change: (Activity-two)

Margaret's pre-interview status for the Activity-two concept was I, no P, no F status. During the post-interview, Margaret demonstrated that she possessed the status of I, P, and developing F. Thus her status increased. This status change represented a conceptual capture. During the pre-interview, she possessed the ability to mentally represent this concept. However, she did not have plausibility for her idea. During the post-interview, she possessed intelligibility, plausibility, and fruitfulness for the idea that the meter dial reading decreased with decay. However, no dissatisfaction with and replacement of her pre-interview ideas occurred.

Felix's interviews: (Activity-two)

Felix's pre-interview: (Activity-two)

When filling out column two of the work sheet, Felix stated "But over time . . . . your dial's gonna de decrease. Your reading's gonna decrease . . as you go through . your time." (I-t) Later in the interview, when asked by the researcher if he believed that the meter reading went down with decay, Felix responded "If were the maximum range, I

think as over a period of time, and you didn't change the scale, you would see a decrease." (I-t) Later in the interview, when asked why he believed that the meter reading would go down with decay, Felix responded "Your mass. "Your mass of energy goes down. Because of the decomposition process." (I-t;P-o) These statements revealed that Felix understood that the meter dial would decrease with decay, and that this decrease was related to the "mass of energy" which decreased with decay. Thus, Felix demonstrated pre-interview intelligibility for this concept. In addition, the last statement also had a plausibility feature where Felix related his understanding of decreasing activity to an element of his conceptual ecology, the decreasing mass of radioactive material with decay. Thus, he demonstrated plausibility for concept Activity-two.

During the pre-interview, Felix made no statements concerning his fruitfulness for his thoughts about concept Activity-two. Thus, his fruitfulness is unknown.

Felix's post-interview: (Activity-two)

During the post-interview, when filling out the meter column of the work sheet, the learner commented "And your dial would be . . . at a hundred in the beginning. . Then and it would be . . . lower. Let's say five-eights . . . At the third it'd be three-eights. . . And at the end it'd be zero." (I-t,e) This statement indicated that Felix understood that the reading on the meter dial would decrease over time. In response to a researcher question about the meaning of the term activity, Felix stated "The amount of . . I guess if you looked at a Geiger counter . be the amount of . . pulses per second. Or whatever it is." (I-t) Together, these two statements revealed that Felix understood that the meter dial was a measure of the activity of a radioactive material, and that this activity went down as the radioactive material progressed through the decay process. Because Felix had the ability to mentally represent this idea, he demonstrated intelligibility for concept Activity-two.

However, as delineated under the Activity-one concept discussion, these statements appeared to represent rote memorizations. Statements made later in the interview indicated that Felix had an alternative explanation for why the meter dial readings went down with decay. Later in the interview he expressed thoughts that the activity remained constant over time. Thus, due to this vacillation in understandings, he expressed no plausibility for the scientifically accepted version of concept Activity-two.

Since no other statements were made concerning this concept, he demonstrated unknown fruitfulness for concept Activity-two.

Felix's status change: (Activity-two)

Felix's pre-interview status was I,P and unknown F. During the post-interview, he demonstrated that his status was I, no P, and unknown F. Thus his status for concept Activity-two decreased. As indicated under the Activity-one discussion, this status change is due to the fact that during the pre-interview, Felix understood and believed that the reading on the meter dial was related to the "mass of energy" (radioactivity) possessed by a radioactive material. During the post-interview, Felix thought and believed that the reading on the meter dial decreased with time because it was related to the ratio of (the amount of radioactivity)/(combined mass of parent + progeny) and that activity stayed constant through-out the decay process because it was related to (the amount of radioactivity)/(mass of remaining parent).

Mark's interviews: (Activity-two)

Mark's pre-interview: (Activity-two)

When filling out his pre-interview work sheet, Mark commented "Um . . the radioactivity would be the highest at the beginning, and then (clears throat) . um . . an

intermediate time . . . it'd be a little bit lower . . . . and lower and then down to zero. . . . um clock at zero." (I-t) This indicated that he understood that the reading on the meter dial, which was a measure of activity, would go down with radioactive material decay. When asked if he believed his representation of the meter's changes was true, he responded "Yup. . Because as the . . material radioac material is decaying, you have less material there to give off radiation." (P-d,o) This indicated that the had plausibility for concept Activity-two.

When asked if he found his understanding of the meter dial's changes to be useful, he replied:

> Ya. It's, you know, if you're trying to use this as in in a practical . means methods, you know, measurement device or whatever, you've got to know that it's decaying. That the ah radio and the same thing with disposal. There's all sorts of practical implications. (F-p,r)

This statement revealed that Mark could see "all sorts" of practical implications for his knowledge, and he mentioned two. Thus, he demonstrated developing fruitfulness for concept Activity-two.

Mark's post-interview: (Activity-two)

When filling out the work sheet, Mark commented "Meter dial initially will be . . . . all the way on high. . . . . And then . . . it'll come lower . . . lower . and then . . . to zero." (I-t) When the researcher asked Mark if he believed that his work sheet represented how a meter would really behave, he replied "I think it's correct. . . . Ah because the the . less material . . radioactive material that you have as time goes down, the lower the . . radioactivity . the activity." (P-d,o) During the interview, Mark was shown a correctly filled out work sheet. When examining this correct work sheet, the researcher asked Mark why he thought it's meter dial was more accurate. Mark responded:

> . Indicated you . probably have . that's one-half . . um . it takes longer and longer . . to . . . . let me see. trying to express that . . . . . um . . the more radioactive material you have . . um . I guess . the more radioactivity, the more radioactivity your emit emitting. But that is you get to less and less material, you're emitting less and less. (P-r)

During the portion of the interview when Mark was asked to compare the falling-tacks analogy with radioactive material decay, he commented "ah it showed . it showed (clears throat) . . um . . . that . . as . . um . . . . . as time went on . the amount of radioactive decay decreased . just because you had less radioactive material there." (I-t;P-l,o) These statements indicated that Mark possessed intelligibility and plausibility for concept Activity-two. When the researcher asked Mark if he found any usefulness to his ideas about how the meter dial changed, the learner responded "Yes, for any practical uses of radioactive material. Well with a , with a a gauge that's used to measure . . the basis weight on a paper machine, you need to know that . the activity of that material is gonna go down over time." (F-p) In this statement, Mark revealed that he recognized that there are practical uses of his knowledge, and he gave one example concerning the determination of the basis weight of paper [density] during manufacture. Thus, he demonstrated developing fruitfulness for this concept.

Mark's status change: (Activity-two)

During the pre-interview and post-interview, Mark demonstrated the status of I, P, and developing F for the Activity-two concept. Thus, no change in status was detected.

Edgar's interviews: (Activity-two)

Edgar's pre-interview: (Activity-two)

When filling out the work sheet, Edgar represented the meter dial as moving from a reading of 100 to a reading of zero over the course of the radioactive material's decay. (I-

e,t) When asked why he drew the meter dial that way, the learner responded "Because as the . as the ah . . . as the material changes it's form it loses radioactivity." (I-t;P-o) Later in the interview, when talking about the usefulness of his understanding of the meter dial's change over time, Edgar made the comment "Ya (??) like I said it would depend on the level of radioactivity we're talking about, as the material decays and becomes less and less radioactive" (I-t;P-o) These statements revealed that Edgar had intelligibility and plausibility for concept Activity-two.

When asked if he found his understanding of the meter dial's changes to be useful, Edgar responded:

> Ah yes you would, . . depending on the level of radia radiation given off, . . would depend upon the . safety equipment, or the . . ah means by which you would transport the equipment. Something highly radioactive . obviously you would hope . you would put it into a a lead lined container. . . Ah-um something slightly radioactive . maybe a thinner lead-lined container. Um . something even less radioactive maybe you wouldn't even need lead, maybe heavy steel. . And finally something that would, that had lost its radioactivity . . or it was very trace, . you could just ah transport it . . in the jar, or whatever. (F-p)

Edgar could site an example of where his understanding would be useful. Thus, he possessed developing fruitfulness for the Activity-two concept.

Edgar's post-interview: (Activity-two)

While filling out the work sheet, Edgar commented "ah now later on . . . . we're still a solid mass . but radiation . has diminished." (I-t) Later in the interview, Edgar was asked to compare his work sheet with a correctly filled out comparison work sheet. During this comparison, he commented "They go through a change in state . . from a solid to a gas. Over a period of . . time. And the radioactivity levels also decrease." (I-t,e;P-o) A little later in the interview, the researcher asked the learner to explain the process of radioactive material decay. During his response, the learner said:

> It is the . . it is what happens to a radioactive material over a period of thousands of years . in that it changes its . . . level of radioactivity . and in true fact change its physical form also. It decreases its radioactivity level and change and also may in fact change form. (I-t)

At one point in the interview, the researcher asked Edgar what the correspondence was between the falling-tacks analogy and a radioactive material in terms of activity. During his response, Edgar stated 'Well, the activity levels were decreasing." (I-t) These statements revealed that Edgar had intelligibility and plausibility for the Activity-two concept.

Edgar gave no statements concerning the usefulness of his understanding of this concept. Thus, his fruitfulness is unknown.

Edgar's status change: (Activity-two)

During the pre-interview, Edgar demonstrated the status of I, P, and developing F. During the post-interview, his status was I, P, and unknown F. Thus, no change in status was detected.

Fred's interviews: (Activity-two)

Fred's pre-interview: (Activity-two)

While filling out the start position of the work sheet, Fred commented "And we'll move this needle over towards high at the start of this thing." (I-t) While filling out the second intermediate position of the work sheet, he commented:

> Alright . on the meter . . ah-um . . . . I I don't . I don't know exactly where the meter would be. . . . The intensity . God . let's think about this. . . . would have . . less . . . amount there . isotope . . emitting a radioactive signal. I would assume my intensity, if I'm staying the same distance away, my intensity I would have less . amount hitting the the meter. I'll assume that it it would drop. I don't know. I'm a, I don't know. I'm gonna put it at . roughly half . . I don't know that that's quite true. It may have . . may have moved . . farther . not quite as much . but for the

moment I'm putting it at at about half. (I-e,t;P-r)

Later in the interview, the researcher asked Fred if he believed his column-two work-sheet information to be true. During his response, Fred commented:

> I'm still showing I've got a high level of . of activity with it. After that, I cut cut it down. That that's all I'm trying to show is that as I move down [in amount of parent material], I should start to decrease the amount of activity . that would register on some kind of a meter. (I-t;P-o)

A little later in this same response, Fred commented "A again, you know, these meters, like a Geiger counter or something like that, is measuring what's being given off. And if I have less being given off, it's . gonna show me less on the meter." (I-t) These statements revealed that Fred understood that the activity of a radioactive material decreased as decay progressed. He also believed his understanding. Thus, he possessed intelligibility and plausibility for the Activity-two concept.

When the researcher asked Fred if he found his understanding of column two of the work sheet to be useful, the learner replied "Ya. Absolutely. Ah-um . . in giving . . someone a . . an understanding of the level of radioactivity . . in that area." (F-d,r) This statement revealed that Fred thought that his understanding of how a meter dial behaved being next to a radioactive material was useful. Thus, he demonstrated developing fruitfulness for the Activity-two concept.

Fred's post-interview: (Activity-two)

When filling out the work sheet, Fred commented "And at the start . well I'll put the meter . we'll make it some good stuff, it's at full, and ah . . full scale" (I-t) and "I should lose . . my radioactive counts on the meter . should be a lot less. . . And I'm gonna . . . . put a quarter . . for . first half-life [first intermediate position]" (I-t) and "Ah it'd be down,

again, at about a quarter . . of the radioactivity. . May be even less." (I-t) These statements showed that Fred understood that the meter dial responded to the amount of radiation and that the dial decreases with radioactive material decay. Thus, he had intelligibility for the Activity-two concept.

When the researcher asked Fred if he believed his column two information to be true, the learner responded:

> Of the the the meter may still be getting a heavy dose. And I guess all I'm trying to show on that is . . at the start . . all the radioactive mass is there. I haven't really started any decay. At the second intermediate, the first intermediate . time, which is the first half-life, half of my material would be gone. Is I guess what I'm trying to show there. More than a meter scale that to how much is actually being emitted at that point in time. (P-r)

and

> Which is what the meter would be reading . the decay. And um, I guess also the the activity . of the material is starting to lower, to drop off. As as I lose . . mass on the radioactive material itself, the parent . I start to lower the activity. It it starts to drop off. (P-o)

These statements revealed that Fred believed his understanding of the Activity-two concept to be true. Thus, he demonstrated plausibility for this concept.

No other statements concerning the concept were made. Thus, his fruitfulness is unknown.

Fred's status change: (Activity-two)

Fred's pre-interview status was I, P, and developing F. His post-interview status was I, P, and unknown F. Thus, no change in status for this concept was detected.

Wilbur's interviews: (Activity-two)

Wilbur's pre-interview: (Activity-two)

While filling out the work sheet, Wilbur commented "But ah . . . as time goes by, the the ah . . ah ah radioactive emission will be less and less" (I-t) and "Well the meter would would gradually . . come down" (I-t) These statements revealed that the learner understood that the amount of radiation emitted by a radioactive material decreased over time. Thus, he demonstrated intelligibility for this concept.

When the researcher asked Wilbur if he believed his column two information to be true, he responded ". . . Ya I I believe that's true." (P-d) When then asked why he believed it to be true, he responded "Because the the the radioactivity would go . (??) that dial over" and "I guess just from my past ah education or . readings. I have no no real . concrete . working . experience with it." (P-u) These statements indicated that Wilbur had plausibility for the Activity-two concept.

No statements were made by the learner that concerned the usefulness of his Activity-two concept understanding. Thus, his fruitfulness for this concept is unknown.

Wilbur's post-interview: (Activity-two)

While filling out the work sheet, Wilbur commented "Ah I would imagine that the needle is high . at the beginning. . Um . . goes down to a to a ah" (I-t) When asked to explain the meaning of the term activity, the learner responded "The activity in the beginning would be very high and at the end would be would be very low or nothing." (I-t) A little later in the interview, the researcher asked Wilbur if he believed his column two information to be true. Wilbur responded "Yes. Given given the ah . . indefinite time bet periods between em." (P-d) The researcher then asked why be thought his column two was correct. Wilbur responded:

> But ah . and I I for the sake of example, I said . six hours ah three hours ah you know . one and a half hours. Um . . but it . it could go on longer that that. You know you finally get down to the . to zero. That's that that other thing is um, you know, half and half and half and . keep going till . down to practical zero. (P-o)

These statements revealed that Wilbur understood that the activity decreases as decay progresses, and he believed this understanding to be true. He thus possessed intelligibility and plausibility for the Activity-two concept.

When asked if he found his column two information to be useful, Wilbur responded:

> . . Maybe in a in a limited range. If you could see it something something decaying or . . ah . . something that maybe . . there is no . ah . probably wouldn't detect it even. Probably wouldn't ah realize that maybe the . the danger of something like that. (F-p)

Wilbur was able to give an example of an application for his understanding of the Activity-two concept. He thus exhibited developing fruitfulness for this concept.

Wilbur's status change: (Activity-two)

During the pre-interview, Wilbur possessed the status of I, P, and unknown F. His post-interview status was I, P, and developing F. Thus, no change in status was detected.

Florence's interviews: (Activity-two)

Florence's pre-interview: (Activity-two)

When filling out the work sheet, Florence put the meter dial at zero, one eight, three quarters, and at full scale for the four time positions. While completing the work sheet, she commented "Ya. It [referring to the meter dial's needle] moved a little. Well actually what I'm thinking . to show is . at beginning it's slow. It . the . you know it's like a actual . acceleration process." (I-t) and "At the end of the process there'll be nothing left. . . . . Ok they're all gone. . . . This . . the dial points to the full scale. Which means that the

amount of radiation reaches the maximum."(I-t) A little later in the interview, she commented "Cause the way I understand the amount of radiation . you are exposed to ah one is exposed to, is related is time dependent. The long you're exposed to the . radiation, the more you got." (I-t;P-o) These statements indicated that Florence thought that the meter dial increased as the decay process progressed. She did this because she thought that the meter dial indicated accumulated radiation exposure, not instantaneous radiation [revealed during post-interview]. Hence, her statements did not relate to the Activity-two concept and she therefore exhibited unknown intelligibility for the Activity-two concept. When asked if she believed her column two information to be true, Florence replied "I'm not sure." (P-d) This statements, along with the plausibility feature of the above statement, indicated that Florence possessed developing plausibility for her notion that the meter dial needle moved up as the radioactive material decayed. However, this did not relate to the Activity-two concept. Thus, she expressed unknown plausibility for this concept.

When asked if she found her column two information to be useful, Florence responded "I . I don't know. I don't ah . . . I don't my opinion. It's just my opinion. No." (F-d) Thus, she expressed no fruitfulness for her idea that the meter dial needle mover up the scale with decay. However, since this did not relate to the Activity-two concept, her fruitfulness for this concept is unknown.

Florence's post-interview: (Activity-two)

While filling out the initial meter dial position of the work sheet, Florence commented "I have this radioactive material . at beginning. I . this much in volume. And a the meter dial . um . is in full scale." (I-t) When filling out the first intermediate position she commented "And the other meter dial um is gonna be less than full scale. So you can draw maybe . somewhere ah . . center." (I-t) When filling out the second intermediate

meter position, she commented:

> In the second intermediate time will be . more material lost. Um . . . . . and this the dial goes more towards the the the zero position. Ah . so . what I'm indicating here is . the activity . reduced as the material . is getting um less and less. (I-t;P-o)

A little later in the interview, the learner commented "So the activity . will be less and less. You know, towards the end of the process" (I-t) These statements revealed that Florence understood that the activity of a radioactive material decreases as the decay process proceeded. Thus, she demonstrated intelligibility for this concept.

When the researcher asked her if she believed her column two information to be true, Florence responded "Yes I do." (P-d) When asked why, she replied "Just the same reason. That's how . I . I learned it. How I read it in a book. How I remember it." (P-u) These statements indicated that Florence had plausibility for the Activity-two concept.

When the researcher asked the learner if she found her column two information to be useful, she responded:

> I think that's useful information as far as like personal safety concerns. Like if you . get exposed to a large amount of a radioactive material . and you know you got exposed to like a . large quantity of activity, radioactivity. And that's more dangerous than just a . a small . . amount of radioactivity. (F-r)

This indicated that Florence could conceive of an application of her column two information. Thus, she possessed developing fruitfulness for the Activity-two concept.

Florence's status change: (Activity-two)

During the pre-interview, Florence possessed unknown status for this concept. During the post-interview, her status was I, P, and developing F. Thus, no status change was detected.

Ralph's interviews: (Activity-two)

Ralph's pre-interview: (Activity-two)

While filling out the work sheet, Ralph commented "Let's see . . (clears throat) . . and . we'll . . . . . we'll say that it [the meter dial] starts out at one-hundred units" (I-t) and

> And then three hours later at which we . the time we have half the material . left . . . Um . I'll say we have . what . Um . . . fifty . . . . it's times per hour after three hours. . . . . Um I'll need (laughs) ok three pm. Ya that's the first intermediate . time and after that you would have . twenty five . I believe . a rate of twenty five at six . thirty, six o'clock. (I-t;P-o)

These statements revealed that Ralph understood that the meter dial reading, which was shown under the Activity-one discussion to relate to decays/second, went down as decay progressed. Thus, he demonstrated intelligibility for the Activity-two concept.

During his response to being asked to explain what he meant by his term "events", Ralph commented "And more . the more mass . the more of these . radioactive . particles . that you have . the more of this radioactive mass that you have, the more . events you would have. That's that is my thinking on that." (P-r) Later in the interview, when asked if he believed his column two information to be true, Ralph commented:

> Well I'm not sure of that. I'm base that on the . . ah . my belief that . there is a rate of decay that is exactly proportion to the amount of radioactive material present. If that's . remains . (clears throat) if it doesn't change into any other kind of radioactive material in the process. (P-o)

The researcher asked Ralph to explain why it made sense to him that the meter dial went down with decay. In response, Ralph said:

> Um . well . I . . . because the amount of material . . is propor the um . I I am . saying that the . um . because I believe that the amount . of material directly affects . the rate . of radioactive decay. so if there is half the amount of material, there should be half the rate . of radioactive events . measured detected. . . . and um . . . that's says . that's my that's my entire reason. (P-o)

These statements revealed that Ralph believed that his understanding of this concept was true. Thus, he expressed plausibility for the Activity-two concept.

When asked if he found his column two information to be useful, Ralph made the comment discussed under the Activity-one concept. Thus, he expressed developing fruitfulness for this concept.

Ralph's post-interview: (Activity-two)

While filling out the work sheet, Ralph made the following four comments: "Then I'll place . . oh . . the meter reading to be . . a unit or radiated radiation activity I guess . which would be . . a one [start position meter dial reading]." (I-e,t) and "the meter reading has dropped to point five [first intermediate dial reading] . . of its unit activity" (I-e,t) and "and there's only one quarter of it left [second intermediate column one]. . . . . um . . . so it's point five units of radioactivity. Point two five [second intermediate meter dial reading]." (I-e,t,;P-o) and "and you have an activity of zero [end meter dial reading]" (I-e,t) These statements revealed that Ralph understood that the activity decreases as the radioactive material decay process progressed. Thus, he possessed intelligibility for the Activity-two concept.

When the researcher asked Ralph if he believed his column two information was true, he responded "Ya I think that's accurate." (P-d) When asked why, he responded "Mostly what I was taught. . . . After it undergoes certain . after every half-life, . the amount that is there will be exactly half and . it's activity will be exactly half." (P-o) Near the end of the interview, Ralph was asked what the correspondence was between the melting-ice analogy and the decay of a radioactive material, in terms of activity. He responded "Um . . I guess that would be . defined as drips per unit time." (P-a) These statements, along with the plausibility features of the statements in the preceding paragraph, revealed that

Ralph believed his understanding of this concept to be true. He thus demonstrated plausibility for this concept.

When the researcher asked Ralph if he found his column two information to be useful, he responded "Um ya um . . . .. I suppose . it would be useful to some. But the direct measurement of the radioactivity does . um . ah . indicate . how dangerous or safe that mass is." (F-p) and " Well I suppose it's useful for a lot of things I just . can't really . be to specific about that." (F-r) These statements revealed that Ralph thought that his knowledge of activity was useful, and he could think of an example of its usefulness. Thus, he demonstrated developing fruitfulness for this concept.

Ralph's status change: (Activity-two)

Ralph's pre-interview and post-interview statuses for this concept were I, P, and developing F. Therefore, no change in status was detected.

Appendix G

Protocol Clearance From the Human Subjects Institutional Review Board

Human Subjects Institutional Review Board

Kalamazoo, Michigan 49008-3899
616 387-8293 329

WESTERN MICHIGAN UNIVERSITY

Date: Sept. 21, 1994

To: Charles T. Lohrke

From: Richard Wright, Interim Chair

Re: HSIRB Project Number 94-09-10

This letter will serve as confirmation that your research project entitled "The use of analogies in an industrial environment to facilitate status changes for radiation science concepts" has been **approved** under the **expedited** category of review by the Human Subjects Institutional Review Board. The conditions and duration of this approval are specified in the Policies of Western Michigan University. You may now begin to implement the research as described in the application. In giving approval the Board assumes that you will add to the consent letter the phone number of the Vice President for Research (616-387-8298) and that you will submit a copy of the revised letter to the HSIRB. The Board also compliments you on a well written submission.

Please note that you must seek specific approval for any changes in this design. You must also seek reapproval if the project extends beyond the termination date. In addition if there are any unanticipated adverse or unanticipated events associated with the conduct of this research, you should immediately suspend the project and contact the Chair of the HSIRB for consultation.

The Board wishes you success in the pursuit of your research goals.

Approval Termination: Sept. 21 1995

xc: Poel, SST

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