REVIEW OF TRAINING
IN THE AREAS OF
SCIENCE FUNDAMENTALS
AND EQUIPMENT PRINCIPLES

by

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ABSTRACT

Three training manuals for Canadian nuclear power plant Control Room Operators (CRO) and Shift Supervisors (SS) are reviewed, namely, *Course 22104 - Fluid Mechanics and Thermodynamics*, *Course 22106 - Nuclear Physics and Reactor Theory*, and *Course 22107- Principles of Reactor Safety*, to determine the pertinence and adequacy of the training objectives, the accuracy and adequacy of the technical content, and the prerequisite knowledge required. These manuals form part of the training program in the areas of science fundamentals and equipment principles.

Since an adequate basis for the assessment of these manuals was not available, pedagogical considerations were used to develop the needed framework. This report presents a framework based on a categorization and characterization of what we mean by *understanding*. The central thesis presented is that the job of the CRO / SS requires a level of understanding of concepts that can be quantified in terms of cognitive and affective behaviours.

It was found that for all three manuals, the course objectives were improperly formulated: they are incomplete in the coverage of the required concepts, incomplete in the coverage of behavioural levels and incomplete in that the objectives as stated did not include the standards and conditions that the trainees must meet. The assessment given in this report shows specifically where the material succeeds and where it fails as judged by the specific criteria presented. The *Fluid Mechanics and Thermodynamics* manual is badly imbalanced in its treatment of the course material and lacks a defining identity. The *Nuclear Physics and Reactor Theory* manual, on the other hand, is well written and maintains a fairly consistent theme throughout. The *Principles of Reactor Safety* manual is a good compendium of the essentials of the subject. However, revision is recommended to make the material more suitable to learning.

In a larger context, it was found that the central issue to be resolved is the disagreement between the regulator and the utilities on the level of understanding (or more properly, the degree of higher level cognitive functioning) required by the trainees. The issue is essentially one of *education* vs *training*. Resolution lies in the systematic and detailed assessment of the training material, such as attempted in this report. It is difficult to see how course material can be developed to the satisfaction of the utilities and the regulator if there is no agreement on the goal.

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1. Introduction

1.1 Preamble

This report documents the findings of a review of three training manuals for Control Room Operators (CROs) and Shift Supervisors (SSs), henceforth collectively called the trainees, for Canadian nuclear power stations. The scope of work for this report is given in Appendix 1.

The task at hand is to evaluate the following training manuals:

- Course 22104 - Fluid Mechanics and Thermodynamics
- Course 22106 - Nuclear Physics and Reactor Theory
- Course 22107 - Principles of Reactor Safety

to determine

- the pertinence and adequacy of the training objectives
- the accuracy and adequacy of the technical content
- the prerequisite knowledge required.

These manuals form part of the training program in the areas of science fundamentals and equipment principles.

A conceptual flowchart of the training program as typically envisioned by industry is given in figure 1.1. Simply put, job task analysis sets the requirements of the job and hence of the trainees, which in turn sets the training objectives. Once the objectives are set, then the training material can be prepared, the trainees can be trained and they can be assessed by examination. As I show in this report, this schema is flawed.

The IAEA and others recommend a Systematic Approach to Training (SAT) which focuses on the use of an auditable process. The task here, however, is directed at the objectives and training material themselves, rather than an evaluation of whether an audit trail exists.

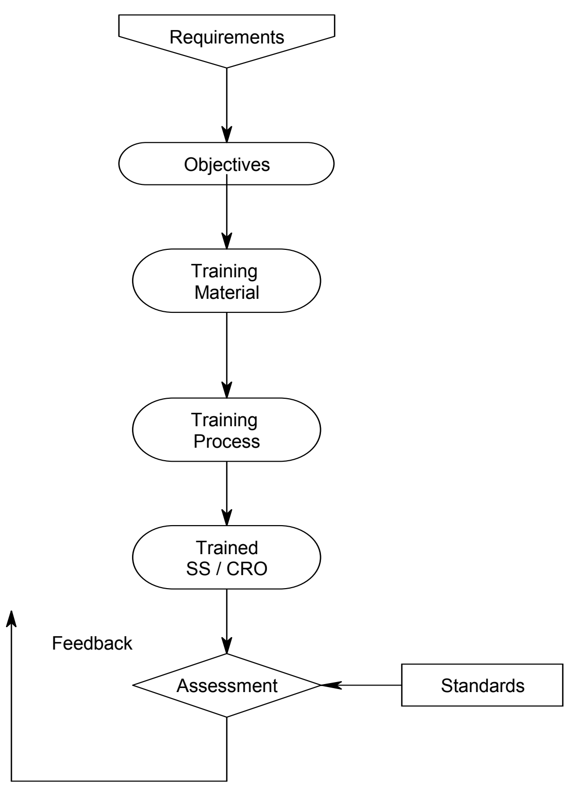

Figure 1.1 The training program

Consultants Jervis and Evans conducted an evaluation focussed on a review of the validity of the analysis performed by the utilities based Working Group (WG) to define the training needs in the areas of science fundamentals and equipment principles [JER96]. The consultants emphasized the need for a level of trainee understanding in the areas of science fundamentals and equipment principles. I concur and also share their sense of a lack of proper justification and of structure in the setting of training objectives in the supplied WG documentation. A guiding philosophy appears to be lacking. In truth, it appears that the objectives were set to match existing training material, quite the reverse of the proper order. If the objectives are inadequately set, it is moot whether the material meets the objectives or not. The first (and largest) task is, then, an assessment of the training objectives themselves. One cannot assess in a void; points of reference are required. Jervis and Evans allude to the seminal work of Bloom et al [BLO71] that could provide the needed framework. However, a framework or philosophy is of little value unless it is quantified. We must be very clear on the overall vision (goal); we must be very clear on how we pursue that goal; we must be very clear on how to measure our progress. For all these things we need to define our terms and place these definitions within a defendable theory of learning, however modest. Since the needed framework is not forthcoming from the WG, herein I address:

- the goals of the training program
- the goals for the operator
- the objectives of the training program
- the objectives for the operator
- a model of learning
- what all this means with respect to the task at hand - setting objectives.

In addition, it is necessary that the training material be placed into context. Adequacy and completeness of course material and objectives depend on what other courses and preparation the trainees have mastered. Once the above is set, the review of the training material with respect to the stated objectives can be done.

1.2 Goals

The goal is the purpose [BLO71]. The goal for a nuclear power plant is safe and effective operation. The CRO / SS must do the right thing, do it efficiently and do it safely. The CRO / SS is needed to the extent that robots cannot do the job. We need operators who are capable of functioning beyond the level of automatons. Some jobs, for example a field operator's job, are more procedural in nature. The field operators' jobs exist because they are cheaper and more effective than robots in gathering data and executing procedures and because they are more adaptable to non-standard situations. All jobs require a level of robotic response but higher level jobs are characterized by the degree to which automatic responses are inappropriate. Fault Detection, Diagnosis and Response (FDDR) is needed in the jobs of the CRO and SS. Module 3 of the *Principles of Reactor Safety* states:

> *"*The Control Room Operator (CRO) is trained to diagnose process failures using diagnostic aids. The SS independently verifies the CRO's diagnosis, providing a layer of *Defence in Depth* on the diagnosis...*"*

Module 10 of the *Principles of Reactor Safety* states:

> *"*The CRO is required to **monitor the assigned unit or systems, and operate as per the approved procedures. The CRO does not have authority to operate outside approved procedures.** In monitoring the unit, the CRO is required to recognize any deviation or change in unit state ...*"* [emphasis theirs]

It appears that if all deviations or changes in state could be identified beforehand and if the CRO could remember them all, then the job of a CRO would require little higher level cognitive functioning. Reality is, however, that we cannot pre-enumerate all possibilities and no one could remember them all in any case. The function of the SS is defined as:

> *"*...The primary responsibility of the SS is to ensure that plant operations are conducted safely ... To fulfil this role the SS requires sufficient knowledge to be able to recognize non-standard operating conditions....*"* [Module 10 of the *Principles of Reactor Safety*]

Clearly, this is a job of considerable responsibility requiring a high level of understanding of the plant. Even if higher level cognitive functioning were not required, how can one remember all the details and act in the correct context without a higher level understanding of the plant?

Higher level cognitive functioning is the norm for the SS and is sometimes required of the CRO - the trainees in the current context. The successful trainee must, in the final analysis, understand and be adaptable. Further, the trainee must show a commitment to act. It is insufficient to know what to do - action is required. For the purposes of this review, I propose that the management's goal with respect to the CRO / SS is, then, to ensure that the successful trainee is able and willing to provide safe and effective plant operation.

Further, the goal of the training program is to provide the means by which the successful trainee is empowered with the ability and commitment required for safe and effective plant operation. The courses that comprise the science fundamentals and equipment principles segment enable the CRO / SS to operate at the higher level of understanding required for the job. These enabling courses are, thus, essential.

1.3 Objectives

For the management and for the trainers, the above goal is a target or desired end state, the lofty vision. For the trainee it is a target state of being. The training objectives are the observable outcomes that provide a measure of the degree to which the trainee has reached the goal (ie satisfied the purpose). If goals were nouns, then objectives would be verbs. A convenient enabling phrase for the setting of objectives is *"*the Student Will Be Able To ...*"* or SWBAT. The IAEA [IAEA96, see section 6.2, pp33-35] offers a complete and concise definition of a training objective:

> *"*Training objectives must always have the following components:
> - Subject (always the trainee)
> - Verb (a measurable, action type verb)
> - Object (upon which the action (verb) is to be taken)
> - Conditions (the conditions under which the action is to be undertaken)
> - Standards (the standards which the trainee must achieve)*"*

The objectives need not and should not define how the trainee is trained to meet the objectives.

A key issue in operations is to ensure that the CRO / SS will respond appropriately to the job at hand. Most of the time, the CRO / SS deal with normal operations, including maintenance. This requires a high degree of familiarity with the plant details and with procedures. There is some latitude in deviating from procedures during normal operations. Obviously, such deviations can only be allowed if the CRO / SS exhibits a high degree of understanding of the fundamental processes. Off-normal operation, in contrast, permits little latitude for deviation from procedures, assuming that the procedures exist. The job task for abnormal events is primarily FDDR. Detection is not all that onerous. Diagnosis is the subtle task. Response is straightforward given the diagnosis if procedures exist. It is relatively easy to design objectives that measure the trainee in the areas of detection and response. The telling measure of the fundamentals part of the training program is how well it ensures that the trainee can and will (a) diagnose appropriately, (b) respond to gaps in procedures and (c) recover from errors in procedure implementation.

The overall objectives of a training program are:
- to create a change in the trainee's cognitive ability, ie the level of understanding.
- to create a change in the trainee's affective ability, ie the level of commitment to act.

- to create a change in the trainee's psychomotor ability, ie the level of physical ability to act.

But what is understanding? What is commitment? What is physical ability? How much change is required? How can it be measured?

1.4 On Defining What We Mean

Concepts like *understanding* and *commitment* are hard to pin down. A dictionary definition of *understand* is *"*comprehend, perceive the meaning of, grasp mentally, perceive the significant of, etc.*"* *Comprehend* means *"*to understand, grasp mentally*"*. Dictionaries are circular at best since they define only relationships, not meaning. To define the meaning, we need look at how the word is used, that is, one must operationalize: we look at what the person does. *Understanding* is defined by statements of the form:

The CRO understands because he/she can do X.

Statements like:

The CRO can solve X because he/she can understand.

do not define *understand*.

In order to define the objectives in a meaningful way, we need to explore our *understanding* of how people think so that we can build a learning framework and finally determine how training objectives should be set and evaluated. I attempt to elaborate on this in chapters 2 and 3. At the risk of being overly pedantic, I believe it essential to establish an explicit framework before a proper analysis of the training material and objectives can be carried out. At the very least, defining our terms allows a meaningful exploration of areas of disagreement and, hopefully, will lead to their resolution. As with many things, the process of exploration is as important as the final destination.

1.5 The Context

The scope of my review is limited to three courses in the fundamentals area. The review cannot, however, be conducted in isolation. Through interviews with the trainers and some trainees at Pt. Lepreau, Bruce and Pickering sites as well as through past personal experience, some insights into the overall training process and issues have been gained. These deserve comment up front since they form the context of the review.

We should recognize the limited role that even the best training material plays in the final analysis. How much of our own successes and failures are attributable to the quality of the courses that we endured in our own education? I suspect that many succeeded in spite of, rather than because of, the instructors and the lecture material. It is prudent to ask: *"*What are the main variables that determine the desired qualities in the product (the trainee)?*"*.

The preparation of a complete nuclear training program of the scope, depth and rigour contemplated here is an enormous undertaking and many positive steps have already been taken. Many more are required, nevertheless. Yet, for all its worth, the training material is just an enabling tool. The process by which a novice becomes a qualified staff member is complex and multifaceted, involving student attitudes and readiness to learn, teacher willingness and ability to identify with the student mind set and issues, mentorship, hands-on experience, and so much more. As important as training material is, I suspect that it is not the single most important contributor to training success. Accepting this implies that priorities and resources for training material development should be keep in perspective with other program needs. Figure 1.2 elaborates on the one-dimensional or linear process depicted in figure 1.1. The Training Process (where the trainee is actually experiencing the learning process) is made prominent to remind us that this is the point of contact with the trainee and hence should be the main activity of concern. The relative role of training material is placed in perspective by showing the other factors in the learning process. Since resources are finite, there is an opportunity cost of going overboard on any one aspect; as always, a balance should be sought.

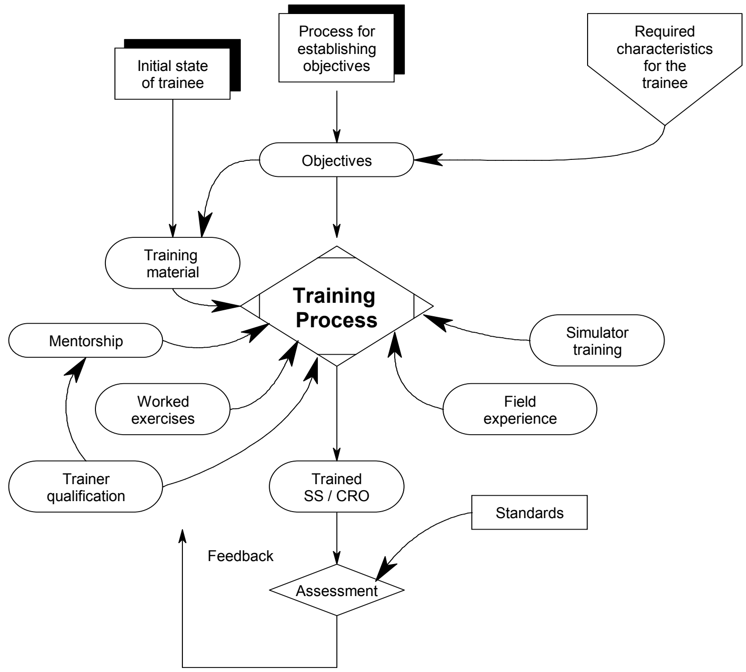

Figure 1.2 Training material in perspective

We must also bear in mind that a large percentage of the detailed information acquired while in training will be forgotten soon afterwards if not reinforced while on the job. The lasting messages of training are attitudes, approaches to problem solving, concepts and frameworks. A program cannot be considered a success, in my view, if the trainee does not carry away from the training program (which consists of the various elements such as training material, mentorship, etc.) a knowledge of and respect for his / her own limitations, an enthusiasm and desire for lifelong learning, an appreciation of responsibility and a proper safety culture. **A training program that does not deliver these things is worse than a waste of time; it is destructive for it will have created an ability without responsibility.**

I hope to show in this report that we must acknowledge the profound influence that the mechanisms of cognitive functioning have on the training process and, in particular, on the setting of objectives and the development of training material. Figure 1.3 depicts the complete overall training program schema; this is elaborated on and justified in the following sections.

Since the courses under review herein are given early in the CRO / SS training program, it is assumed that the trainee has had extensive field experience and is familiar with the physical equipment. It is further assumed that the trainee does not have an extensive understanding of plant behaviour at the systems level.

There appears to be no formal training or evaluation of the trainee's attitudes towards safety culture, belief in the theory, people skills, problem solving skills, etc. These seem to be left as intangibles that are dealt with indirectly during the training period and by the selection process as the trainee moves through the ranks. I fear that the emphasis is wrong: the approach seems to be pay most attention to what can measured because it can be measured, not because it is important. The balance is off.

From interviews with the trainers at Pt. Lepreau, Bruce and Pickering NGS, it appears that substantial informal classroom material is used to supplement these official course modules. Whether the supplement material should form part of the distributed modules will depend on the pedagogical strategies used. However, it is possible that very useful material (that provides expanded views and, indeed, different views on concepts to be learned) is deliberately withheld from the official modules for fear that the supplemental content might be treated as examinable. This situation, if it exists, is an undesirable outcome of the current dynamics of regulation and on the inappropriate direct linkages of objectives with course content. As I hope to show in this report, the objectives should be keyed to concepts. The course content is more of a statement on how the concepts are learned. As such, it should, in my estimation, be sufficient for the trainee to meet the objectives by any means, not all means. If this were to be acknowledged by all parties and if the supplemental material were made visible, then evaluation and regulation would be more meaningful.

It appears that currently the utilities consider the AECB exams as hurdles to get over; it is considered that the real training occurs elsewhere and that the AECB exams are not really meaningful. There is a definite gulf between AECB expectations and the utilities vision of what is needed. This gulf exists apparently because the utilities believe that the AECB should limit its examination questions to the knowledge defined by their learning objectives while the AECB considers these objectives incomplete in defining the understanding that the CRO / SS needs to perform the job competently. The result is an emphasis on *learning so as to pass exams* as opposed to *learning so as to be able to perform the job*. This issue is just a symptom of a deeper problem.

There appears to be a corporate belief that classroom training consists primarily of the pouring in of knowledge into the recipient's mind and that the truly important part of the training occurs elsewhere. The importance of the other parts of the training program is undisputed. The role that classroom training in the fundamentals play is the area of dispute: the corporate belief appears to be that fundamentals training is largely superfluous, that trainers are interchangeable and that pedagogy has little place in training; the regulator disagrees. So do I. There is little evidence, in the material that I have seen and the conversations that I have had, that consideration of how people learn has any significant priority in the corporate policy of the utilities. Indeed, it was suggested that I seem to be making the assumption that upper management actually cared about pedagogy and the role it plays in training. As one trainee put it: *"I have had many trainers, but I have had only one teacher."* The trainee went on to elaborate that for that one teacher they worked harder and more willingly, learned much more, felt better about themselves, could utilize that knowledge on the job better than for any other instructor or course. Although this is anecdotal evidence, it should not be ignored; it is at the heart of the issue. At the risk of oversimplification, the heart of the matter is whether the CRO / SS should be educated or trained[1]. Or, to use the words of the pedagogue: To what degree is higher level functioning required? All substantial shortcomings noted in this report have this unresolved issue as their root cause.
Until this is addressed and resolved, I suspect that there will be little progress in improving the current training program. The current exercise of course revision may generate improvements and updates on a technical level but it does not address the fundamental pedagogical shortcomings. The end product of the training program is, indeed, a product of the individual parts of the process, not the sum. Inadequacies in one aspect of the program are not easily compensated for by the other parts of the product. If the role that *learning the fundamentals* plays is not understood and agreed to by both the utilities and the regulator, then little progress will be made.

It is preferable that the utilities accept the above as an issue to be resolved and to go about resolving it. *Defence in Depth* requires the regulator to play a key role as well. The AECB measuring sticks need to be

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[1] The word *training* is commonly used both to denote learning that do not primarily involve higher level cognitive functioning (such as the trades) and to denote learning in general (ie, training in engineering, training in typing, etc.). In this report the term will be used in the generic sense of learning unless otherwise indicated, either explicitly or implicitly by context.

recalibrated to assess the important learning outcomes. Whether the regulator measures by approving the training process, by setting examinations or by monitoring checkouts, it can maintain its requirement of a higher level of understanding. **Experience has shown, however, that unless the measures are accepted by the utility management, by the trainers, and by the trainees as relevant and appropriate, the process will be subverted.**

The interviews also revealed that there have been suggestions that the fundamentals courses be incorporated into the specifics courses in a *just in time* approach to training. This has merit from an efficiency of delivery point of view and even has pedagogical merit in that new material is placed into context at the time of introduction of that material. Evaluation of learning at the time of material coverage may even show improved performance. However, long term retention of the essence of the fundamentals is best achieved if the key concepts are introduced over a longer time span with periodic revisits and links to the specifics material as the training progresses. People need repetition to internalize effectively. It is this long term retention that forms the enabling abilities. Hence, I recommend that the fundamentals be kept apart from the specifics training. To dismiss it into the specifics courses would be "penny wise and pound foolish". It is recognized that some specifics are needed as examples in courses on fundamentals and that fundamentals need to be revisited in the specifics courses. Such delivery "inefficiency" is, in fact, necessary for effective learning. Efficiency of delivery is hardly a valid measure of success if the training is ineffective.

There is a move toward each training centre developing its own training material optimized for its particular site. This is driven, most likely, by the desire for efficiency and the need to expedite course revisions. Normally the efficiency of the collective process of course design and preparation would push one toward a common set of courses. However, once the material has been prepared, the process of updating material in lock-step with other sites can be overwhelmingly bureaucratic. While I am not in a position to comment on the correct path (common or divergent), it appears that the root cause of the divergence is, once again, the lack of agreement on training philosophy, particularly the role that the fundamentals area plays in the overall training program and, as a consequence, the focus on course content rather than measured outcomes. I hope that this report will help in clarifying these issues.

This report does not attempt to differentiate between the learning needs of the CRO from that of the SS. To do so would require an investigation that is beyond the scope of this study. More importantly, the issues arising from the question on whether to educate or train overshadows nuances of CRO vs SS needs.

This role of the fundamentals in CRO / SS training forms the context of this report. The next two sections (sections 2 and 3) develop the framework for assessing the fundamental area. Sections 4, 5 and 6 look at the three course manuals that are the subject of this report. Overall conclusions and recommendations are collected in section 7.

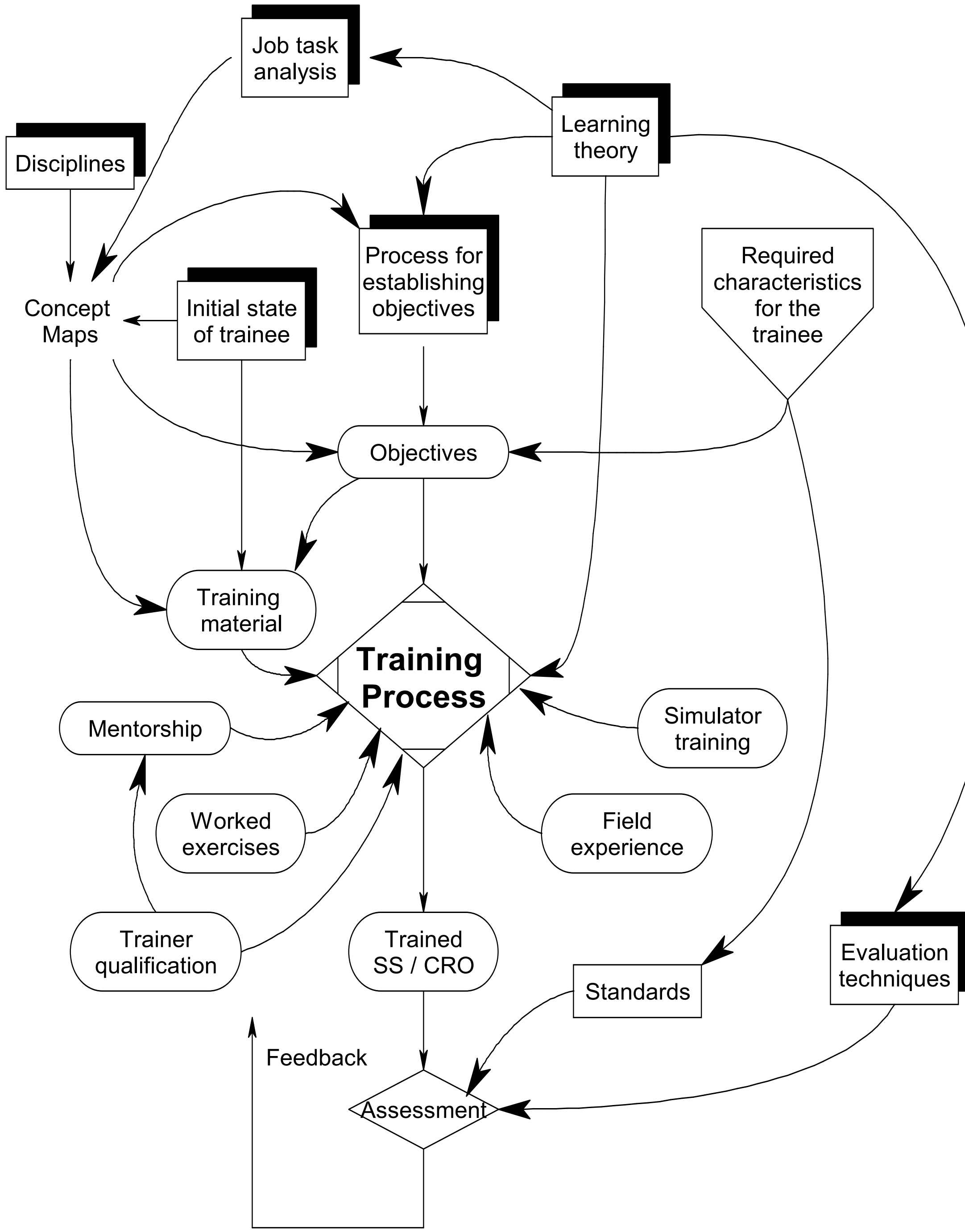

Figure 1.3 A training program schema

2. Towards a Learning Framework

2.1 The Concept Map

People differ greatly in their ability to abstract and otherwise think. It would be the rare exception, however, who did not learn from the bottom up, from the particular to the general. Figure 2.1 illustrates the notion of knowledge bits on the level of *facts* that the trainee learns about through direct experience and association. After the bits are assimilated (ie, the trainee can regurgitate the facts), it is possible to cluster the facts into groups, or knowledge islands to form a concept. This is the process of abstraction. The trainee should now be capable of viewing the knowledge domain from the top down as well as the bottom up. The clustering process provides a structure for recall and use of information; the concept is the memory recall tag. It is efficient and it is effective. The currently accepted model of cognition is that long term memory serves as a vast data bank. The stored knowledge and input stimuli are processed in short term memory. Some people are capable of processing up to 9 isolated bits of information in short term memory; the normal range is 3 -7 items. It is not a coincidence that number sequences like telephone numbers are clustered in groups containing 3 to 4 numbers. We conclude from this that clustering is not only efficient and effective, **it is necessary**. The CRO / SS (or anyone else for that matter) could not possibly handle anything but a trivially simple situation without abstraction. Understanding is required. There are simply too many situations to remember and recall. Hence we must interpolate and extrapolate from the known. To do this we must abstract.

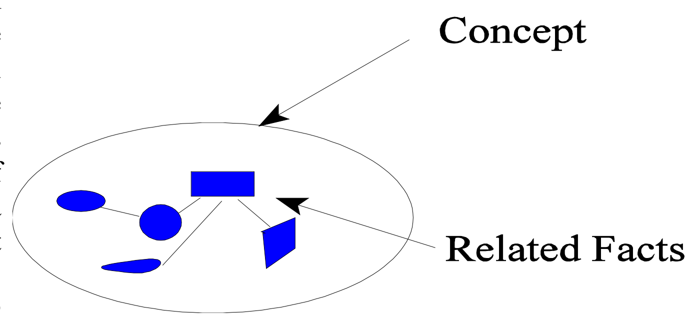

Figure 2.1 Clusters of related facts form a concept

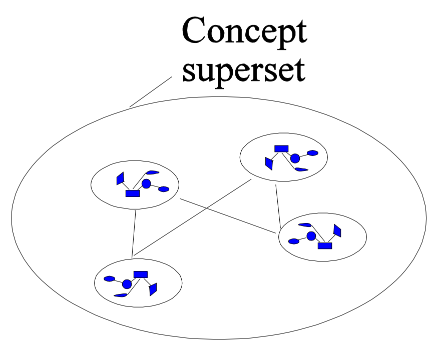

Figure 2.2 Related islands of knowledge form a higher level concept

The cluster becomes a bit of knowledge to be related to other clusters, thus forming a higher level concept, as illustrated in figure 2.2.

While we learn from the bottom up, once the hierarchy of concepts have been formed into a framework of cognition, a proficient trainee should be able to draw on this framework as the situation dictates to demonstrate that he/she can conceive of the situation, the issues, possible solutions, selection criteria, the path forward, and so on. Typically, these demonstrations or explanations take on the form of words, graphs, equations and illustrations. These are all special forms of a general construct called the CONCEPT MAP. The figures in this report are examples. **Since abstraction is required for a proper CRO / SS response (since all possible situations cannot be enumerated, let alone remembered) and since concept maps are expressions of abstraction, proficiency in the use of concept maps is a quantifiable and meaningful measure of trainee cognitive ability.**

Concept maps can be constructed for discipline areas such as mathematics, physics, etc. And, of course, concept maps can be constructed in a variety of ways, across disciplines, for example nuclear engineering draws on concepts from mathematics, nuclear physics, metallurgy, etc. These frameworks are constructions of convenience; groupings are not unique and a concept map constructed for a student novice may look quite different from that for an expert. The form follows the intended use.

2.2 The Cognitive Domain

Bloom [BLO71] et al have formulated a hierarchy of the cognitive domain with six distinct levels as follows.

- 1 Knowledge
- 2 Comprehension
- 3 Application
- 4 Analysis
- 5 Synthesis
- 6 Evaluation.

Appendix 2, reproduced from an in-house McMaster University course on *Course Design*, provides some explanation of each of these levels. Note the action words in the right hand column. These words have been carefully selected to characterize the cognitive level. We can use these action words to formulate training objectives. Furthermore we can use the levels to characterize the training objectives for the purposes of evaluation - of both the trainee and the program.

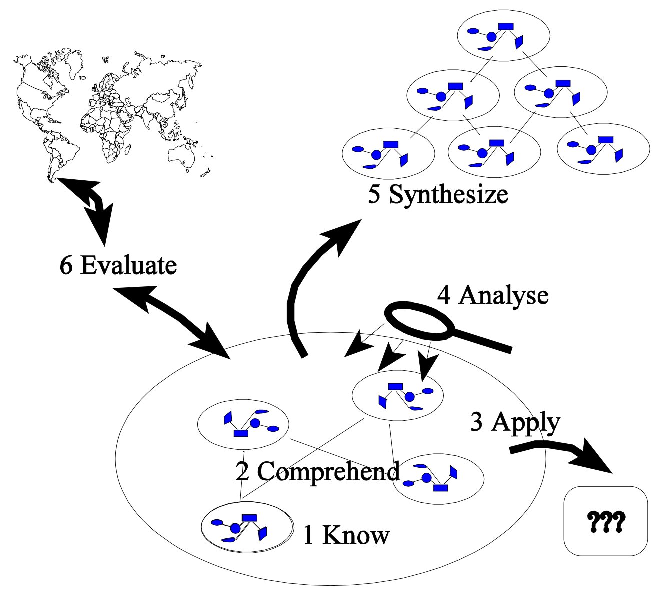

Figure 2.3 Concept map of Blooms hierarchy if the cognitive domain

We have already met the KNOWLEDGE level. This is the level of basic facts that must be recalled to some specified degree of fidelity. Multiplication tables must be recalled precisely; properties of water need only be known approximately, etc.

The knowledge facts and clusters of knowledge facts (concepts) are COMPREHENDED on the second level, that is, there is an understanding of the concepts and connection between the concepts within the narrow domain (the large ellipse of figure 2.3). At this level the trainee is not expected to be able to extrapolate outside this narrow domain.

The APPLICATION level, however, entails the use of the knowledge and comprehension in the solution of some application that lies outside of the learned domain. This implies being able to determine <u>when</u> to use acquired knowledge and skills, not just <u>how</u> to use them.. The applications are on the level of "plugging in the numbers" although this understates the real cognition required.

The ability to ANALYSE is the ability to appreciate and understand the relationships of the concepts within the domain. This is a *picking apart* activity to see how it works and why it works.

SYNTHESIS is the ability to recombine the pieces resulting from analysis and the other lower cognitive levels into novel arrangements.

Finally, the ability to EVALUATE is the ability to compare or judge the knowledge domain (as understood by the other levels) against the outside world (ie against given standards or other criteria).

The level of understanding required of the CRO / SS can now be quantified somewhat. It is apparent to me that the first three levels are certainly required. Likely, proficiency on the analysis level is also required in most topic areas. Since the reactor does not follow procedures and since the procedures do not cover off all possible accidents or deviations from normal operation, the operator may be required to switch from one procedure to a more appropriate one. In addition, if an error was made in the execution of a procedure, the operator would be required to recover from this error. These situations require analysis, perhaps interpolation of current practice, and, to the extent that extrapolation of current procedures are required, synthesis. If synthesis is required by the CRO / SS, then this is an indication that station operating procedures are lacking. Evaluation would likely only be required in some isolated conditions, such as low probability accident scenarios.

2.3 The Affective Domain

Attitude is equally as important as cognition, yet it is usually neglected. Consider [BLO71]:

> "The reasons for this emphasis on the cognitive in preference to the affective are several and interactive. Our system of education is geared to producing people who can deal with words, concepts, and mathematical or scientific symbols so necessary for success in our technological society....
>
> This is not to imply that the realizations of cognitive outcomes are not accompanied by changes in affect - quite the contrary; these outcomes may be very closely related ... Indeed, certain established pedagogic techniques for producing acceptable cognitive outcomes can destroy any positive feeling a student might have toward a subject area. Suffice it to say that it is possible for a learner to understand and be quite proficient in a subject matter and still have a deep aversion or other negative affect toward the discipline...."

In short, there is not much point in the CRO being trained in some skill (say ordinary differential equations) if he /she is averse to using the skill when it is required. On a more subtle level, one can comprehend without having a commitment. This can lead to inaction when action is required. Quite apart from a loss in effectiveness, safety could be compromised. It is important, then, to quantify the affective domain so as to define standards to judge learning outcomes (objectives) by.

In a manner analogous to the cognitive domain, the affective domain is divided into hierarchical levels [BLO71, pp 229-230]:

- 1 Receiving
- 2 Responding
- 3 Valuing
- 4 Organization
- 5 Characterization.

See appendix 2 for additional details. Referring to figure 2.4, RECEIVING is the lowest attitudinal level required for learning. It represents a willingness to receive input. RESPONDING refers to the level at which there is voluntary attentiveness. VALUING implies perceiving the subject matter as having some worth. The student becomes involved. ORGANIZATION is defined as the conceptualisation of values and the employment of these concepts for determining the interrelationship among values. CHARACTERIZATION is the organization of values, beliefs, ideas, and attitudes into an internally consistent system. At this level, the consistent system of ideas are internalized; belief is consistent with the rational (cognitive) side; a commitment to action is achieved.

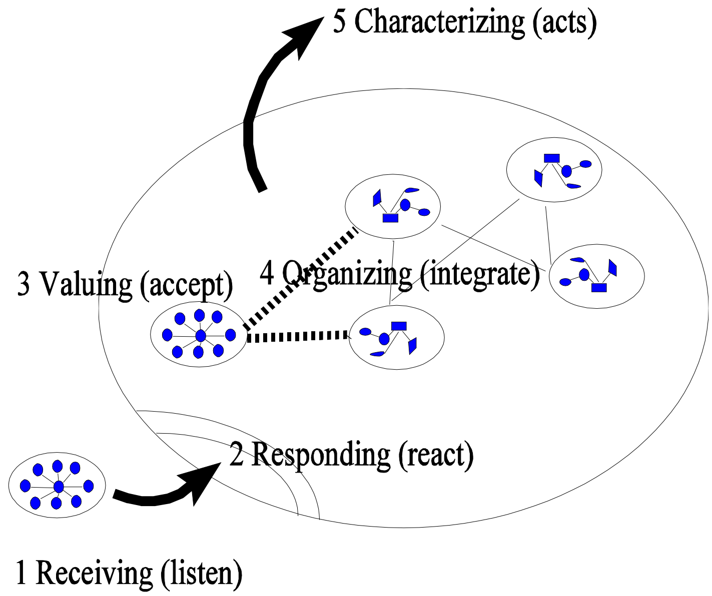

Figure 2.4 Affective domain

A successful trainee will, by definition, have achieved at least the VALUING level. Anything less would have led to failure. It is highly desirable for the trainee to have reached the CHARACTERIZATION level for reasons of safety, as stated above.

Setting and evaluating objectives in this domain are more problematic than in the cognitive domain. The affective domain is, by its very nature, more qualitative and less quantitative. In addition, the trainee can easily hide true feelings, thus subverting the evaluation process. Nonetheless, these difficulties in measurement do not lessen the importance of measurement of performance in the affective domain.

2.4 <u>The Psychomotor Domain</u>

One other domain is important for the training of professionals. The psychomotor domain is the domain of the performing of a physical act and is broken down into 7 hierarchical levels in a manner analogous to the other domains, as shown in appendix 2. This domain does not directly apply to the training of science or equipment fundamentals as currently envisioned; however, it is mentioned here as a pointer to another dimension of learning that should be addressed if a laboratory component is added to the courses or if the trainee is experiencing difficulties that are not identifiable in the cognitive or affective domains. The psychomotor domain is more relevant to the practical exercises such as simulator training and, hence, will not be discussed any further in this report.

2.5 <u>Mental Models</u>

While the foregoing sections delineate the various levels and types of behaviour, they do not address the way people think and solve problems, that is, they do not address the mental models used. Some possible models are:

- Memorization (the density of steam at pressure X is Y times that of liquid);
- Rule based (½ of a radioisotope disappears in one half-life);
- Analogy (xenon and iodine concentrations build up and decay like water levels in two interconnected tanks);
- Mechanistic (the water level rises causing the float to actuate the switch);
- Functional abstraction (Defense in Depth is an effective strategy as an overall safety philosophy and as a teaching methodology since both safety and teaching do not rely on any single strategy for success);

- Mathematical ($dN/dt = -\lambda N$).

It appears, from conversation with plant trainers and from personal experience as an educator, that the primary mental models used by successful technical workers (on all levels) are the mechanistic and functional abstraction models. They form the basis for the internalization of a subject matter; they permit and guide an internal and external dialogue when thinking through a problem.

The mechanistic model is a quite literal translation of the physical mechanism. Indeed, in most cases, the CRO / SS has a clear mental picture of the physical device internals. However, this is a necessary but not sufficient condition for a systems level understanding of the function of the device. For that, functional abstraction is required. For example, understanding that towns tend to grow around major transportation routes would lead one to suspect that the city core is down hill from the suburbs in a city with a major waterway. Thus, functional abstraction is extremely useful for charting one's way through a situation. It is this generalization that most effectively compensates for our limited memory. This, in my estimation, depicts what we generally mean when we talk of *understanding* and this is the meaning used in this report. The cognitive and affective level as used herein are with respect to this meaning of the *understanding* activity - that is, with respect to the task of developing mechanistic and functional abstraction mental models. These are the concepts that the trainee must learn.

However, this does not mean that mathematics should be ignored. Good pedagogy involves the use of multiple descriptions of the same phenomena from different aspects. The judicious use of the proper level of mathematics has an important role to play in learning in spite of the fact that calculations are not often required in the control room.

The mental model for problem solving proposed by Rasmussen [RAS86] is one that is based on functional abstraction. Rasmussen's figure (reproduced in part in figure 2.5) illustrates this generic algorithm. The generic algorithm for problem solving is to observe and identify the state of the situation, interpret, evaluate, plan actions and execute the actions. Rasmussen notes that shortcuts can be taken at any stage. In fact, most of what we do involves shortcuts to some degree. ALL problem solving is covered by this figure but the technician often employs strategies and tactics that do not rely as heavily on a detailed knowledge of system and component behaviour as might an engineer. That is, the CRO / SS cannot usually afford the luxury (time and effort) to travel all the way to the top of the tree and down again to solve the problem; short cuts to Rasmussen's full solution path are taken. This is a form of shallow reasoning. This is not to say that the CRO / SS does not have a detailed knowledge of the systems and components. He or she indeed does. It is simply that it is not appropriate to spend days and weeks reflecting on control room issues. As depicted in figure 2.6, the desired strategy for a CRO / SS is the middle road of using a level of abstraction consistent with the time of response required for the task at hand. The "sweet spot" is somewhere between an in-depth, slow analysis and an immediate unconsidered reaction.

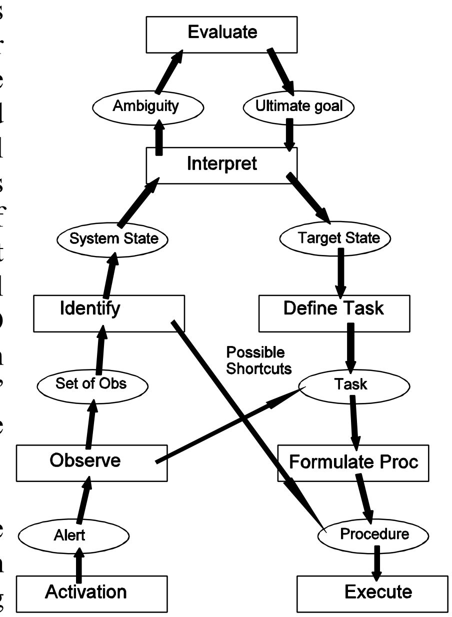

Figure 2.5 Rasmussen's mental model (simplified)

It is essential that the required problem solving strategies appropriate for the CRO / SS be delineated. Like mathematical skills, problem solving skills may best be introduced as an integral part of the existing subject matter courses. However, it is recommended that a series of modules devoted to problem solving approaches and techniques be developed so that, at the very least, the developers of training modules have a common point of reference and a resource to draw on.

. . . .

We now turn to the actual job of setting objectives.

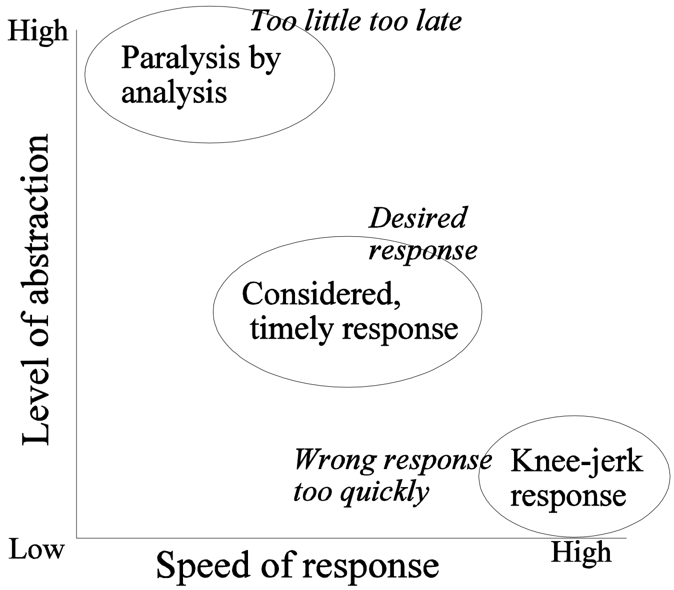

Figure 2.6 Desired SS / CRO response

3. Specification of Objectives

3.1 Mapping the Job Tasks

The currently recommended practise is to do a job task analysis to directly define what objectives need to be met. This is illustrated in figure 3.1. There are two problems with this approach:

1) There are typically many job tasks and, consequently, many objectives. This many-to-many mapping is an onerous task if done to completion.

2) It is difficult to link the job tasks to objectives because there are many enabling principles associated with all but the most menial of tasks. The linkage of tasks to objectives is not direct.

Given that there are enabling principles to be learned, it follows directly that some level of understanding is required. The requirement of understanding leads directly to consideration of pedagogy, as illustrated in figure 3.2.

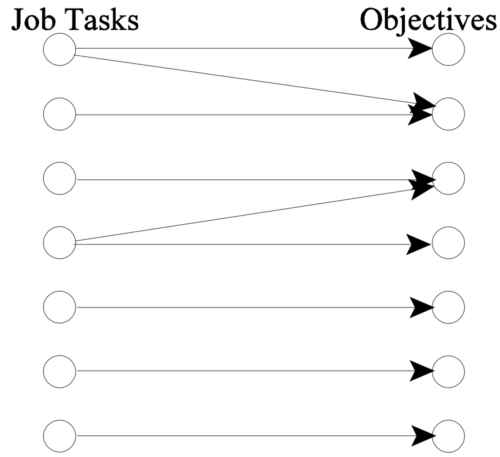

Figure 3.1 Many-to-many mapping of job tasks to objectives

To understand we need to built and employ mental models, ie, to conceptualize. In the inevitable tautology of trying to understand *understanding*, we need concepts to conceive!

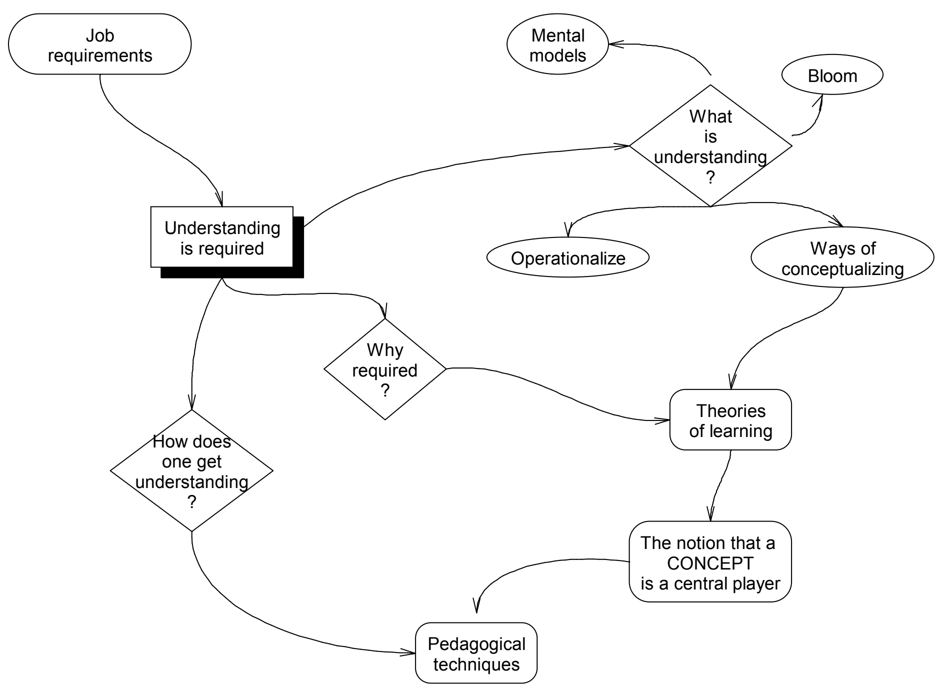

Figure 3.2 The requirement of understanding implies the needs for concepts

This notion of a CONCEPT, a central player in learning, is the missing link between the tasks and the objectives, as illustrated in figure 3.3, and is the key to a resolution of the above problems. Note that:

1) We now have a much smaller set (usually) of objectives that relate directly to the concepts.

2) The objectives are now linked directly with the knowledge and skills grouped in a manner that is conducive to learning and training, ie the objectives relate to the concept. For example, an objective would be to understand (in some sense of the word) the concept.

3) We now have a workable link to the elusive enabling principles which invariably are concepts.

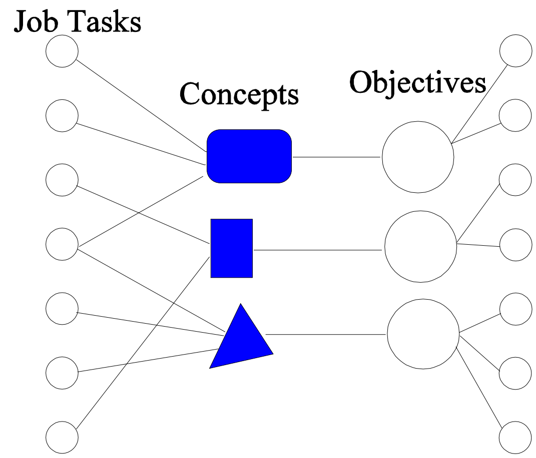

Figure 3.3 Many-to-few-to-few mapping of job tasks to concepts to objectives

Since we are interested (ultimately) in measuring how well the job tasks are performed and since we defined the cognitive and affective behaviours as measures of performance, it directly follows that we characterize the job tasks by the behavioural levels. Further, since concepts are linked to job tasks, it follows that the concepts are also linked to behavioural measures, as are, subsequently, the objectives.

The CRO / SS is required to apply concepts (which includes fundamental knowledge as well as application of procedures) to the job at hand. The training objectives thus relate to the understanding of the concepts in the context of the job function, that is, the depth of understanding should be commensurate with the need.

3.2 Linking Job Tasks to Concepts

The overall job of the CRO / SS has been presented as the execution of normal operation functions plus off-normal Fault Detection, Diagnosis and Response (FDDR). Underlying these activities is the basic task of maintaining an understanding (in the sense of cognitive awareness) of the operating plant. It is not the function of courses in fundamentals to train the trainee in procedures. Hence four task categories are defined: *Awareness*, *Detection*, *Diagnosis* and *Response*. It has been suggested that a job function analysis would be appropriate in this context. Indeed, *Awareness*, *Detection*, *Diagnosis* and *Response* are, in the jargon of the technique, job functions, not job tasks. Job function analysis entails the use of "standardized categories which can be used to identify and organize specific tasks" (CAR85). Job function analysis is easier and quicker than job task analysis, permits the use of a standardized language and is complete in its coverage of tasks, albeit at the expense of detail. But in addressing the enabling principles, a detailed accounting of job tasks is neither appropriate nor necessary. Hence the loss of detail is immaterial.

Whether by task or by function, job analysis results are not available, and since it is very difficult, if not impossible, to establish a direct relationship between fundamental principles and the job, no further breakdown has been attempted. This is perhaps appropriate given that fundamentals are, after all, fundamental; they form the basis for a wide variety of tasks and functions and give the trainee flexibility in dealing with the unexpected. It may be sufficient to simply identify the key effectiveness areas as done in the *Principles of Reactor Safety* manual. I suspect that, in the end, a full job analysis would reveal what a person with plant experience already knows: that any specific job ultimately relies on mental models, internal concepts, fundamental functional abstractions, etc., that have been accumulated by training and experience over the years. It may be difficult to connect one's appreciation of, say, steady state flow, with the performance of a procedure; but few would deny that the CRO / SS should have a well developed understanding of what is meant by a steady state.

This reviewer has insufficient experience with job task or function analysis to make specific recommendations other than to note that the job function technique appears to be better suited to the fundamentals area than the job task analysis technique. The four broad job breakdown categories used herein are sufficient to illustrate the points made in this report and, for the purposes of this report, the words *task* and *function* are synonymous.

Each of the four broad task categories arguably requires mental functioning as illustrated in table 3.1. **Please note that the behaviours assigned in table 3.1 are for the purposes of discussion only.**

Table 3.1 Required behaviours for the job tasks

	BEHAVIOURS																	
	Cognitive Domain						Affective Domain					Psychomotor Domain						
TASK	C 1	C 2	C 3	C 4	C 5	C 6	A 1	A 2	A 3	A 4	A 5	P 1	P 2	P 3	P 4	P 5	P 6	P 7
Awareness	✔	✔																
Detection			✔							✔								
Diagnosis	✔	✔	✔	✔						✔								
Response			✔								✔							

Legend:
C1 = level 1 (knowledge) of the cognitive domain
C2 = level 2 (comprehension) of the cognitive domain
Etc.

✔ = the behaviour as it relates to the task is required. For example, for the task of diagnosis, mental functioning for levels 1 through 4 of the cognitive domain and level 4 of the affective domain are required.

3.3 Relationship to the Concepts

It is the job tasks that ultimately define what concepts are needed and to what degree the concepts have to be understood. In the fundamentals area, the job tasks tend to translate into a broad coverage of the basic principles in a number of key disciplines - the concepts. Each concept would need to be assessed and the degree to which that concept is needed for each of the four tasks (*Awareness*, *Detection*, *Diagnosis* and *Response*) should be set. This is illustrated in table 3.2. One could assign a numerical rating for the table entries to indicate the importance or weight of the entry. A 0-10 scale would be more than sufficient. Perhaps a MUST - SHOULD - COULD (a - b - c) rating might suffice as well. Herein, the a-b-c scale is used. **Please note that the weights assigned in table 3.2 are for the purposes of discussion only.** Depending on the concept and its relation to the job tasks, it may only be necessary for the trainee to have memorized some facts. Other concepts may require a deep and full understanding and a demonstrated commitment to employ a technique under adverse conditions.

Table 3.2 Example concept required for the job tasks

	TASKS			
CONCEPT	Awareness	Detection	Diagnosis	Response
t/s 01.00 Thermosyphoning equations	a	b	a	b

Since each concept is linked to the tasks and each task is linked to behaviours, it is straightforward to generate the required behaviour for each concept. For the example given here, the concept is a MUST (ie., the weight is "a" for the awareness task and the awareness task involves behaviours C1 and C2. Hence the concept MUST be understood to the level of C1 and C2. The concept is a SHOULD (ie., a weight of "b") for detection, hence the concept SHOULD be understood to the level C3 and A4. Consideration of diagnosis and response are given in a similar fashion and the cumulative coverage of behaviours is determined for the concept. This process is easily automated using a computerized database. Table 3.3, an excerpt from such a database, illustrates the procedure. The end result of the exercise is a tabulation of the behavioural targets for each required concept as shown in table 3.4. **This is the benchmark for the objectives that the trainees have to satisfy.** Recall that the concept to be learned is invariably internalized as a mechanistic model or a functional abstraction of the mechanistic model. This should be kept in mind when defining objectives, and consequently, when evaluating given objectives.

To summarize, the concepts to be learned by the trainees are defined based on a job task analysis (if possible) or based on the experience of the expert (the wise old man [WAR97]). The objectives are then keyed to the concepts. From there the course content can be designed so as to fulfil the objectives.

The course concepts form the basis of **what** the instructors are leading the trainees to understand so that they can fulfill the requirements of the job tasks. The course content, on the other hand, forms the means by which the trainee is led, ie **how** the training takes place. **The objectives, therefore, should be derived from the concepts, not to the course syllabus.** Hence, it is essential that the structure of the discipline, that is, the inter-relationships of the main principles of the discipline, also be delineated. Concept maps are useful devices for that purpose. It is quite possible that the course outline may follow the concept map quite closely, or it may not; it will depend on pedagogical dictates. However, the usual trap is to first construct a course outline and associated material and then define the learning outcomes (objectives) from the content. This is both backwards and incorrect since the setting of the objectives should come before the setting of the content and, in any case, the content does not define the objectives.

Table 3.3 Sample database page for the assigning of behaviours to a concept based on the tasks

In the database entry form below, the user inputs the concept ID and description along with the linkage to the tasks. In this example, the user has specified that the trainee MUST know the concept for the awareness and diagnosis tasks (ie weight = a) and SHOULD know the concept for the detection and response tasks (ie weight = b). The computer automatically looks up the required behaviours and displays them as shown. Assignments for the learning targets for each behaviour are made based on the behaviour level needed to cover off all task requirements for this concept.

```
+--------------------------------- Entry form ------------------------------+
 Concept: t/s01.00   Thermosyphoning equations

                             Cognitive Domain  Affective Domain
 Task category                 1 2 3 4 5 6       1 2 3 4 5
   Awareness  a   --->         a a
   Detect     b   --->             b                   b
   Diagnose   a   --->         a a a a                 a
   Respond    b   --->             b                     b
                               ___________________________
        Assigned behaviours    a a a a                 a b
        for this concept
 Notes:
                               C1 Knowledge               A1 Receiving
                               C2 Comprehension           A2 Responding
                               C3 Application             A3 Valuing
                               C4 Analysis                A4 Organizing
                               C5 Synthesis               A5 Characterizing
                               C6 Evaluation
+---------------------------------------------------------------------------+
```

Table 3.4 Behavioural targets for a concept

ID	Description	Awa	Det	Dia	Res	C 1	C 2	C 3	C 4	C 5	C 6	A 1	A 2	A 3	A 4	A 5
t/s01.00	Thermosyphoning equations	a	b	a	b	a	a	a	a						a	b

3.4 The Objectives

From the above, the job tasks are translated into required concepts and behaviours while the objectives define the target behavioural levels for the concepts. Formulating a specific course objective along the lines of "the student will be able to do...", then, necessarily involves two main dimensions: concept and behaviour. Thus the specification of objectives requires:

- the specification of required course concepts (as required by the job tasks)
- the specification of relevant job task behaviours (based on learning theory)
- the specification of the intersections of concepts and behaviour (driven by the job tasks)
- the specification of the objectives themselves, including the conditions and standards as discussed previously, to meet the specified behaviours.

The first three steps have been delineated in the previous section. To make the fourth step more concrete, consider the specification of an objective in the area of reactor physics fundamentals. A sample concept map is given in figure 3.3 showing the hierarchical relationships for the concepts of cross sections, flux and simple balance equations. In general, that is, for any and all concepts (invariably associated with a concept map), the trainee is required to show an understanding of the concepts and how they depend on each other. The trainee is also required to demonstrate the ability to quantify the approximate size of the quantities involved and the impact on operations. For cross reference purposes, the list of concepts might be itemized as:

r/p01.00 Fundamental variables
r/p01.01 Neutron density
r/p01.02 Neutron velocity
r/p01.03 Neutron flux
r/p01.04 Microscopic cross section
r/p01.05 Macroscopic cross section
r/p02.00 Basic interactions
r/p02.01 Neutron absorption
etc.

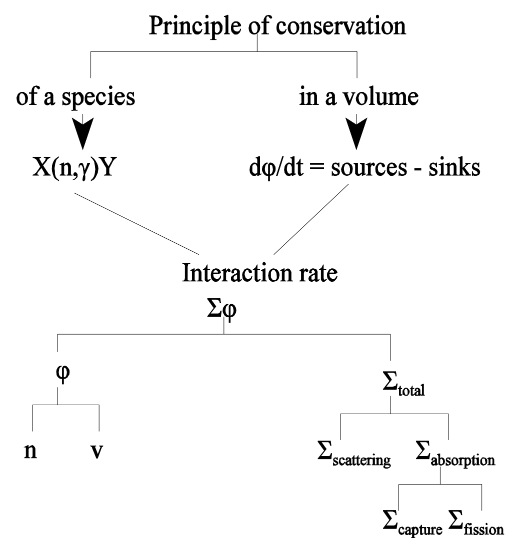

Figure 3.4 Sample reactor physics concept map

One objective might be:

Objective 1.1	The trainee should be able to identify the main physical phenomena involved in the interaction of neutrons with materials common to reactors.										
Condition	closed book written or oral examination										
Standard	100% on definition and units, answer may be given using word descriptions, diagrams or graphs as appropriate.										
Related concept(s)	r/p02.00 Basic interactions										
Classification	C1	C2	C3	C4	C5	C6	A1	A2	A3	A4	A5
Weight	a	a	a						a	a	

Another objective for the same module might be:

Objective 1.2	The trainee should be able to identify the dominant phenomena involved in the interaction of neutrons in the fuel, moderator, coolant and control rods and deduce how changes in the interactions affect criticality.										
Condition	closed book oral examination										
Standard	Correct outcomes for changes in one example material each for fuel, moderator, coolant and control rods										
Related concept(s)	r/pxx.00 Reactor criticality r/p02.00 Basic interactions										
Classification	C1	C2	C3	C4	C5	C6	A1	A2	A3	A4	A5
Weight			a	b					a	a	

Objectives are thus constructed for a given module or concept until the trainers consider the set to be exhaustive. As a check, all behaviour levels as given in the specification matrix for that module should be covered by the collection of objectives for that module or concept.

Note that the above objectives are not direct questions in disguise. Rather, questions are derived from the objectives as subsets; there would typically be many possible questions resulting from an objective. A typical lower level question might be:

> List the three types of neutron - matter interactions, giving an example of each, stating units and typical values.

A typical higher level question relating to those objectives might be:

> Given a sketch of the flux as a function of energy and the cross section of heavy water as a function

of energy, sketch the neutron interaction rate in the moderator as a function of neutron energy. This question requires a degree of analysis since it covers more than one concept and presents a situation that is not directly covered in the training material.

It is worth emphasizing that, although it may appear that the above prescription for setting objectives is more onerous than that currently employed, it is actually less so. This is because, while the setting of each objective requires extra effort, there should be a lesser number of objectives to set since there are far fewer concepts than fragments of knowledge. This is a classic case of working smarter, not harder. Conditions and standards could be stated at the beginning of each manual or modules as defaults unless otherwise stated.

Finally, there is often a tendency to focus on one mode of training program delivery at a time when setting the objectives. Since some objectives are more easily and naturally reached through simulator based training than classroom based training, focussing too early on delivery mode can lead to deeming that some objectives are covered off elsewhere. This is an error-prone practise since it is far too easy for some objectives to "fall between the cracks". It is incorrect to consider the training delivery mode when constructing concepts and objectives: rather, they should be based on the job requirements. How the objectives are to be met is a subject of a later phase in the development of a training program.

3.5 The Evaluation Process for the Objectives

With the framework and methodology established, the actual task of evaluation of the three training courses can begin. The evaluation of the objectives involves the following steps:

1. Construct concept maps for each course. Where necessary, link to concepts developed in other courses or to missing concepts.
2. Assess the concepts in relation to the job tasks and behaviour categories.
   This represents the **target coverage** of course material.
   - Summarize this information in a table.
3. Link the stated objectives to the concepts, noting the degree to which they satisfy the behaviour categories.
   This represents the **actual coverage** of course material by the stated objectives.
   - Summarize this information in a table ordered by concept.
4. Compare the tables generated in step 3 to the target of step 2. Insufficiency of the objectives is indicated by lack of coverage of concepts and behaviours, and by indirect inference, the tasks.

4. Fluid Mechanics and Thermodynamics

4.1 Overview and Concept Map

This course manual contains 6 modules covering secondary side thermodynamics, primary side thermosyphoning, heat transfer and an assortment of topics relating to the behaviour of steam generators, pumps and compressors. Discussion herein will focus on the first 3 modules. Figure 4.1 shows a concept map of the thermodynamic cycle portion of the manual based on modules 1 and 2. Figure 4.2 is a concept map for module 3. The top level concepts for these 3 modules are listed in tables 4.1 and 4.2. Within each concept, a hierarchy of sub-concepts can be drawn but the current review is limited to the concepts shown. These fundamental concepts form the basis of understanding system behaviour and performing job tasks. As an example, concept *t/d01.00 State parameters (intrinsic)* is needed for the job tasks *Awareness* and *Diagnosis*. Referring to table 3.1, we see that the combination of these tasks require C1->C4 plus A4. Hence these behavioural tasks are a must (ie., an "a" rating) for this concept. With respect to job tasks, the overview concepts are a must for *Diagnosis*. The more specific concepts are useful for the more procedural tasks of *Detection* and *Response*. This is summarized in table 4.1 and represents the target against which the objectives are assessed.

In modules 1&2 on thermodynamics, the range of concepts is good: from basic parameters through to thermodynamic processes and turbine cycles. The text provides a good coverage of the inter-relationships between physical concepts along with the mathematical constructs needed for a full understanding. But I question the need and desirability of such mathematical detail. The material seems more appropriate to design tasks than to operational tasks.

Module 3 on thermosyphoning also covers the range of concepts appropriate to the topic but falls short on the use of mathematical constructs to support the phenomena under consideration. **In fact, all modules beyond module 2 fall short on the use of mathematical concepts.** With words and illustrations, a lot of ground can be covered, but the coverage is necessarily superficial. Mathematics provides the additional dimension necessary for a more in-depth and critical coverage of the material.

Module 4 on heat transfer crises covers the range of top level concepts appropriate to the subject but coverage of the more basic heat transfer phenomena is all but nonexistent. This is only acceptable if the basics of heat conduction and convection (such as units, heat capacity, conductivity, physical mechanisms, etc.) are covered in other courses.

Concept coverage in module 5 on assorted fluid phenomena is quite superficial. It is difficult to imagine how a trainee could come to appropriately appreciate boiler dynamics and water hammer, etc. without a more quantitative and rigorous treatment.

Module 6 (including the supplement) on pumps has an uneven coverage of basic concepts (which may be dealt with in other courses) but does cover the range of operational issues that seem appropriate for the CRO / SS.

Overall, the coverage of thermodynamic cycle concepts is adequate, assuming that thermodynamic basics are covered elsewhere. The coverage of fluid mechanics as normally defined by the discipline is just not there. Perhaps the title for this course should be *Thermodynamic and Fluid Systems* to emphasis the focus as system behaviour, rather than fluid fundamentals. As a fundamentals course, it is not fundamental enough and concept coverage is grossly incomplete. As a systems course, the concept coverage maintains a nicely flowing thread for modules 1 and 2. But the remaining modules are not well integrated into a course theme.

Further, if this is meant to be a thermal hydraulic systems course, a module on system modelling would be required to bring in the concepts of mass, momentum and energy balances and to discuss the role of thermodynamic state properties in system modelling. If this course is neither a fluid fundamentals course nor a fluid systems course, then what is it?

This course needs a defining identity, ie., an introduction which defines the theme, the prerequisites assumed, the overall course goals and, if possible, a description of courses for which this course is a prerequisite. In short, this course needs to be put into context. The theme needs to be developed throughout; a course should tell a story.

Notwithstanding the fact that job task analysis results are not available and that how this course fits into the great scheme of things is not known by the reviewer, the stated objectives are evaluated next in section 4.2. Detail comments on course content are discussed in section 4.3.

Table 4.1 Behavioural targets for Modules 1 and 2

ID	Description	Awa	Det	Dia	Res	C 1	C 2	C 3	C 4	C 5	C 6	A 1	A 2	A 3	A 4	A 5
r/pxx.00	Decay heat	a		a	b	a	a	a	a						a	b
t/d01.00	State parameters (intrinsic)	a		a		a	a	a	a						a	
t/d02.00	State parameters (extrinsic)	a		a		a	a	a	a						a	
t/d03.00	First law of thermodynamics	a		a		a	a	a	a						a	
t/d04.00	Second law of thermodynamics	a		a		a	a	a	a						a	
t/d05.00	Third law of thermodynamics	a		a		a	a	a	a						a	
t/d06.00	Material properties	a		a		a	a	a	a						a	
t/d07.00	Thermodynamic processes	a		a		a	a	a	a						a	
t/d08.00	Thermodynamic cycles	a		a		a	a	a	a						a	
t/d09.00	Thermodynamic devices	a		a		a	a	a	a						a	
t/d10.00	Thermodynamic systems	a	b	a	b	a	a	a	a						a	b
t/d10.01	Thermodynamic systems - boiler pressure effects	a	b	a	b	a	a	a	a						a	b
t/d10.02	Thermodynamic systems - turbine steam flow effects	a	b	a	b	a	a	a	a						a	b
t/d10.03	Thermodynamic systems - condenser pressure effects	a	b	a	b	a	a	a	a						a	b
t/d10.04	Thermodynamic systems - feedheating effects	a	b	a	b	a	a	a	a						a	b
t/d10.05	Thermodynamic systems - reheat effects	a	b	a	b	a	a	a	a						a	b

Table 4.2 Behavioural targets for Module 3

ID	Description	Awa	Det	Dia	Res	C 1	C 2	C 3	C 4	C 5	C 6	A 1	A 2	A 3	A 4	A 5
t/hxx.00	Convection	a		a		a	a	a	a						a	
t/hxx.01	Convection - natural	a		a		a	a	a	a						a	
t/hxx.02	Convection - forced	a		a		a	a	a	a						a	
t/s01.00	Thermosyphoning equations	a	b	a	b	a	a	a	a						a	b
t/s01.01	Reactor heat balance	a		a		a	a	a	a						a	
t/s01.02	HTS momentum balance	a		a		a	a	a	a						a	
t/s02.00	Required conditions for t/s	a	b	a	b	a	a	a	a						a	b
t/s03.00	Process monitoring	a	b		b	a	a	b							b	b
t/s04.00	Mitigating systems	a		a	a	a	a	a	a						a	a
t/s04.01	Mitigating systems - primary side	a		a	a	a	a	a	a						a	a
t/s04.02	Mitigating systems - secondary side	a		a	a	a	a	a	a						a	a
t/s05.00	Voiding Issues	a			b	a	a	b								b
t/s10.00	Thermosyphoning systems	a	b	a	b	a	a	a	a						a	b

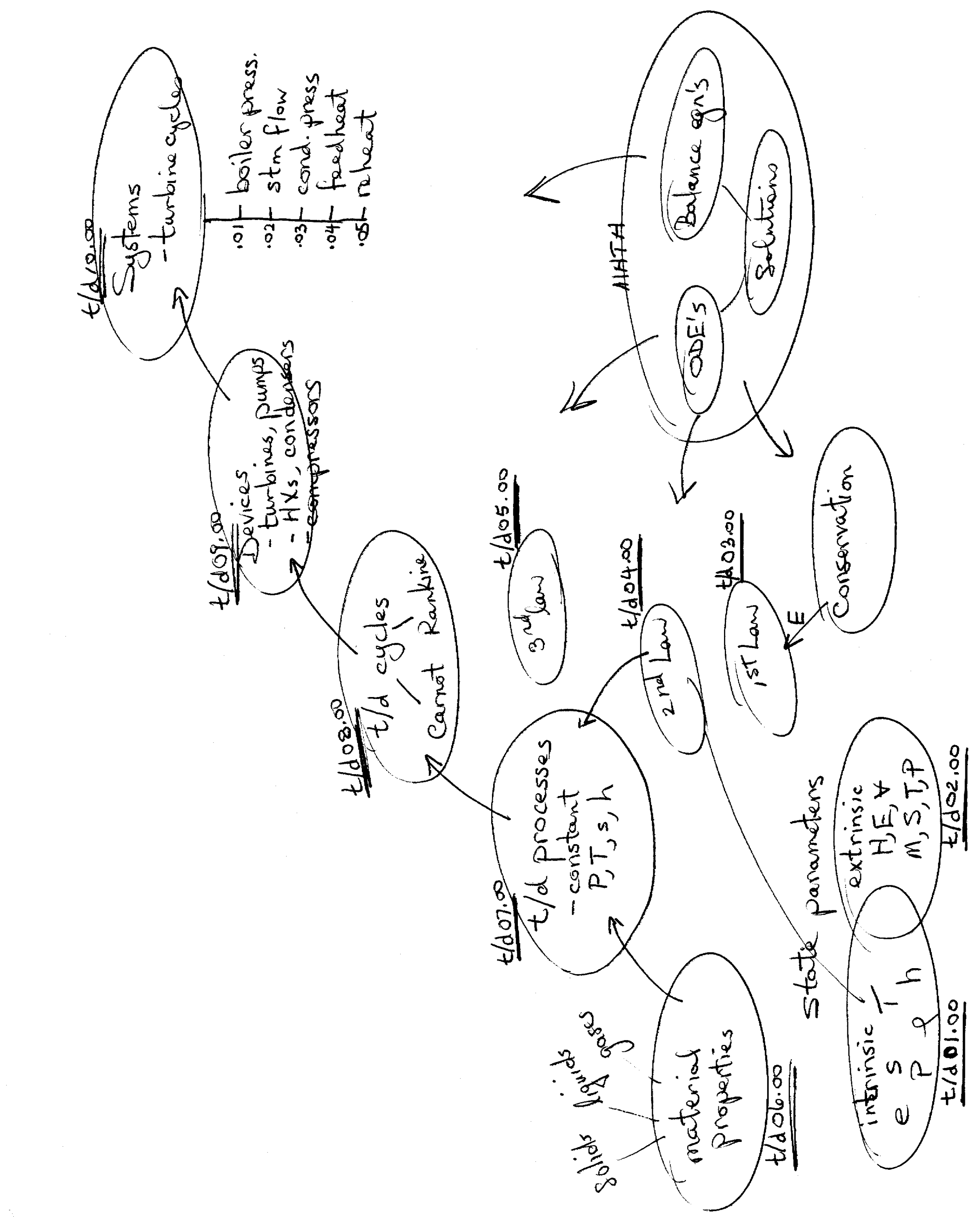

Figure 4.1 Overall concept map for Thermodynamic cycles

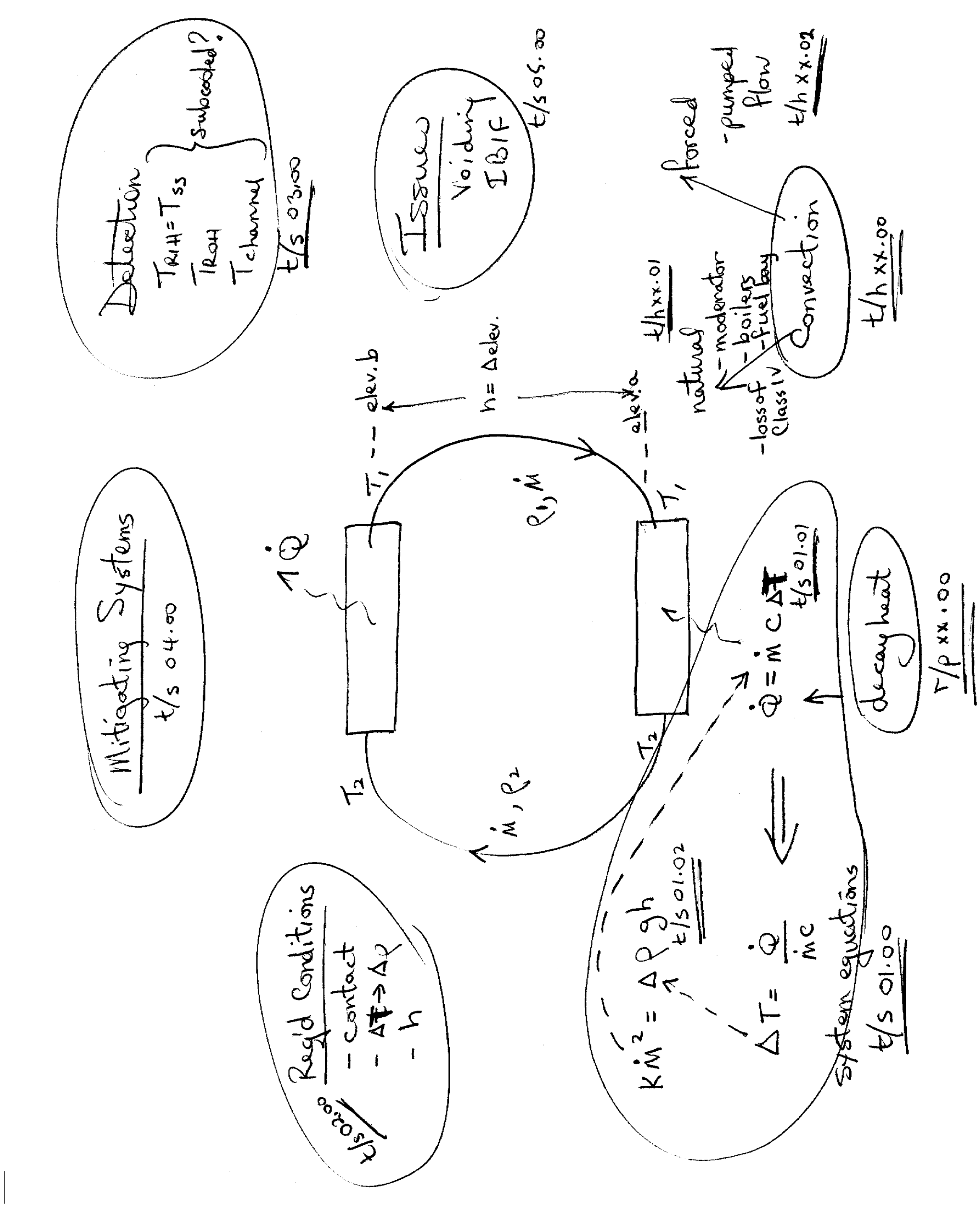

Figure 4.2 Overall concept map for Thermosyphoning

4.2 The Objectives

The objectives as stated in the first three modules of this course were assessed according to which concepts and behavioural levels they related to. The objectives for the remaining modules were not assessed in detail since the comments on the first three modules apply equally to the remaining modules.

Tables 4.3 and 4.4 summarize the ratings, ordered by concept.

Comparing tables 4.1 and 4.2 to tables 4.3 and 4.4 shows that there are no objectives relating to the following concepts that are the subject of this course:

- t/d02.00 State parameters(extrinsic)
- t/d03.00 First law of thermodynamics
- t/d05.00 Third law of thermodynamics
- t/d06.00 Material properties
- t/d10.02 Thermodynamic systems - turbine steam flow effects
- t/s01.00 Thermosyphoning equations
- t/s01.01 Reactor heat balance
- t/s04.02 Mitigating systems secondary side

The subjects of material properties and the first law of thermodynamics are likely covered in separate courses, as might be true for the other objectives. **More damning, however, is the low cognitive level of all the stated objectives.** None test a level of understanding above a comprehension level. There is no stated objective that is targeted to the trainee's ability to apply the information or use the concepts to analyse problems or situations in a manner other than a restatement of course material. Since levels C3 and C4 require some degree of figuring things out, some of the objectives must be worded to this end. The objectives need to be reformulated to address this shortcoming as in the following example relating to thermosyphoning:

<table>
<tr><td>Objective 1.1</td><td colspan="11">The trainee will be able to deduce the qualitative system behaviour from the thermosyphoning equations for prescribed scenarios.</td></tr>
<tr><td>Condition</td><td colspan="11">closed book written or oral examination</td></tr>
<tr><td>Standard</td><td colspan="11">Answer may be given using word descriptions, diagrams or graphs as appropriate. Physical mechanisms and system function should be correctly related to the equations.</td></tr>
<tr><td>Related concept(s)</td><td colspan="11">t/s01.00 Thermosyphoning equations</td></tr>
<tr><td>Classification</td><td>C1</td><td>C2</td><td>C3</td><td>C4</td><td>C5</td><td>C6</td><td>A1</td><td>A2</td><td>A3</td><td>A4</td><td>A5</td></tr>
<tr><td>Weight</td><td>a</td><td>a</td><td>a</td><td></td><td></td><td></td><td></td><td></td><td></td><td>a</td><td></td></tr>
</table>

This requires the trainee to operate at the required higher cognitive levels.

The need for objectives aimed at higher levels does not negate or reduce the need for objectives aimed at the lower behavioural levels. However, when the objectives are pitched at levels C1 and C2, ie., are recall based, the test questions and the objectives tend to look the same. As a consequence, learning tends to be limited to just satisfying the explicit statement of the objectives and no more. As a rule, the more specific the objective, the less general the learning. A balance must be struck so that the objectives provide enough focus to define the nature of the target understanding but not so specific so as to give away the question. For example, instead of stating an objective as

"Define Thermal Driving Head under thermosyphoning conditions",

a more general objective would be

"The trainee will be able to recall the key physical phenomena by name and by function".

A subsequent exam question might be

"Define Thermal Driving Head under thermosyphoning conditions".

Although only the objectives of the first three modules were assessed in detail, the objectives of the other modules were similar in their shortcomings. None of the objectives rise above the lowest two cognitive levels, that is, none require much more than recall. None of the stated objectives in this course addresses the issues of standards (conditions, time and accuracy) under which the trainee is to meet the objective.

Table 4.3 Ratings for the objectives for Modules 1 and 2.

Concept		Objective		C1	C2	C3	C4	C5	C6	A1	A2	A3	A4	A5
t/d01.00	State parameters (intrinsic)	1.04	Explain the concept of entropy.		a									
t/d04.00	Second law of thermodynamics	1.01	State the laws of thermodynamics.	a										
t/d07.00	Thermodynamic processes	1.05	Explain the relationship between energy degradation and entropy increase.		a									
t/d07.00	Thermodynamic processes	1.08	Describe different thermodynamic processes such as constant pressure,	a										
t/d08.00	Thermodynamic cycles	1.02	Explain that energy conversion and efficiency are governed by these laws		a									
t/d08.00	Thermodynamic cycles	1.03	Explain the concept of thermal efficiency.		a									
t/d08.00	Thermodynamic cycles	1.06	Describe the steam-water cycle (Rankin).	a										
t/d08.00	Thermodynamic cycles	1.07	Explain the limitations of steam-water cycle efficiency.		a									
t/d09.00	Thermodynamic devices	1.09	Explain various turbine processes such as constant entropy and constant		a									
t/d09.00	Thermodynamic devices	1.10	Define turbine internal efficiency.	a										
t/d10.00	Thermodynamic systems	1.11	Describe the effects of moisture separation and reheating on the steam	a										
t/d10.00	Thermodynamic systems	1.12	Describe the importance of feedwater heating.	a										
t/d10.00	Thermodynamic systems	1.13	Describe the limitations in efficiency improvement due to feedwater heating.	a										
t/d10.01	Thermodynamic systems - boiler pressure effects	2.01	Explain the effect of boiler pressure on generator MW output and	a	a									
t/d10.03	Thermodynamic systems - condenser pressure	2.02	Assuming constant reactor power, explain the effect of condenser pressure (or	a	a									
t/d10.04	Thermodynamic systems - feedheating	2.03	Assuming constant reactor power, explain the effect of loss of a bank of the	a	a									
t/d10.05	Thermodynamic systems - reheat effects	2.04	Assuming constant reactor power, explain the effect of total or partial loss	a	a									
t/d10.05	Thermodynamic systems - reheat effects	2.05	Explain the major reason why reheat is not used at light turbine loads.	a	a									

Table 4.4 Ratings for the objectives for Module 3.

Concept		Objective		C 1	C 2	C 3	C 4	C 5	C 6	A 1	A 2	A 3	A 4	A 5
t/s01.02	HTS momentum balance	3.02	Define Thermal Driving Head under thermosyphoning conditions.	a										
t/s02.00	Required conditions for t/s	3.01	Describe the general conditions (3) necessary for natural circulation to	a										
t/s02.00	Required conditions for t/s	3.08	Give the parameters (3) which are normally monitored to confirm	a										
t/s04.00	Mitigating systems	3.04	Explain thermosyphoning operation subsequent to a loss of class IV power and	a	a									
t/s04.01	Mitigating systems - primary side	3.03	Explain the role of the main HTS pumps immediately following a loss of class		a									
t/s05.00	Voiding Issues	3.10	State and explain the governing condition which provides assurance of	a	a									
t/s10.00	Thermosyphoning systems	3.05	Explain the relationship between flowrate and temperature difference		a									
t/s10.00	Thermosyphoning systems	3.06	Explain the relationship between decreasing decay heat levels and the		a									
t/s10.00	Thermosyphoning systems	3.07	Explain the self regulating characteristic of thermosyphoning.		a									
t/s10.00	Thermosyphoning systems	3.09	Describe the controlled variable in normal thermosyphoning.	a										

4.3 The Content

Herein, specific comments are made on course content. It must be emphasized that since the results of a job task analysis is not available, since the evaluation of the objectives has shown that the objectives as stated are grossly lacking, and since the context of this course in the overall training program has not been made explicit, a detailed content analysis is largely perfunctory. There is no point in fine tuning the content (which is the specification of **how** concepts will be taught) until it is clear **what** is to be learned. Nevertheless, in the following, comments of the more enduring nature are offered.

4.3.1 Module 1: Thermodynamic Cycles

Pg 1, last sentence: "It should be noted that neither the thermodynamic calculations or the thermodynamic diagrams constitute examinable material but are for illustrative purposes only."

- I do not understand the rationale for this approach. It must be decided up front just what needs to be presented and to what depth. If the trainee is not required to do calculations, then a great deal of the calculational detail in this module should be deleted. The notes are far too detailed if the objective is to only deal with general concepts. Some calculations are needed to more firmly establish an understanding since calculations involve the explicit and precise expression of concepts. This is important for fault *Detection*, *Diagnosis* and *Response*. I suggest that a middle ground be sought (subject to the results of a task analysis) wherein college level mathematics and calculations be used to quantify the descriptive content. It needs to be ensured that the trainee is comfortable (ie has reached appropriately high levels in both the cognitive and affective domains) with first order ordinary differential equations in time, with steady state and transient mass, energy and momentum balances, and with problem solving techniques in general. With that established, then succinct mathematical expressions of concepts can be used for effective learning.

Pg 5:

- The specific volume is missing in the pv term on the left hand side of energy equation in the middle of the page.
- It should be stated that this energy balance equation assumes no nuclear or chemical reactions.

Pg 6:

- It should be noted that heat capacity is generally a function of temperature. Illustrating this with a graph would be appropriate.

Pg 7, Equations for efficiency and energy balance:

- The equations are stated with little pedagogical explanation. This is very unsatisfying to an engineer and not understandable by a technician. From this point on the student must learn by rote if understanding is not achieved. It is better to illustrate with words to go with the equations and the diagrams on page 8. It is not evident that this material was written with consideration of how the student learns.

Pg 8:

- I suggest that the heat out be drawn at the bottom of the diagram rather than the top to be more consistent with the turbine system diagrams to come later in the module.

Pg 13, "The cycle efficiency is the inverse of the heat rate ..."

- This concept should be derived or otherwise explained to aid recall.

Pg 17:

- Perhaps it can be assumed that the student is familiar with steam tables but, in any case, a reference to the source of the h and s values should be given.
- This example includes a slight hot side - cold side differences due to “slight heat losses”. This is a distracting detail and serves no pedagogical purpose at this point. I recommend that the example be altered to eliminate this unnecessary element.

Pg 19, In the example,”...the enthalpy will remain the same...”:

- Is this true? If there is pressure drop, then there is turbulent heating. This would be a good point to add an explanation of the physical processes that are going on.

Pg 24, Last two sentences on conversion of heat energy to mechanical work:

- There should be an explanation of the physical process that is going on here. Each thermodynamic process can be expressed in terms of state variables and the equations relating them. This is required. But each process also has a direct physical explanation which should be given as well. As it is, the reader is left to speculate on the mechanism for this magical transformation of heat into mechanical work.

Pg 28, $q=c_p\Delta T$:

- This assumes a constant heat capacity. The assumption should be noted.

Pg 29, Whole section on the constant enthalpy process:

- The explanation would be considerably aided by the use of a energy balance equation showing which terms are affected.
- There should be an explanation of why expansion causes cooling of the steam.

Pg 32, Last sentence of paragraph 2:

- A physical explanation of the phenomena should also be given.

Pg 39, Wetness:

- This is another place where the energy balance equation could be used to aid the explanation. As a general comment applicable to all technical courses, descriptions, diagrams, graphs and equations when used alone to explain a phenomena is inferior to the balanced use of all.

Pg 49:

- A h-s diagram might aid the explanation of the feedwater heating effect on efficiency.

General comments:

- There is no summary of the key concepts.
- The level of rigour and detail is quite high and inconsistent with the other modules and with the other two courses reviewed.
- Use of textbook explanations should be considered. See, for instance, [RUS79] or [SEA75].

4.3.2 Module 2: Assorted Operational Aspects Regarding the Turbine Cycle

Pg 3,Figure 1:

- The relation between figure 1 and point 2 of the previous page should be explained more explicitly.

Pg 6, Second last line, "...because there are no more blades."

- This begs the question: "Why are there no more blades?" Presumably, you need some exhaust velocity to remove the mass.

Pg 9:

- In this section on partial loss of feedheating and, indeed, in all such sections, consideration should be given to the *Detection* and *Diagnosis* of the fault. Given the orientation of the trainee, this is not only a pertinent approach, the information would likely be more easily assimilated by the trainee if the concepts are reinforced by the practical aspects.
- In this section on partial loss of feedheating and, indeed, in all such sections, the graphs and diagrams developed in module 1 should be used more extensively.

4.3.3 Module 3: Thermosyphoning

Pg 4:

- The examples given are good. This reassures the trainee that HTS thermosyphoning is not an esoteric and unreliable phenomena.

Pg 5, Point 3:

- Justifications are given for points 1 and 2 but not 3. Why?

Pg 7, Thermal driving head:

- This is not defined and units are not given. The equation should be derived.

Pg 8:

- The explanation of thermosyphoning stands in stark contrast to the level and tone of the previous modules. As illustrated by the concept diagram in figure 4.2, the equations are not that onerous and the concepts are not difficult. This is another case where the verbal explanation is in dire need of support from equations and diagrams.

Pg 11, Monitored variables:

- This is a meaningful section. There should be more like this. "Slow" needs to be quantified. It should also be noted <u>why</u> the response time is slow at low decay heat levels.

Pg 12:

- The reason why subcooling margin is so important should be reinforced.
- Presumably, the reason why inlet header temperature is directly controlled by boiler pressure has been covered in another course. If not, it should be. This is central to understanding process system statics and dynamics.

4.3.4 Module 4: Boiling Heat Transfer, Dryout & Critical Heat Flux

Pg 1, Footnote:

- The equation given for heat conduction is not true in general. Assumptions should be noted and some indication of the magnitude of the error should be given.

Pg 6:

- The calculated temperatures should be compared to the sheath melting point to provide relevance.
- Once again, calculations are given but the student is instructed that he / she will not be required to do calculations from this section and, once again, I fail to see the rationale. If calculations are not required, then why is the methodology presented? Surely, the methodology is presented because understanding (at some cognitive level) **is** required. If calculations associated with radiative heat transfer are deemed to be beyond the scope of or irrelevant to the job function, then the calculational details should be omitted. If the information is supplemental (ie., for the purposes of reader enrichment), then the material should be relegated to an appendix or simply referenced.

Pg 13 and following, Fuel Dryout:

- I personally find a diagram of power and CHF vs. quality, such as illustrated in figure 4.3, helpful in explaining CPR, centerline melting and dryout limits. This would help decrease the reliance on descriptive explanations.

Pg 16, Channel Cooling Conditions - Flow:

- The word description of a channel energy balance can surely be replaced with $Q = W\ c\ \Delta T$ for greater effect in learning. The use of figure 4.3 would also aid in the CHF discussion.

Pg 17:

- The presented figures on temperature and enthalpy vs. channel position are effective. The curves can be approximately generated from simple heat balances for the reactor and for the boiler, thus linking the primary and secondary sides. First order effects from systems perturbations can then easily be quantized. This exercise is best done in a course on the Heat Transport System but the concepts would be reinforced if cross links to this module were established.

Pg 31, Summary:

- The summary is not on par with that of other modules. I personally do not find the summaries in any of the modules particularly useful. A comprehensive index and a table of contents are perhaps sufficient. I would recommend a de-emphasis on the summaries unless there is evidence that the trainees find them useful.

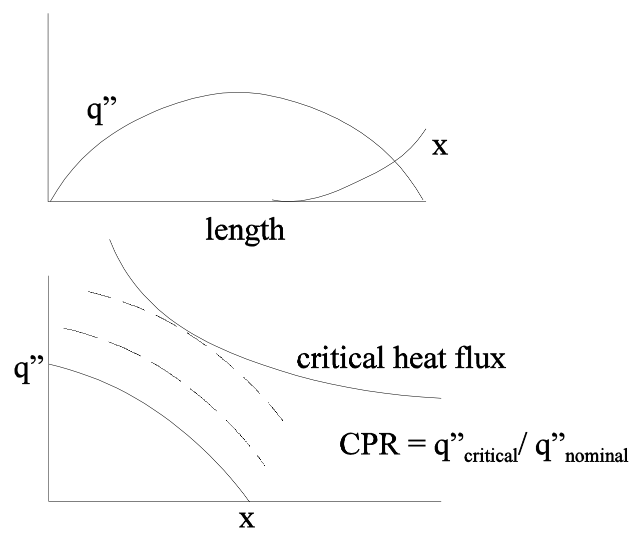

Figure 4.3 CHF and channel power vs. Channel quality

4.3.5 <u>Assorted Fluid Phenomena</u>

Pg 3, “For each load there is an appropriate water level ...”

- This discussion is based on the assumption that the steam generator inventory is the same irrespective of the power. I understand that the point being made is that at higher power there is more void and hence the level is higher. But in the actual plant, the boiler level is controlled; hence inventory may not be constant.

Pg 14, Last sentence:
- This sentence seems to be misplaced or is irrelevant.

4.3.6 Centrifugal Pumps and Systems

Pg 7, Definition of head:
- A useful concrete example would be that the head, measured in metres, is the height, in metres, of water that could be supported by the pump pressure rise, or words to that effect.

Pg 8, "Operating in this flattened region will result in instability..."
- It would be helpful to explain the mechanism of this instability. This will assist understanding and recall.

Pg 9, First sentence:
- The first sentence is poorly worded.

Pg 10, Last sentence:
- It is not clear how maximum power can occur at zero flow.

Pg 16, "Take a look at Figure 23 and list the parameters that you should alter during pump or system operation. This list will be revisited later."
- This is a good technique to engage the student.

Pg 16, "Under poor suctions, small vapour bubbles..."
- The explanation of the cause of cavitation seems inaccurate. To the best of my knowledge, it occurs in the low pressure region behind the trailing side of the impeller vane when the pressure there is low enough.

Pg 17, NPSH:
- The definition of NPSH is very obscure. Diagrams and equations might help considerably.

Pg 34, Footnote:
- This footnote is good. More practical tips like this would probably be appreciated by the student as a nice change of pace.

Pg 49, Runout:
- Runout is not defined.

Pg 51, Last sentence:
- This sentence does not make sense.

General comments:
- This module is disjointed, primarily at the beginning - it lacks a thread and a sequence. The initial portions need a buildup to figure 1, with an emphasis on the physical phenomena and the inner

workings of pumps. Perhaps this is covered elsewhere but if "head" must be defined, then the assumed knowledge level must be quite low. The jump straight into NPSH, etc., is too quick. As with modules 3 to 5, the descriptive explanations are almost impossible to recall later. It is highly recommended that a balance of charts, diagrams, equations, calculations and descriptions be used to provide a richer environment to aid learning.

4.4 Conclusions and Recommendations

It is the opinion of the reviewer that a detailed analysis of each stated objective is unnecessary, given the overall shortcomings. The objectives need to be reworked completely, starting with the development of more complete concept maps than presented here for illustrative purposes. Clear statements of desired outcomes (via a task analysis perhaps) need to be made, including desired performance levels and standards. Finally, the objectives need to be developed so as to link the concepts (the underlying tools) to the job tasks. Each objective should be a clear statement of what the trainee or student will be able to do (SWBAT), under what conditions and to what standard. It is recommended that a quantifiable measure of performance level such as the cognitive and affective hierarchy as presented here be used.

Since people have diverse learning styles, there is a strong motivation to present a given concept in a variety of ways (descriptive, graphical, diagrammatical, abstract equations, worked examples, case studies). The student can then vector in on the meaning of the material. After all, for the student, it is the ideas themselves, the concepts, that are to be understood, not the way that these ideas are learned or expressed per se. Course content is best viewed as learning devices and learning devices only. The learning outcomes (objectives) are keyed to the concepts, not the course descriptions for this very reason. If the distinction is not made by both the trainee and the trainer, then learning in the sense of understanding at the analysis level will degenerate to the rote memory levels of knowledge and comprehension. The training program becomes an exercise in anticipation of what will be on the exam. If this is the intent, then a clear statement should be made at the outset of the course about the pedagogical approach that is being taken and how the trainees are to be assessed. Further, the approach should be applied uniformly over the entire course if possible.

The mathematical rigour should be reduced in Module 1 and increased in the other modules to a level similar to the *Nuclear Physics and Reactor Theory* manual.

This course needs an identity. There should be a clear statement of course intent and the manual needs to receive a uniform treatment over all modules. The manual should tell a story.

5. Nuclear Physics and Reactor Theory

5.1 Overview and Concept Map

This manual contains 14 modules covering the basic definitions and phenomena of nuclear and reactor physics pertinent to nuclear operation. Figure 5.1 shows a concept map of the dominant concepts included in the manual. The actual concepts needed by the CRO / SS depend on the job task analysis results but, as previously discussed, it is unlikely that a direct linkage between job tasks and enabling principles can be made. In my estimation, the concept coverage is reasonably complete. The concepts for the first 5 modules are listed in table 5.1 along with my suggested linkage to the job tasks of *Awareness*, *Detection*, *Diagnosis* and *Response*. Using table 3.1, the required behavioural standards that result from this linkage are also listed in table 5.1. This represents the target against which the objectives are assessed.

The manual is well written and maintains a fairly consistent theme throughout; it tells a story, is reasonably self contained and is engaging. It builds smoothly and logically from definitions and first principles through to operational considerations. There is some discussion of design issues which may be superfluous but the concepts are not onerous to learn and will help the trainee appreciate the reasons behind operating procedures and concerns. Of particular note is the appropriate use of mathematics throughout. The balance between word descriptions, graphs, illustrations and mathematics is good.

There is anecdotal evidence to suggest that this course was well received by trainees but is a tough course. There was no suggestion for change. It appears that the trainees felt empowered by the experience. This will translate into effective CRO / SS behaviour in the end.

Table 5.1 Behavioural targets for Modules 1 to 5

ID	Description	Awa	Det	Dia	Res	C 1	C 2	C 3	C 4	C 5	C 6	A 1	A 2	A 3	A 4	A 5
r/p01.00	Nuclear structure	a				a	a									
r/p01.01	Atomic nucleus	a				a	a									
r/p01.02	Mass scale	c				c	c									
r/p01.03	Radioactivity	a	a	a	a	a	a	a	a						a	a
r/p01.04	E=mc^2	c				c	c									
r/p01.05	Mass defect and binding energy	c				c	c									
r/p01.06	Nuclear stability	c				c	c									
r/p02.00	Nuclear reactions	a		a		a	a	a	a						a	
r/p02.01	Elastic scattering	a		a		a	a	a	a						a	
r/p02.02	Inelastic scattering	a		a		a	a	a	a						a	
r/p02.03	Nuclear transmutation	a		a		a	a	a	a						a	
r/p02.04	Radiative capture	a		a		a	a	a	a						a	
r/p02.05	Fission	a		a		a	a	a	a						a	
r/p02.06	Fission products	a		a		a	a	a	a						a	
r/p02.07	Prompt neutrons	a	a	a	a	a	a	a	a						a	a
r/p02.08	Delayed neutrons	a	a	a	a	a	a	a	a						a	a
r/p02.09	Energy released in fission	b				b	b									
r/p02.10	Fission power	a	a	a	a	a	a	a	a						a	a
r/p02.11	Fuel consumption	a		b		a	a	b	b						b	
r/p02.12	Photoneutrons	a		a		a	a	a	a						a	
r/p03.00	Reactor physics variables	a	a	a	a	a	a	a	a						a	a
r/p03.01	Microscopic cross section	a		a		a	a	a	a						a	
r/p03.02	Macroscopic cross section	a		a		a	a	a	a						a	
r/p03.03	Neutron flux and reactor power	a	a	a	a	a	a	a	a						a	a
r/p03.04	Reaction rate	a	a	a	a	a	a	a	a						a	a
r/p03.05	Sigma vs energy	a		a		a	a	a	a						a	
r/p04.00	Reactor design	a		a		a	a	a	a						a	
r/p04.01	k, multiplication factor	a	a	a	a	a	a	a	a						a	a
r/p04.02	Criticality	a	a	a	a	a	a	a	a						a	a
r/p04.03	Energy decrement	c				c	c									
r/p04.04	Moderating ratio	a		b		a	a	b	b						b	
r/p04.05	Lattice pitch effect	c				c	c									
r/p04.06	Resonance absorption	a		b		a	a	b	b						b	
r/p05.00	k and rho	a	a	a	a	a	a	a	a						a	a
r/p05.01	Neutron life cycle	a	b	a	b	a	a	a	a						a	b
r/p05.02	6 factor formula	a	a	a	a	a	a	a	a						a	a
r/p05.03	Leakage	a		a		a	a	a	a						a	
r/p05.04	rho, reactivity	a	a	a	a	a	a	a	a						a	a

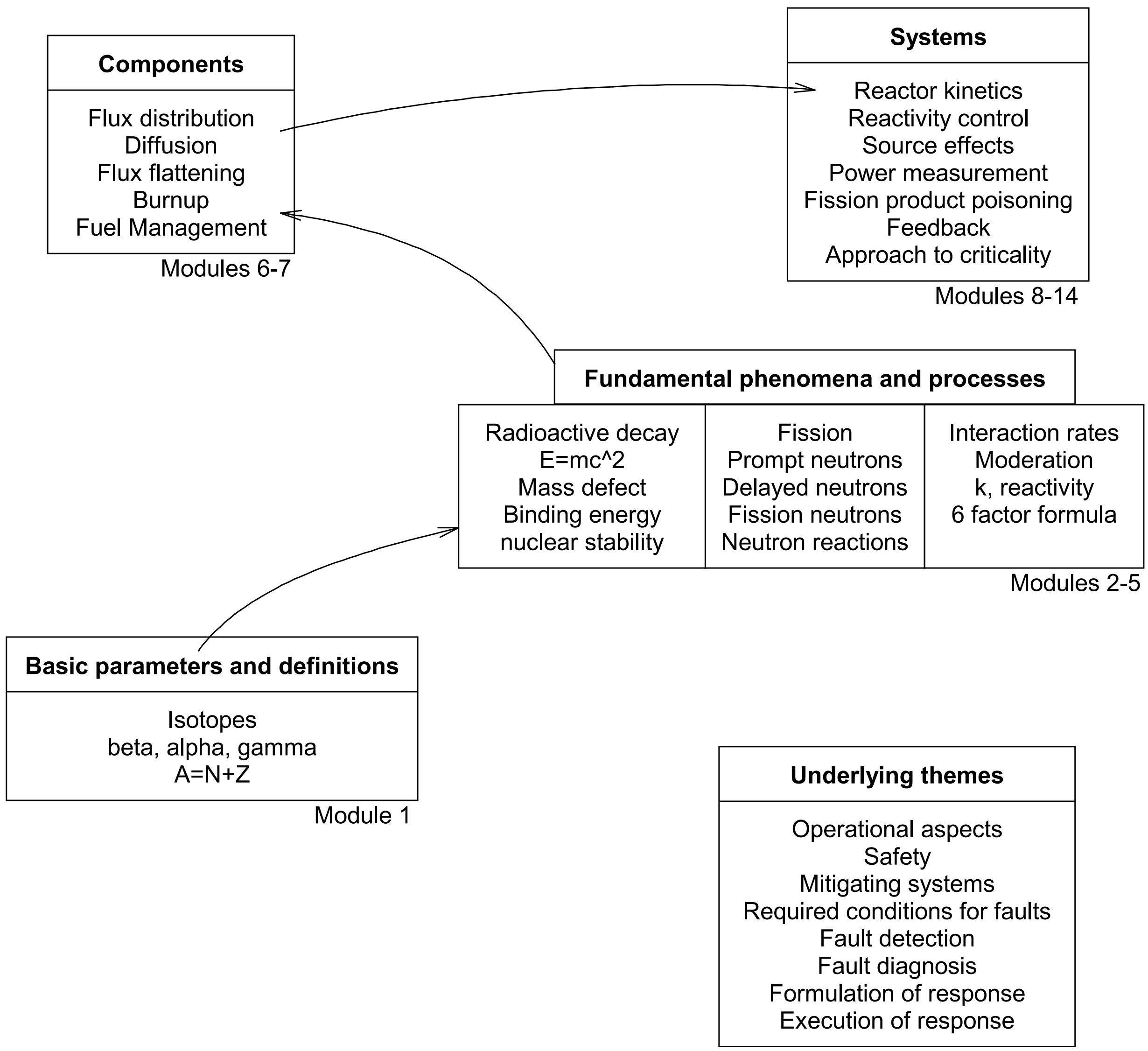

Figure 5.1 Overall concept map for reactor physics

5.2 The Objectives

The objectives as stated in the first 5 modules of this manual were assessed according to which concepts and behaviours they related to. The remaining objectives were not assessed since the comments given below for the first 5 modules apply equally to the remaining modules.

Table 5.2 summarizes the ratings, ordered by concept. Comparing table 5.1 to tables 5.2, 5.3 and 5.4 reveals that there are no objectives relating to the following concepts that are the subject of this course:

r/p01.02 Mass scale
r/p02.10 Reactor power
r/p03.04 Reaction rates
r/p04.03 Energy decrement

The *Mass scale* and *Energy decrement* concepts are of minor importance and are covered off implicitly to some degree in objectives relating to other concepts (the concept demarcation is never unique and overlaps are inevitable). However, there appears to be a definite lack of objectives relating to reactor power and reaction rates, key concepts for nuclear operations. The objectives of later modules do relate to these concepts directly or indirectly and it is difficult to imagine a trainee emerging from the program without a firm grasp of these concepts since so much depends on the power and reaction rates. This being granted, the concepts should have objectives related to them in the modules in which they first appear.

The coverage of behavioural levels is inadequate as per the *Fluid Mechanics and Thermodynamics* manual. Coverage is spotty for cognitive levels 1,2 and 3, and almost nonexistent for level 4. As before, the objectives as stated are just questions in disguise. The objectives need to be reformulated so that they focus on what the trainee will be able to do with the concepts. They should be stated in general enough terms so as to not to be a single, limited question in disguise, but not so general that the focus is lost. I suggest that the objectives be stated so that they address the requirement that the trainee develop adequate mechanistic and functional abstraction models.

Some example objectives for reactor physics that address these issues have already been given in chapter 3. The general comments on the objectives of *Fluid Mechanics and Thermodynamics* discussed in chapter 4 apply for the *Nuclear Physics and Reactor Theory*.

Table 5.2 Ratings for the objectives for Module 1

Concept		Objective		C 1	C 2	C 3	C 4	C 5	C 6	A 1	A 2	A 3	A 4	A 5
r/p01.01	Atomic nucleus	1.01	Define and use the X/AZ notation.	a		a								
r/p01.01	Atomic nucleus	1.02	Use the atomic mass unit.			a								
r/p01.03	Radioactivity	1.03	Define alpha, beta and gamma emissions.	a										
r/p01.03	Radioactivity	1.04	State the basic law governing radioactive decay.	a										
r/p01.03	Radioactivity	1.05	Define the decay constant and half-life of a radioisotope.	a										
r/p01.03	Radioactivity	1.06	Calculate the activity if a radioisotope of a given half-life.			a								
r/p01.04	E=mc^2	1.07	State the mass-energy equivalence principle.	a										
r/p01.05	Mass defect and binding energy	1.08	Define mass defect and binding energy.	a										
r/p01.05	Mass defect and binding energy	1.09	Explain the origin of energy releases in nuclear reactions.		a									
r/p01.05	Mass defect and binding energy	1.10	Describe how binding energy per nucleon varies with atomic mass number.		a									
r/p01.06	Nuclear stability	1.11	Explain how the stability of nuclei varies in terms of their neutron-proton		a									

Table 5.3 Ratings for the objectives of Module 2

Concept		Objective		C1	C2	C3	C4	C5	C6	A1	A2	A3	A4	A5
r/p02.00	Nuclear reactions	3.01	List the various reactions that a neutron can undergo during its lifetime.	a										
r/p02.01	Elastic scattering	2.01	Explain what is meant by elastic scattering, and how this process depends		a									
r/p02.02	Inelastic scattering	2.02	Describe what happens in inelastic scattering, giving an example of the		a									
r/p02.03	Nuclear transmutation	2.03	Describe what happens in nuclear transmutation, giving an example of the		a									
r/p02.04	Radiative capture	2.04	Describe what happens in radiative capture, giving an example of the process.		a									
r/p02.04	Radiative capture	2.08	Describe the process by which Pu-239 is produced in a CANDU reactor.		a									
r/p02.05	Fission	2.05	Differentiate between spontaneous and induced fission.				a							
r/p02.05	Fission	2.06	Describe what happens in induced fission.		a									
r/p02.05	Fission	2.07	Differentiate between thermal and fast fission, and list the nuclides for				a							
r/p02.06	Fission products	2.09	State why fission products frequently decay by beta emission.	a										
r/p02.06	Fission products	2.10	State five important consequences of fission product production in the	a										
r/p02.07	Prompt neutrons	2.11	Differentiate between prompt and delayed fission neutrons, and explain how		a		a							
r/p02.08	Delayed neutrons	2.11	Differentiate between prompt and delayed fission neutrons, and explain how		a		a							
r/p02.08	Delayed neutrons	2.12	Define the quantities beta and nu.	a										
r/p02.09	Energy released in fission	2.13	Calculate the energy released in a specified mode if fission, given the			a								
r/p02.09	Energy released in fission	2.14	List the various forms in which the energy released in fission may appear, and	a										
r/p02.11	Fuel consumption	2.15	Estimate the rate at which uranium is being burnt up for a given reactor power			a								
r/p02.12	Photoneutrons	2.16	Explain the process of photoneutron production and state why it is		a									

Table 5.4 Ratings for the objectives for Modules 3 to 5.

Concept		Objective		C 1	C 2	C 3	C 4	C 5	C 6	A 1	A 2	A 3	A 4	A 5
r/p03.01	Microscopic cross section	3.02	Define the microscopic reaction cross-section (including the unit used).	a										
r/p03.02	Macroscopic cross section	3.03	Define the macroscopic cross-section (and its unit).	a										
r/p03.03	Neutron flux and reactor power	3.04	Define the neutron flux and its use in determining the reaction rate per unit	a										
r/p03.05	Sigma vs energy	3.05	Describe in general terms the variation of absorption cross-section	a										
r/p04.00	Reactor design	4.04	Define the roles of elastic and inelastic scattering in a reactor.	a			a							
r/p04.01	k, multiplication factor	4.01	Define the terms: critical, subcritical, supercritical and neutron	a										
r/p04.02	Criticality	4.06	Describe the effect of downgrading the moderator or heat transfer fluid.	a										
r/p04.04	Moderating ratio	4.02	List the desirable properties of a moderator with particular reference	a										
r/p04.04	Moderating ratio	4.05	State why heavy water is used as the moderator in CANDU reactors.	a										
r/p04.05	Lattice pitch effect	4.07	State how and why the multiplication factor varies with lattice pitch,	a										
r/p04.06	Resonance absorption	4.03	Explain why "lumping" the fuel is necessary in a reactor fuelled with		a									
r/p05.01	Neutron life cycle	5.03	Sketch a neutron life cycle for the reactor, and explain what happens at		a									
r/p05.02	6 factor formula	5.01	State the expression for the multiplication factor (k) in terms of the six	a										
r/p05.02	6 factor formula	5.02	Define each of the factors in the six-factor formula.	a										
r/p05.02	6 factor formula	5.04	Calculate the values of the six factors for a life cycle diagram with			a								
r/p05.02	6 factor formula	5.05	Define k-infinity and explain what it means when the core contains a large	a	a									
r/p05.03	Leakage	5.06	Explain why the CANDU reactor is designed in the form of a large cylinder		a									
r/p05.04	rho, reactivity	5.07	Define reactivity and the unit used for it (milli-k).	a										

5.3 The Content

Herein, specific comments are made on the manual contents. As previously stated, the manual is well done. The manual makes good use of the sidebars to note the key points being discussed. This should be emulated in the other courses. The following comments are relatively minor in nature.

5.3.1 Module 1: Nuclear Structure

Pg 3, sidebar: "Atomic number":
- Spelling mistake.

Pg 5:
- It is instructive to add that the difference in mass between a neutron and a proton is about that of an electron.

Pg 7, "Symbol...":
- Spelling mistake.

Pg 8, "...where the symbol $^{0}v_{0}$ ...":
- Change to $^{0}_{0}\nu$.

Pg 10:
- $e^{-\lambda t}{}_{1/2} = 2$ --> $e^{+\lambda t}{}_{1/2} = 2$.
- In --> ln.
- Font size on subscripts and superscripts are too small. This is true throughout the manual.

Pg 12:
- Dm and DE --> Δm and ΔE.

Pg 13:
- Define nucleons
- nown --> known
- In equation 1.8, E.E. --> B.E.

Pg 89, "...the gamma rays emitted ... have energies that are characteristic of that nucleus and no other.":
- It would be instructive to say why this is important (detection, penetration, identification, etc.).

5.3.2 Module 2: Neutron Reactions

Pg 1, "The purpose of the moderator is to slow down the neutrons as rapidly as possible":
- This is not true. The purpose is to slow down the neutrons with as little absorption as possible. It is the relative probabilities that is important, not the speed. This error occurs also in section 4.4 and 4.5.

Pg 2, paragraph e) "Fission":
- should be bold and italic.

Pg 4, Section 2.3 Nuclear Reactions:

- Why not show the energy dependence graphically as well? A picture is worth a thousand words...

Pg 11, "The most common neutron reaction of all is radiative capture...":

- Is this true in general? I suspect it would depend on the circumstances.

5.3.3 Module 3: Neutron Cross Sections, Neutron Density and Neutron Flux

*Pg 3, "The neutrons just emerge with a changed kinetic energy (**elastic scattering**) ...*:

- The statement could be confused as a definition of elastic scattering, which it is not.

Pg 11, Equation 3.2:

- ν --> v (ie velocity, not nu).

Pg 13, Bottom of page, "...the average distance travelled ...":

- This appears out of the blue. No relation of Σ to distance has been established.

Pg 14, Equation 3.6:

- ν --> v (ie velocity, not nu).

Pg 15, Equation 3.8:

- ν --> v (ie velocity, not nu).

Pg 18:

- ν --> v (ie velocity, not nu).

5.3.4 Module 4: Thermal Reactors (Basic Design)

Pg 3:

*"...definition of k is only valid if the number of **source neutrons**... is negligible...":*

- The reason should be stated.

"...we are ignoring the fact that some of the fission neutrons are delayed...":

- This is irrelevant.

Pg 5, Explanation of the "lumping effect":

- The explanation is flawed. Of what possible benefit would it be to "screen" the inner fuel from resonance neutron when the outer fuel will absorb them anyway? The "minor advantage" of slowing down the neutrons through the whole range in actually the major effect.

Pg 11:

- "slowingdown" --> "slowing down".
- Including the properties of degraded D_20 in table 4.2 is good.

5.3.5 Module 5: Neutron Multiplication Factor and Reactivity

Pg 4, "The first thing that happens is we actually gain some neutrons...":
- The diagram shows leakage first.

Pg 7:
- Why not define the factors in the 6 factor formula so that you get cancellation of the denominator of one factor with the numerator of the subsequent factor? I find this useful for pedagogy.

Pg 9:
- The symbols used in figure 5.2 do not correspond to the text. Also, the thermal neutron box is missing a "p". It would be preferable to re-do figure 5.1 to match the configuration of figure 5.2.

Pg 11, "...on-load refuelling":
- Change to "on-line refuelling".

Pg 12, Section 5.5, first paragraph:
- This is not a good analogy. The size of the vat is not changing as more fuel is added. Consequently, the leakage is not changing all that much.

Pg 13, Last paragraph, discussion on number of bundles for criticality:
- This is important information for the trainee. Excellent.

5.3.6 Module 6: Neutron Flux Distribution

Pg 3, "neutral flux":
- Change to neutron flux.

*Pg 4, "**neutron diffusion**, because...":*
- Remove the ",".

Pg 8, figure 6.4:
- Label the curves A, B and C to match the text.

5.3.7 Module 7: Effects of Fuel Burnup

Pg 5, Equation 7.1:
- The flux appears incorrectly as a subscript.

Pg 6, Equation 7.2:
- The last term should be the exponent of e. Also, this equation is only true if flux is constant. In general the flux will rise for the same power as burnup increases.

Pg 8, Equation 7.4:
- The last term should be the exponent of e.

Pg 9:

Equation 7.6:

- The last term should be the exponent of e.

"$N_{9(eq)}$ N_8 = 0.27%":

- Change to "$N_{9(eq)}$ / N_8 = 0.27%".

Pg 11, Figure 7.3:

- Why is there a kink in the Pu-291 curve?

Pg 19, "...the physics data of the program are modified by intelligent guesses...":

- This is a bit too cynically stated for my liking.

5.3.8 Module 8: Reactor Response to Changes in Reactivity

Pg 6:

- Inconsistent use of the symbol for neutron lifetime. Also, there is an error in the last term of the second last equation: n / *l* ℓ--> n / *l*

Pg 7, Section 8.4.2 Reactor Period:

- Why define e=2.7183 at this late stage?
- The whole section is awkward. Why not simply define τ from $e^{-t/\tau}$ and work from there?

*Pg 11, "**We start with the reactor in a steady critical condition**...":*

- Should emphasize that the reactor has been at steady state for some time so that the precursors are in equilibrium.
- I like the analogy that follows but, in the end, I find it a bit off the point. I think it would be better to introduce the notion of being subcritical on prompt neutrons alone.

Pg 16:

- I wonder if it would be simpler to just present the neutron balance equation and its solution rather than simplifying so much at the beginning and then bending over backwards to compensate for the simplifications. There is too much to remember when you simplify too much and it just reinforces the notion that math is akin to voodoo. The equation setup is no harder than the mind bending that is done here.

Pg 1:,
Second paragraph:

- The reference to the precursor bank is misleading. I prefer the notion that the real reason that the prompt jump is limited is because $1 + k + k^2 + \ldots$ is a bounded sum when $k < 1$, ie the reactor is subcritical on prompt neutrons alone. What is happening in the precursor bank is irrelevant in the short term.

At the bottom of the page:

- 10,000 --> 1,000.

Pg 21, Equation:

- In the last term, = --> + and + --> =.

Pg 22, Last paragraph:

- Incorrect symbol for τ.

Pg 23, Last line:
- "." missing.

5.3.9 Module 9: Source Neutron Effects

Pg 6, Example:
- Examples like this should be used more frequently.

Pg 9, Last sentence:
- Why not include the formula for k_1: $k_1 = 1 - \Delta k /(1-P_1/P_2)$?

5.3.10 Module 10: Power and Power Measurement

Pg 3, "Normally, we calibrate ...to provide the design heat input...":
- This implies that we fudge to give the design values. I think you mean that the RRS is calibrated to the actual secondary side heat load.

Pg 5, Figure 10.1:
- The zero in the graph is not "suppressed". This is a log scale. The trainee should be comfortable with this by now.

Pg 7, Section 10.5.2:
- It would be nice to add why the lin N and log N detectors are used as they are.

Pg 8:
- Typos for symbols throughout this page.
- The derivation is awkward. Would it not be easier and more understandable to start with the rate equation: $dP/dt = P/\tau$ --> $(dP/P)/dt = 1/\tau$ --> $d(\ln P)/dt = 1/\tau$?

Pg 9, Equation:
- This equation is not correct as it stands. The power should be in fractional units, not %FP. Inverse Period has no % in its units.

Pg 11, Bottom of page and middle of page 12:
- P0 --> $P_{0.}$

Pg 14, Discussion on approach to criticality:
- This is an interesting and important practical point. As I see it, the operator would be basically trying to control the (γ, n) source term by varying the $(\rho-\beta)/\Lambda$ term, ie the prompt term. This is tough when the (γ, n) term dominates the neutron balance equation. Wouldn't it be better to state it this way? Why not spend some time up front to put this on a proper footing (full point kinetics neutron balance equation)? Otherwise, explanations become long and hard to learn and remember. This has an adverse effect on operators. But the recall speed will be slower. How can we get depth and

speed? Could we have an on-line aid to pop up the equations and show the size of the various terms at the current reactor conditions? Too obscure?

Pg 15, "...3% full power...(3% is the maximum capacity of the auxiliary boiler feed-pump)...":
- Surely this is no coincidence. If not a coincidence, point out the connection as a deliberate design / operational feature.

5.3.11 Module 11: Fission Product Poisoning

Pg 3, Typo:
- 106 barns --> 10^6 barns.

Pg 5, Typos:
- Superscripts required in 2 places.

Pg 6, Xenon-135:
- If the trainee is expected to understand these rate equation, then why not introduce the neutron balance equation?

Pg 7, Typos:
- NI --> N_I, plus other similar typos.

Pg 9:
- It might be helpful to plot X_{eq} vs flux as well.

Pg 10:
- "Xenon load" belongs in the sidebar.
- It might be worthwhile to show that $\rho_{Xe} \approx -\Sigma_{Xe} / \Sigma_{total}$.

*Pg 17, "**Figure 11.7** show that this is true...":*
- Show that what is true?

Pg 20, Last sentence:
- "Oscillations of this kind are easily..." --> "Oscillations of this kind, ie, involving flux changes in the whole core in harmony, are easily...".

Pg 24, Last paragraph, "...its reactivity is ...":
- "...its effect on reactivity is ...".

Pg 25, Second paragraph, "The equation for SM-149 buildup is simpler...":
- If it is simpler, why not just write the equations down; the explanations will be easier.

5.3.12 Module 12: Reactivity Effects Due to Temperature Changes and Coolant Voiding

Pg 1, Last sentence:
- Why is it not done for the coolant coefficients as well?

Pg 4:
First paragraph, "...in which it increased is rather...":
-"...in which it increased was rather...":
Third paragraph, "...power would have continued to rise...":
- It would be instructive to allude to why.

Pg 9, Typo:
- Put "Thermal neutron" in the sidebar.

Pg 10, Figure 12.4:
- I don't think the Maxwellian distribution looks like that shown.

Pg 13, Figure placement:
- Figures should go after the text in which they are referred.

Pg 14:
First paragraph, last sentence:
- The point needs to be more clearly illustrated.
Full page:
- Does the trainee need this level of detail?

Pg 16, Equation 12.1:
- Replace first + sign with = sign.

Pg 18:
- Typo in second line of text.
"...and so increases the distance a neutron travels...":
- Add that this means that it is more likely that the neutron will interact with the fuel and thus more likely that it will get absorbed by a resonance.
"The result is that, while the calculations predict a strong...":
- The wording implies that the calculations are incorrect. I don't think that this was the intended meaning.

Pg 19, Last paragraph:
- The implication here is that since the theory behind the coolant coefficient is too complicated, there is no <u>need</u> to discuss it! So, I assume that the reason that the other coefficients were discussed was because it was easy, not because it was <u>needed</u>.

Pg 21, Table 12.1:
- Move the table to the next page.

Pg 27, Point b):
- Perhaps this could be reworded to say that the main effect is that more neutrons are thermalised in the moderator, away from the U-238 resonances.

Pg 28, Last paragraph:
- This would be a good place to get into a discussion on the pros and cons of positive and negative feedback.

5.3.13 Module 13: Reactivity Control

Pg 4, "...will have to consist of more than one type of reactivity ...":

- I don't think that a reactor's complexity has anything to do with the number of control mechanisms needed.

Pg 5, Table 13.1:

- What does (+ve, -ve) mean?

Pg 8, Typo:

- I) --> i).

Pg 23, Moderator dump:

- Another disadvantage of a moderator dump would be the loss of a heat sink.

5.3.14 Module 14: The Approach to Critical

Pg 3, Second last paragraph:

- It would be useful to mention the position of the control rods and liquid zone controllers.

Pg 6, Equation:

- Remove the "1" in the last term.

5.4 Conclusions and Recommendations

This is a good manual overall. The objectives need to be reworked as indicated so as to be a better study guide for the trainees, a check list for trainers and developers, and a resource for the setting of exam questions. Before the objectives are reworked, concept maps should be constructed. Given the high level of accuracy, completeness and appropriateness of the training material, this should not be a onerous task.

6. Principles of Reactor Safety

6.1 Overview and Concept Map

The manual supplied for review is undated but appears to have been released about mid-1995. Towards the end of this review, a later version, February 1997 R-1, was supplied. The comments following relate to the 1995 version although some reference is also made to the 1997 version where appropriate.

This manual contains 18 modules covering the principles and policies governing the approach to nuclear safety used by Canadian nuclear utilities. Module 0, *Introduction to the Course*, does not provide an overview of how the various modules form the whole. This could be easily done using a concept map. Figure 6.1 shows a possible map of the layout of the modules and how they relate to the main concepts covered by the manual. The manual makes good use of concept maps on a module by module basis. One excellent example is the *Defense in Depth* concept map, but it does not tie the modules together. The small illustration on the cover page of the version of the manual under review (*Defense in Depth* on a course overview level) might be a good basis for a course level concept map. I notice that this logo is missing from the 1997 version of the manual; I suggest that it be retained. I am sure that the course developers could come up with a more imaginative and comprehensive map than my offering. It would be most helpful to the trainee if they did.

The relationship of the concepts such as safety culture, defense in depth, nuclear safety management, etc., to the job tasks is of a different nature than that of the other courses reviewed in this report. Previously, the focus was on the actual performance of the operating tasks under normal and abnormal conditions. The concepts of nuclear safety, in contrast, relate more to the attitude and approach of the CRO / SS to the conduct of safe practices, irrespective of the particular task at hand. Hence, the concepts do not relate to fault detection and diagnosis. Rather, they relate to an awareness of the safety principles and the application of these principles in responding to plant situations. As an example, table 6.1 shows the main concepts relating to module 2, *Safety Management and Safety Culture*, as depicted in figure 2.1 of the manual. I have added one additional concept, *r/s02.03.4 Empowerment*.

The issue of empowering the individual, whether an operator, a designer, a manager or a CEO, is an important one. Policies and principles, delineation of responsibilities, training, etc. relating to reactor safety are necessary. But all is for nought if the individual is not empowered to act. Empowerment requires that the following be ensured:

- mandate
- roles
- responsibilities
- authority
- means
- time
- protection.

From the brief interviews with the various sites and from occasional discussions in the past, I sense a definite lack of empowerment of the individuals at the utilities (notably OH). Safety culture cannot become a reality without empowerment. For this reason, I suggest that the concept be added to the manual in the hope that, over time, this issue might receives some attention on all levels.

The concepts of table 6.1 must now be linked to the desired outcomes. Recall that the job tasks of *Awareness, Detection, Diagnosis*, and *Response* have been previously keyed to the behavioural levels (see table 3.1). By linking the concepts to the job tasks, the required behaviours are automatically defined. Many of the concepts relate only to being aware of the various policies and principles, ie, relate only to the *Awareness* job task. This implies that understanding at the lower levels of the cognitive domain is all that is required. The concepts relating to the individual's response in the workplace have the added dimension of actual performance. Those concepts that relate to the *Response* job task involve the affective domain as indicated in table 6.1. Table 6.1 represents the target against which the objectives are assessed.

The manual is generally well written from a consistency of theme point of view; it tells a story and is self contained. The subject matter is very important. Accidents cost in dollars, environmental impact and lives. Following safe work practices has been shown to be cost effective. Most (some 70%) of accidents have human factors as the root cause. The human factors are often in the area of attitude, haste, improper management, failure to follow procedures, etc. It is not usually lack of job skills. It is entirely appropriate that the story begins with the concepts of *safety culture*, *defense in depth* and *control/cool/contain*. These are the important concepts for the CRO / SS to be firmly committed to. The rest of the modules support these safety concepts.

Table 6.1 Behavioural targets for Module 2

ID	Description	Awa	Det	Dia	Res	C 1	C 2	C 3	C 4	C 5	C 6	A 1	A 2	A 3	A 4	A 5
r/s02.00	Safety management and safety culture	a			a	a	a	a								a
r/s02.01	Institutional (executive) commitment	a				a	a									
r/s02.01.1	Policy level commitment	a				a	a									
r/s02.01.2	Management structures	a				a	a									
r/s02.01.3	Resources	a				a	a									
r/s02.01.4	Self-Regulation	a				a	a									
r/s02.02.1	Definition of responsibilities (and authority)	a				a	a									
r/s02.02.2	Definition and control of safety practices	a				a	a									
r/s02.02.3	Qualifications and training	a				a	a									
r/s02.02.4	Rewards and sanctions	a				a	a									
r/s02.02.5	Audit, review and comparison	a				a	a									
r/s02.03	Individual commitment	a			a	a	a	a								a
r/s02.03.1	Questioning attitude	a			a	a	a	a								a
r/s02.03.2	Rigorous and prudent approach	a			a	a	a	a								a
r/s02.03.3	Communication	a			a	a	a	a								a
r/s02.03.4	Empowerment	a			a	a	a	a								a

Principles of Reactor Safety Management

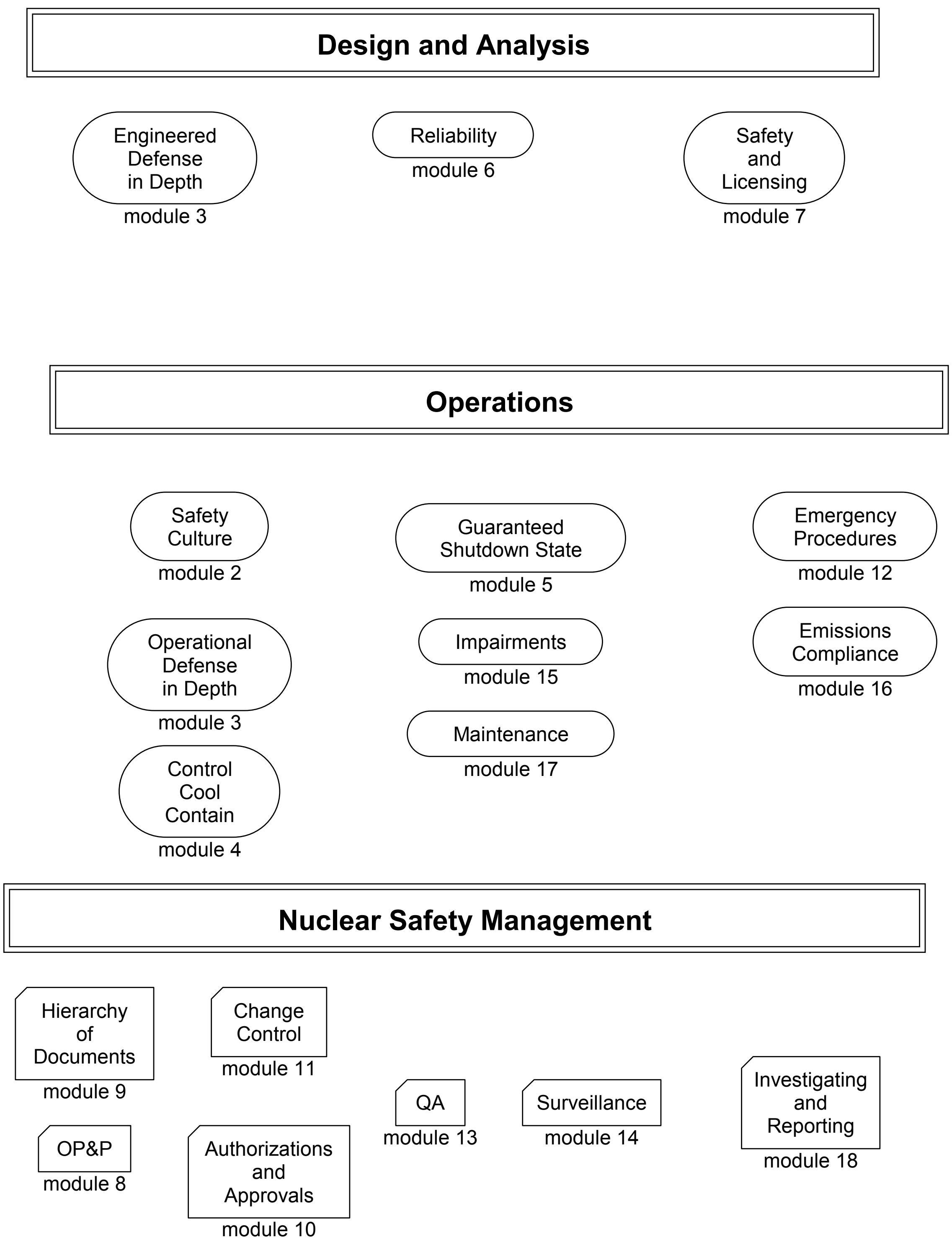

Figure 6.1 Overall concept map for reactor safety

6.2 The Objectives

The objectives as stated in module 2 were assessed according to which concepts and behaviours they related to. The remaining objectives were not assessed since the comments given below for module 2 equally apply to the remaining modules.

Table 6.2 summarizes the ratings, ordered by concept. Comparing table 6.1 to table 6.2 reveals that there are no objectives relating to many of the concepts. This is easily corrected. **More importantly, none of the objectives relate to the affective domain**, just to the cognitive domain. Since the affective domain is important for safety related matters, this shortcoming needs to be addressed. It is likely that the proper operator attitude is encouraged by other parts of the training program but there appears to be no formal assessment. As in the other courses, the objectives as stated as just questions in disguise. They need to be reformulated so that they focus on what the trainee will be able to do with the concepts. They should be stated in more general terms so as not to be a single, limited question in disguise, but not so general that the focus is lost.

As an example, objective 2.5 might be restated as follows:

<table>
<tr><td>Objective 2.5</td><td colspan="11">The trainee will be able to a) identify the main roles of the institution, the management and the individual in ensuring a safety culture; b) show how these groups relate to each other; c) show how the various performance indicators measure the effectiveness of these groups.</td></tr>
<tr><td>Condition</td><td colspan="11">closed book written or oral examination with the aid of figure 2.1 for reference</td></tr>
<tr><td>Standard</td><td colspan="11">100% on items relating to the individual, at least one role example for the other elements. Answer may be given using word descriptions, diagrams or graphs as appropriate. Answer should be given with little hesitation.</td></tr>
<tr><td>Related concept(s)</td><td colspan="11">r/s02.00, r/s02.02.5</td></tr>
<tr><td>Classification</td><td>C1</td><td>C2</td><td>C3</td><td>C4</td><td>C5</td><td>C6</td><td>A1</td><td>A2</td><td>A3</td><td>A4</td><td>A5</td></tr>
<tr><td>Weight</td><td>a</td><td>a</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
</table>

An objective relating to the affective domain might be:

Objective 2.7	The trainee will be able to act in accordance with reactor safety principles in situations which require a prioritization of actions.										
Condition	mock exercise										
Standard	Demonstration of willingness to put safety first, above other operational considerations.										
Related concept(s)	r/s02.00, r/s02.03										
Classification	C1	C2	C3	C4	C5	C6	A1	A2	A3	A4	A5
Weight	a	a									a

It is realized that mock exercises are poor substitutes for the real thing, especially in the area of the affective domain. Other means of testing the commitment to safety principles should be explored outside the context of this manual.

Table 6.2 Ratings for the objectives for Module 2

Concept		Objective		C1	C2	C3	C4	C5	C6	A1	A2	A3	A4	A5
r/s02.00	Safety management and safety culture	2.05	Explain how each of the following organizational elements shows a utility's commitment to a safety culture, and explain why commitment of all three organizational elements is necessary to create and maintain a good safety culture: ...		a									
r/s02.01	Institutional (executive) commitment	2.03	List three key effectiveness areas (KEAs) of a managed nuclear safety program. Give and explain the relevance of one performance measure for each KEA.	a	a									
r/s02.01.1	Policy level commitment	2.04	List and briefly describe the impact on nuclear safety of three Federal Acts.	a	a									
r/s02.02.5	Audit, review and comparison	2.02	Explain how a Utility knows when its nuclear safety program is successful.		a									
r/s02.02.5	Audit, review and comparison	2.06	List four performance indicators that point to the health of a nuclear power plant's (NPP's) safety culture. Describe the relevance of each indicator to a good plant safety culture.	a	a									
r/s02.03.2	Rigorous and prudent approach	2.01	Define the following terms: Nuclear safety, Safety Culture, Self checking, Independent verification, Conservative decision making.	a										

6.3 The Content

Herein, specific comments are made on the manual contents. Specific comments on each module are offered below but, as discussed in section 6.3.11 (following), since the material needs to be reworked for better pedagogy and since a later revision of the material already exists, no attempt was made to be exhaustive in the specific comments.

6.3.1 Module 0: Introduction to the Course

Pg 1, "Reactor Safety is the set of operating philosophies...":

- Perhaps this should read *"*Reactor Safety is made more likely through the use of operating philosophies ...*"* or something to that effect. Presumably, reactor safety is an actual achieved state, not the mechanism to achieve it. This has been addressed in the 1997 revision.

General comment:

- This module does not provide an overview of how the various modules form the whole. It should. This could be easily done using a concept map as discussed in section 6.1 of this report.

6.3.2 Module 1: Definitions

No specific comments.

6.3.3 Module 2: Safety Management and Safety Culture

Pg 3, "An organization knows its nuclear safety program is successful when its performance standards are being met...":

- This is only true to the extent that the measures are adequate.

Pg 4, Key Effectiveness Areas:

- The defining of and evaluation of the key effectiveness areas is a useful approach because it states explicit performance measures. This should be done in the other training courses.

Pg 5, Role of Government in Nuclear Safety:

- The focus should be on how and why something functions (in this case the Government Acts), not on memorizing (although some of that must be done). It would make more sense to require an awareness of the aspects of nuclear that could impact on the outside world. Functionally this would be liability, the environment, transportation, accident mitigation, nuclear safety, pressure vessels, etc. This translates directly into the various Acts. Presented in this way, the material can be integrated (and remembered) much more easily.

Pg 7, Figure 2.1:

- Add *"*Empowerment*"* as a fourth box under *"*Communication*"*, as discussed in section 6.1 of this report.

Pg 8, Management commitment:
"Management commitment is a prerequisite to a good safety culture":

- And proper training is also essential to a good safety culture. Hence, management commitment to training is a prerequisite to a good safety culture.

*"*Definition of Responsibility*"*:

- It should be noted that the authority must be commensurate with the level of responsibility. Far too often, an individual is given responsibility without the proper level of authority. Ask workers if they feel that *"*their hands are tied*"*. The usual response is *"*Yes!*"*.

Pg 12, "A questioning attitude, better training ... would have gone a long way towards preventing both the TMI and Chernobyl accidents.":

- I agree fully and I offer this comment to those who would suggest that the training programs in the fundamentals area are not cost effective or essential to the whole training program. One's ability and willingness to ask meaningful questions depends on an appreciation of the fundamentals principles.

Pg 13, Assignment question 1 "Carefully prepare answers for each of the Module 2 learning objectives.":

- To repeat my refrain, objectives are <u>not</u> questions.

[Pg 13 February 1997 R-1 version only], "Success depends both on having the managed program and on people's perceptions *and* beliefs *about the program elements.":*

- How very true. So why is there such a lack of assessment of the people's perceptions and beliefs?

6.3.4 <u>Module 3: Defense in Depth</u>

Pg 25, "Because approval of abnormal incidents procedures requires an extra layer of review, this ensures a system or unit is placed in a safe state."

- How can review and approval ensure a physical outcome? It should make the desired outcome more likely but it cannot ensure it.

Pg 28, Assignment questions:
Assignment question 1 "Carefully prepare answers for each of the Module 2 learning objectives.":

- Again, objectives are <u>not</u> questions.

Assignment question 3:

- This is an excellent question.

6.3.5 <u>Module 4: Control/Cool/Contain Philosophy</u>

[Pg 2 February 1997 R-1 version only], "A severe power excursion or sustained loss of heat sink ... would also challenge the integrity of the containment boundary.":

- This is a good example of the fact that, although containment is in itself sufficient for public safety, containment <u>requires</u> cooling and controlling sometimes.

6.3.6 <u>Module 5: Guaranteed Shutdown State</u>

No specific comments.

6.3.7 <u>Module 6: Reliability Concepts</u>

Pg 6&7: Definitions of Reliability and Availability:

- My understanding is that reliability of a device decreases over time much like radioactive decay (at least for the special case of constant λ). If the device is tested or repaired, the clock is reset to time zero and one talks of device availability; ie., availability is reliability with repair. It matters not whether the system is continuously running or is poised. It so happens that poised systems are usually tested on a periodic basis and continuously operating systems are not, but "being poised or not" is not the characteristic that distinguishes between reliability and availability.

Pg 16:

- I find it better to talk in terms of unreliability, rather than reliability. That way it is easy to see that the unreliability of 2 pumps in parallel is 0.05 x 0.05 = 0.0025, hence, reliability = 1 - 0.0025 = 0.9975.

Pg 19, "Use of general versus local coincidence logic.":

- If these terms are not general knowledge, they should be defined.

Pg 20, "...oftener...":

- Change to "... more often...".

6.3.8 <u>Module 7 to Module 16</u>

No specific comments.

6.3.9 <u>Module 17:Maintenance</u>

Pg 14, Risk-Benefit "... the SS should weigh the risks...":

- This implies a high levels of cognitive and affective functioning. This job task and associated behaviour sets the requirement for high standards in "understanding", contrary to what some training program developers would have me to believe.

6.3.10 <u>Module 18: Investigating and Reporting Incidents</u>

Pg 5, " A root cause of an accident is one which, if corrected, would prevent recurrence of the incident.":

- This definition seems a bit sloppy. Any number of factors could prevent recurrence of the incident, not just the root cause.

General comment:

- Why does the CRO / SS need to know about Root Cause Investigation and related matters? If it is to understand the nature of an investigation and so be a better participant in post mortems or if it is to appreciate the causes of accidents, then I would concur that this module serves a purpose. But if this is so, then I think the course should also contain a module on PRA concepts since that would help to instill the importance of adjusting test frequencies to compensate for loss of redundancy, etc. It would also enhance the communication between the site and the support analysts who require good site information on failure rates. It is the low consequence, high frequency events that contribute most to risk.

6.3.11 General comments on the course

This is not a skills based course; it is an attitude based one. Therefore it is about the affective domain. Surprisingly, there is little emphasis on how the trainee is to develop the correct attitude and little emphasis in the course on defining the required affective domain outcomes. It cannot be assumed that all one has to do is expose the trainee to safety principles and that a safety culture automatically follows. The manual does a good job at what it does (describe). But is it doing the right thing? It is similar to the role of QA: it focuses on ensuring that the right process is followed, not on ensuring that the right effect is obtained.

Although the 1997 revision was not reviewed in detail, it appears to be a substantial improvement overall. Yet, there remains in my mind a nagging deficiency. The material appears to have been written as a top down encapsulation of the topic of nuclear safety policy and procedures and related matters. The goal appears to have been to collect the breadth of associated ideas and to organize them into one document. The manual succeeds in doing that. As such, this is a valuable resource for defining the concepts and the relationships between these concepts. This forms the basis of what is to be learned. How one is to learn this material is another matter. I see scant evidence that this manual was written with pedagogy in mind.

The course content would make for a very dry delivery unless the topic were somehow brought to life. If not already done, I would suggest the extensive use of case studies, classroom exercises, personal anecdotes, mock situations, etc., to break up the monotony and enhance learning. The manual, for the most part, just describes the various elements of reactor safety and how those elements are connected to each other. The reader is left to image how it behaves as a dynamic system, that is, how it FUNCTIONS. The coverage of the material is not so much dead as it is STATIC.

The extensive cross referencing of objectives to the text is convenient...perhaps too convenient. What is the aim here? Is it to make for an efficient process for passing exams, to aid in learning material or to aid in affecting attitude? I suggest that the sidebars be used to point out the key concepts, rather than the objectives. If the objectives are rewritten to be keyed to the concepts then the point is moot.

6.4 Conclusions and Recommendations

This is a good manual overall from a consistency of theme point of view. The objectives need to be reworked as indicated so as to be a better study guide for the trainees, as a check list for trainers and developers, and as a resource for the setting of exam questions. The objectives need to be reformulated to address the affective domain as well as the cognitive domain. Given the level of accuracy, completeness and appropriateness of the training material, this should not be an onerous task.

I suggest that the concept of empowerment be added to the manual.

This manual should contain a module on PRA concepts.

I suggest the extensive use of case studies, classroom exercises, personal anecdotes, mock situations, etc., to break up the potential monotony, to bring the material to life and to enhance learning, especially in the affective domain. The manual should address how reactor safety functions as a dynamic system. It is not sufficient to just describe all its parts and how these parts are interconnected. In addition, other means of testing the commitment to safety principles should be explored outside the context of this manual.

7. Conclusions and Recommendations

7.1 The Central Issue

The central issue to be resolved is the level of understanding (or more properly, the degree of higher level cognitive functioning) required by the CRO / SS. It is difficult to see how course material can be developed to the satisfaction of the utilities and the regulator if there is no agreement on the overall goal.
This disagreement will not be resolved by the regulator or the utilities establishing a position based on the superficial labels of *education* vs *training*, which represent two extremes in a continuum. The question of *education* vs *training* casts the issues in terms too broad to be answered. The answer lies in the systematic and detailed assessment of the training material, such as attempted in this report. This report presents a framework based on a categorization and characterization of what we mean by *understanding* and the central role played by the *concept*. The central thesis presented is that the job of the CRO / SS requires a level of understanding of concepts that can be quantified in terms of cognitive and affective behaviours. It is my contention that cognitive functioning at levels higher than mere knowledge and comprehension is required. It is also essential that the required behaviour in the affective domain be demonstrated. The objectives of the training program in the fundamentals area, then, need to be specified in terms of these concepts and the required behaviours. Course content, teaching strategy and evaluation strategy follow as a result.

The assessment given in this report shows specifically where the material succeeds and where it fails as judged by specific criteria. The reader may not agree with the assessment or even the criteria used but, at the very least, there is now something concrete to discuss. Since the training material reviewed was not developed with this framework in mind, it comes as no surprise that the material falls far short of meeting the criteria set out in the framework.

Once the central issue mentioned above has been acknowledged and if the framework presented here is accepted as a means of addressing this issue, the next step is to construct concept maps for the subject matter. To aid in this task, it is recommended that consideration be given to devising a generic concept map for the fundamentals area and a generic set of objectives keyed to the concepts, not as a rigid template but as a rough checklist or stating point for the construction of specific concept maps and objective sets. The generic concept map of figure 7.1 is offered as an example for the two technical courses reviewed in this report. It was constructed based on the premise that any device, be it a pump or a complete plant, is a system composed of components. Fundamental phenomena (nuclear, chemical, fluidic, thermodynamic, electrical, civil, etc.) lie underneath, supported by mathematics, material properties, etc. It follows, then, that understanding is required on all levels: fundamental phenomena, component and system. For each level, issues of measurement, safety, operation, repair, diagnosis, etc., arise.

From these issues, a generic set of objectives keyed to the concepts (complete with the specification of standards and conditions) could be set along the lines of:

Phenomena level:

- SWBAT describe the key process variables
- SWBAT explain the interrelationship of ...
- SWBAT show that ...
- SWBAT compute ...
- Etc.

Device level:

- SWBAT identify the key components of ...
- SWBAT describe the operation of ...

SWBAT diagnose ... given ...
Etc.

System level:

SWBAT graphically depict the change in operating point when ...
SWBAT diagnose possible causes of system failure when ...
SWBAT identify the mitigating systems for the following failure modes...
Etc.

The objectives need to be reformulated:

- to be keyed to the concepts
- to be more generally stated (ie, not as questions in disguise)
- to be aimed at covering the higher cognitive levels and affective levels as appropriate
- to be more complete in their coverage of the concepts.

The objectives should be set with the full training program in mind, not just on an isolated course by isolated course basis. It is recommended that a trial set of objectives linked to concepts be struck by the program developers as a starting point for an iterative review and refinement involving the licensee and the regulator. At the very least, this will facilitate the establishment of an agreed upon framework and content.

7.2 Course Specifics

The above represents the main recommendations of this report but a number of specific recommendations applicable to all three courses are offered as follows:

- There should be a more extensive and balanced use made of graphs, diagrams, illustrations, mathematics and word descriptions to provide multiple explanations of the same concept.
- The module summaries should be de-emphasized in favour of a comprehensive index and concept maps. Concept maps should be constructed for each module of each manual (or as appropriate) and for each manual as a whole.
- The sidebars should be consistently used to point to the key concepts.
- The evaluation of the key effectiveness areas as done for the *Principles of Reactor Safety* manual should be done in the other training courses as well. This could well replace a full job task or function analysis.

The following table summarizes the three course manuals with respect to the review criteria stated at the outset. None of the manuals have proper statements of objectives. The content of the *Fluid Mechanics and Thermodynamics* manual is seriously flawed for the intended purpose. The *Nuclear Physics and Reactor Theory* manual, on the other hand, is well written and maintains a fairly consistent theme throughout. The Principles of Reactor Safety manual is a good compendium of the essentials of the subject. However, revision is recommended to make the material more suitable to learning.

Specific recommendations on each manual have been given in sections 4 to 6 and are not repeated here.

Table 7.1 Summary of review results

Review Criteria	**Fluid Mechanics and Thermodynamics**	**Nuclear Physics and Reactor Theory**	**Principles of Reactor Safety**
Objectives are pertinent?	No	No	No
Objectives are adequate?	No	No	No
Content technical accuracy	Good	Good	Good
Content is adequate?	No	Yes	Yes
Required prerequisites	- University level mathematics and physics - Plant familiarization	- College level mathematics and physics - Plant familiarization	- College level mathematics and physics - Plant familiarization
Manual provides adequate understanding of phenomena?	No	Yes	Revision to aid in the learning process is suggested

7.3 The Broader Context

In addition, there are a number of recommendations that relate to the broader context:

- All parties should consider that it is sufficient for the trainee to meet the objectives by any means, not all means. If this were to be acknowledged by all parties and if the supplemental material were made visible, then evaluation and regulation would be more meaningful.
- The utilities should reassess the role that the fundamentals play in operator training. A higher priority is warranted.
- The utilities should incorporate learning methodologies based on pedagogy more so that currently practised. This includes consideration of ensuring that the instructors are *teachers*, not *trainers*.
- In the main, the fundamentals should be kept apart from the specifics training.
- There should be formal training or evaluation of the trainee's people skills, problem solving skills, graphing skills and mathematical skills, etc.
- The required problem solving strategies appropriate for the CRO / SS should be delineated. Like mathematical skills, problem solving skills may best be introduced as an integral part of the existing subject matter courses. However, it is recommended that a series of modules devoted to problem solving approaches and techniques be developed so that, at the very least, the developers of training modules have a common point of reference and a resource to draw on.

....

As courses are revised in the fullness of time, the principles and framework established here should be used as a guide for the course restructuring and revision. The ideas should be tested on a select number of courses and the experience gained should be used to revise the framework itself. It is worth reiterating that these course materials form only a part of the complete training program and, hence, the effort and priority given to the revision of this material should be commensurate with that of the other aspects of the program.

Given the complexity of nuclear operations (and hence the large range and depth of abilities required of the SS / CRO), it would be best if we can produce a trainee who is a life long learner with a sense of learning that goes beyond the immediate job. For this to happen, he / she must understand the basic principles and relate them to the job at hand so that the job can be transformed from a routine button pushing operation to an engaging problem solving endeavour, complete with attendant self-esteem, job satisfaction and empowerment. It is neither safe nor effective to produce trainees who just know the routine.

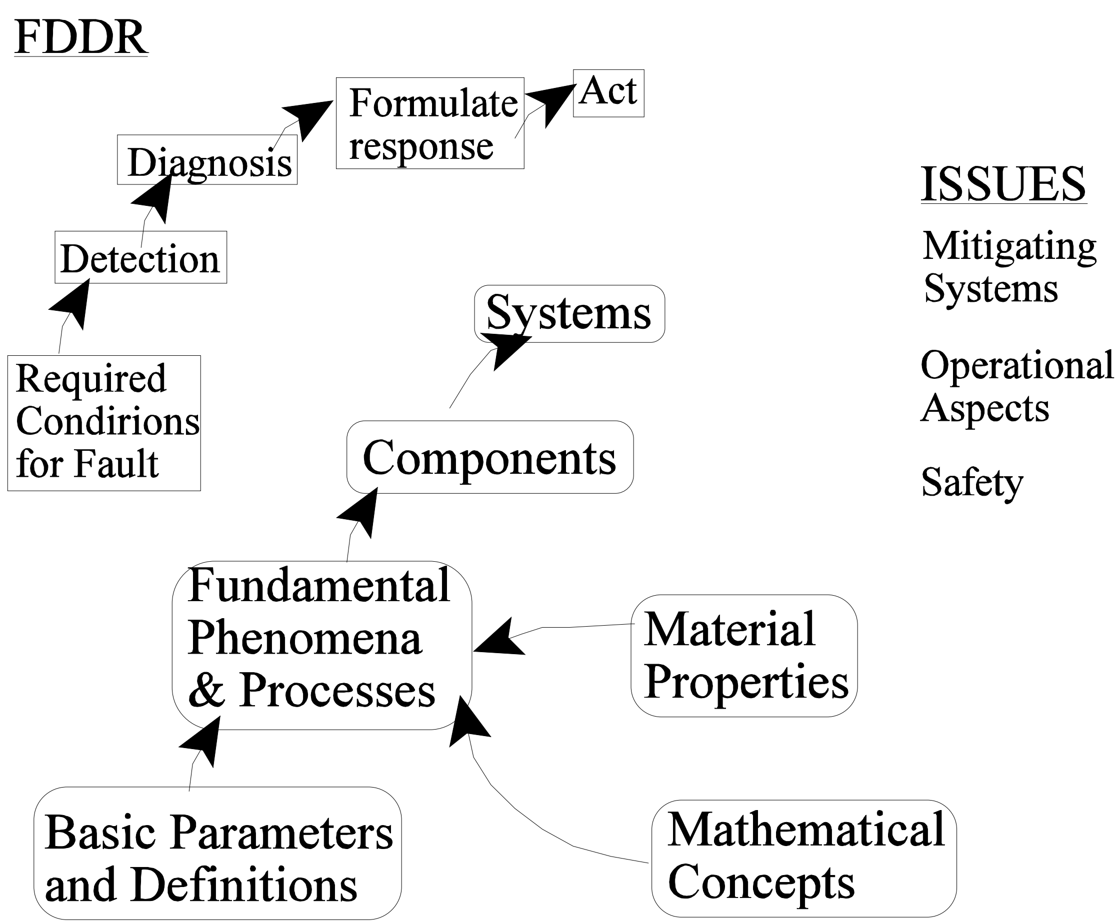

Figure 7.1 Generic concept map

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ACKNOWLEDGEMENTS

This review turned out to be considerably more onerous and captivating than I had imagined. It was made pleasant and stimulating by the conversations with the staff of the utilities and the regulator. I was touched by the level of commitment on an individual level. I emerged convinced that the collective wisdom could prevail in making substantial improvements in the training program.

Early drafts of this report were endured and reviewed by AECB staff. The final draft was presented to the utilities for comment. To the best of my ability, I have incorporated everyone's comments, which were too numerous and pervasive to acknowledge individually. It was only with the guidance of Dale Roy, Instructional Development Centre, McMaster University, that I could make sense of the pedagogical issues and so give form to what I felt. Socrates would have been proud.

APPENDIX 1 Work Statement

1. Background

Training in science fundamentals and equipment principles is an essential component of the training program for candidates to Shift Supervisor (SS) and Control Room Operator (CRO) positions at Nuclear Generating Stations (NGSs). Its purpose should be to give candidates to these positions the required knowledge of the principles that govern the design and operation of the equipment and systems that exist in a nuclear power plant. This training should also develop in trainees an appreciation of the safety principles associated with the operation of the reactor. For historical reasons, training in science fundamentals and equipment principles has become embedded over the years in so many station-specific details and examples that its original purpose is no longer evident. Two years ago, the Canadian utilities have formed a group to review the training requirements in the areas of science fundamentals and equipment principles and to revise the corresponding training manuals accordingly. Analysis of training requirements in those areas relied on the results of Job and Task Analyses (JTAs) done at some nuclear power plants in the US, on data found in guidelines of the Institute of Nuclear Power Operations (INPO) and in documents of the US Nuclear Regulatory Commission, and on information extracted from the existing utility training programs. These data were examined by a committee which produced a CANDU subject area list based on an existing INPO list. Subsequently, specific subject areas were assigned to different working committees charged with the review of the subjects retained, the elaboration of training objectives and the development of the supporting training material.

2. Objective

The Operator Certification Division (OCD) of the Atomic Energy Control Board (AECB) has already performed a preliminary review of the work done by the utilities. However, OCD wishes to obtain an independent evaluation of some training manuals, covering specific areas of the science fundamentals and equipment principles training program that have been developed by the utilities, by an expert with proven experience in teaching technical and scientific subjects at the college or university level. OCD will use the conclusions reached by the expert, the results of the phase 1 of this project and its own evaluations to decide on the acceptability of the material produced by the utilities.

3. Scope of Work

The expert will perform an independent evaluation of the following three training manuals:

- Fluid Mechanics and Thermodynamics
- Reactor Safety
- Nuclear Physics and Reactor Theory

This evaluation will address the pertinence and adequacy of the training objectives, the technical accuracy and adequacy of the courses and the prerequisite knowledge required by each of these courses. The evaluation should also determine whether, in the opinion of the expert, these courses provide the trainees with an adequate understanding of the phenomena that underlay the operation of a nuclear power plant.

Handout Master 12.5
Objectives in the Cognitive Domain

Operationalizing the Taxonomy of Objectives in the Cognitive Domain

Taxonomic Categories and Subcategories	Verbs to Use in Objectives	Examples of Appropriate Content in Objectives
1.00 Knowledge 1.1 Knowledge of specifics 1.2 Knowledge of ways and means of dealing with specifics 1.3 Knowledge of universals and abstractions	Define Distinguish Acquire Identify Recall Recognize	Vocabulary words Definitions Facts Examples Causes Relationships Principles Theories
2.00 Comprehension 2.1 Translation 2.2 Interpretation 2.3 Extrapolation	Translate Give in one's own words Illustrate Change Restate Explain Demonstrate Estimate Conclude	Meanings Samples Conclusions Consequences Implications Effects Different Views Definitions Theories Methods
3.00 Application	Apply Generalize Relate Choose Develop Organize Use Restructure	Principles Laws Conclusions Methods Theories Abstractions Generalizations Procedures
4.00 Analysis 4.1 Analysis of elements 4.2 Analysis of relationships 4.3 Analysis of organizational principles	Categorize Distinguish Identify Recognize Deduce Analyze Compare	Statements Hypotheses Assumptions Arguments Themes Patterns Biases
5.00 Synthesis 5.1 Production of a unique idea 5.2 Production of a plan 5.3 Derivation of a set of abstract relations	Document Write Tell Produce Originate Modify Plan Develop Formulate	Positions Products Designs Plans Objectives Solutions Concepts Hypotheses Discoveries
6.00 Evaluation 6.1 Judgments in terms of internal evidence 6.2 Judgments in terms of external criteria	Justify Judge Argue Assess Decide Appraise	Opinions Accuracies Consistencies Precisions Courses of action Standards

Adapted from N. S. Metfessel, W. Michael, and D. Kirsner, Instrumentation of Bloom's and Krathwohl's taxonomies for writing educational objectives. Psychology in the Schools, 1969, 6, 227–231.

AFFECTIVE DOMAIN OF LEARNING

Five levels of the affective domain:

1. Receiving - Willing to give attention to an event or activity. *Examples:* Listen to, be aware of, perceive, be alert to, be sensitive to, show tolerance of.
2. Responding - Willing, to react to an event through some form of participation. *Examples:* Reply, answer, follow along, approve, obey, find pleasure in.
3. Valuing - Willing, to accept or reject an event through the expression of a positive or negative attitude. *Examples:* Accept, attain, assume, support, participate, continue, grow in, be devoted to.
4. Organizing - When encountering - situations to which more than one value applies, willingly organize the values, determine relationships among values. and accept some values as dominant over others (by the importance to the individual learner). *Examples:* organize. select, judge, decide. identify with, develop a plan for, weigh alternatives.
5. Characterizing by a value complex - Learner consistently acts in accordance with accepted values and incorporates this behavior as a part of his or her personality. *Examples:* Believes, practices, continues to, carries out, becomes part of his or her code of behavior.

Source: Krathwohl, D.R. et. al. (1969). A Taxonomy of Educational Objectives. Handbook II. New York: Longman.

C. Taxonomy for the Psychomotor Domain

The categories in this taxonomy are presented in order, from basic (1.) to most complex (7.).

Categories	*Examples of Verbs to Use When Developing Learning or Performance Objectives*
1. Perception — using the senses to obtain cues to guide motor activities	— detect, differentiate, distinguish, identify, listen, observe, smell, isolate, taste, feel, touch
2. Set — being ready (mentally, physically, emotionally) to take a particular type of action	— proceed, react, respond, volunteer, show readiness
3. Guided Response — learning motor skills through imitation and trial and error	— repair, construct, dismantle, keyboard, assemble, dissect, throw, measure, sketch, display, type, print
4. Mechanism — performing motor skills consistently with some confidence and proficiency	— (same list as for "Guided Response" but at a higher level of proficiency, consistency and confidence)
5. Complex Overt Response — performing accurately, automatically, efficiently and without hesitation, motor skills which involve increasingly complex movement patterns	— (same list as for "Mechanism" but at an even higher level of proficiency, consistency and confidence)
6. Adaptation — modifying particular motor skills or movement patterns to meet a new or unexpected situation	— adapt, modify, change, alter, rearrange, revise, vary
7. Origination — creating a new skill or movement pattern to meet a new or unexpected situation	— originate, create, devise, compose, construct, design, arrange, combine

Source: Making the Grade. (1987). Scarborough: Prentice Hall. (pp. 32).

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