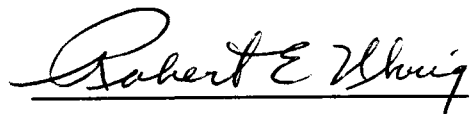
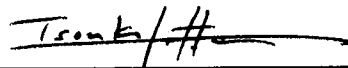


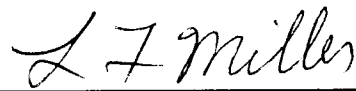
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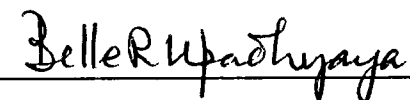
  
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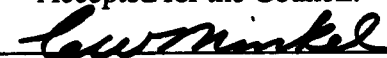
  
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**KNOWLEDGE-BASED RADIOLOGICAL PLANNING AND  
OPTIMIZATION USING FUZZY LOGIC**

A Dissertation  
Presented For The  
Doctor of Philosophy  
Degree  
The University of Tennessee, Knoxville

Javier Reyes-Jimenez

AUGUST 1992

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## DEDICATION

To my father, for he has been an exemplary and inspirational figure throughout my life  
from whom I learned to endure all hardship's that life gives us.



## ACKNOWLEDGMENTS

The author would like to express his appreciation to those who have been of assistance during this study. The author also wishes to thank the members of the committee, Professor Lefteri Tsoukalas, Professor Lawrence F. Miller, Professor Belle R. Upedhyaya , Professor Raj Pal Soni and to committee chairman Professor Robert E. Uhrig for his valuable comments, criticism, patience, and support in this research.

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## ABSTRACT

This dissertation presents a fuzzy logic based methodology for radiological planning and radiation protection optimization. *Fuzzy Cost-Benefit* analysis is used for pre-planned maintenance activities as a technique to determine optimum solutions in radiation protection. It is based on the cost-benefit methodology described in International Commission of Radiation Protection No. 37 and used within a knowledge based framework for the purpose of optimizing radiation protection. This methodology is examined through application to heating ventilation and air conditioning (HVAC) systems. HVAC is used to reduce radioactivity concentration levels in contaminated multi-compartment models at nuclear power plants when higher than normal radiation levels are detected. The overall objective is to reduce personnel exposure resulting from airborne radioactivity, when routine or maintenance access is required. The *Fuzzy Logic* methodology proposed deals with the uncertainties present in ALARA (as low as reasonably achievable). The concept of ALARA introduces vagueness and imprecision because it involves linguistic concepts (fuzzy) such as "as low as" or "reasonable". Fuzzy logic is used to quantify in a more precise and unambiguous manner the meaning of such terms.

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## LIST OF ACRONYMS

|        |                                                  |
|--------|--------------------------------------------------|
| ALARA  | As Low As Reasonably Achievable                  |
| ALAP   | As Low as is Practicable                         |
| ARM    | Area Radiation Monitor                           |
| BWR    | Boiling Water Reactor                            |
| CAM    | Continuous Air Monitor                           |
| CFR    | Code of Federal Regulations                      |
| DM     | Degree of Membership                             |
| HVAC   | Heating Ventilating and Air Conditioning         |
| ICAI   | Intelligent Computer Aided Instructions          |
| ICRP   | International Commission on Radiation Protection |
| LEX    | Lexicographic-sort                               |
| LHS    | Left Hand Side                                   |
| MEA    | Means-end-analysis                               |
| MFS    | Membership functions                             |
| NCRP   | National Commission on Radiation Protection      |
| NRC    | Nuclear Regulatory Commission                    |
| ORE    | Occupational Radiation Exposure                  |
| OPS    | Official Production System                       |
| PRM    | Process Radiation Monitor                        |
| PWR    | Pressurized Water Reactor                        |
| RHR    | Residual Heat Remval                             |
| RP     | Radiation Protection                             |
| RHS    | Right Hand Side                                  |
| RAD    | expert system-Radiological Assessment and Dose   |
| UPFSAR | Updated Final Safety Analysis Report             |
| WME    | Working Memory Element                           |

# CHAPTER 1

## INTRODUCTION

### 1.1 BACKGROUND

The primary purpose of this dissertation is to show that human reasoning can be represented numerically within the context of imprecise terminology used in the As Low As Reasonably Achievable (ALARA) philosophy. This research uses the International Commission of Radiation Protection (ICRP) guidelines and recommendations to determine optimum solutions in radiation protection [1] [2]. A fuzzy logic methodology is also used for the purpose of quantifying the imprecision found in the ALARA terminology [3]. This work relies on an understanding of why we would like to represent human reasoning as mathematical formulas. This work attempts to extend human reasoning within the context of control of systems with precise mathematical formulas for the purpose of quantifying imprecise natural language terminology.

Human reasoning has been of great interest in the engineering sciences because through it we interpret, modify, deduce, or control the data and systems we create. We define our surrounding environment and describe it in concise linguistic terminology. In addition, we define linguistic terminology and determine how this concept fits within a specified context. According to some basic definitions, human reasoning can be viewed as "a sufficient ground of explanation of justification," or "the power of comprehending, inferring, or thinking especially in orderly, rational way." Another definition is: "to discover, formulate, or conclude by use of reason." [4]. Still another definition is: "the drawing of inferences or conclusions through the use of reason." [4] An important aspect

of human reasoning is knowledge acquired in different situations that may remain in our memory in proportion to its importance. Some knowledge becomes common sense knowledge. This knowledge is hard to define because of its broadness in specific areas, but description of specified control can be described by "rules of thumb." For example, a rule of thumb or heuristic rule that describes the behavior of temperature, pressure, and heat exchange of a steam engine would be: "when the temperature is very high and the pressure is slightly low then the heat change should be slightly negative." [5].

Fuzzy logic can be used as an approximation to human reasoning by representing imprecise linguistic terminology mathematically [6] [7]. In science and engineering, experts make use of such rules that use imprecise linguistic means to describe instructions based on experience. Expert systems are computer programs that simulate the reasoning of a knowledgeable engineer. However, imprecision and uncertainty arise when expert judgment is described in linguistic terminology. Fuzzy logic offers a means of representing imprecision in a consistent formulation. Fuzzy controllers have been applied in many areas such as traffic control, heat-exchange processes, industrial processes, steam engines, robot movement, and aircraft control [5]. An analysis of data from controlled environments requires understanding the behavior of variables that describe a system. In order to deduce instructions or conclusions about specific systems, we reason, assess and judge information. Therefore, one may say that human reasoning is critical to the definition of uncertain terms because the definition of imprecise linguistic terminology depends on expert perception.

Much of the interpretation and description of information performed by experts contains imprecise or subjective qualifiers due to the imprecise meaning of words. For instance, words such as: usually, always, commonly, rarely, probably, and frequently are

imprecise. Also imprecise words are associated with the way experts evaluate or perceive events, such as "acceptable", "good", "reasonably", "economical," and "safe" [3].

The ICRP Publication 9 in 1965 stated "As any radiation exposure may involve some degree of risk, the commission recommends that any unnecessary exposure be avoided, and that all doses (from justifiable exposures) be kept as low as readily achievable, economic and social considerations being taken into account." The acronym ALARA (as low as reasonably achievable) means that on the one hand we want to reduce collective doses and on the other we want to be cost effective while implementing radiation protection. This research explores a new approach in the definition and qualification of the ALARA philosophy within a specific environment.

Before undertaking this research, it was necessary to distinguish between "low" and "reasonable" so that a new methodology could be established to quantify their meaning ( i.e., low and reasonable dose, reasonable meaning cost). If one were to examine the interpretation of the "as low as reasonably achievable" principle, one would discover that the terms are vague and imprecise, and thus an interpretation cannot be exact. For this reason, the nuclear industry may not be giving the principle the serious consideration it deserves. However, the ALARA philosophy was established as a result of the uncertainty encountered in establishing a clear connection between cancer diseases and "low low doses" of radiation.

A possible explanation as to why the ALARA principle has not changed is that one must deal with uncertainty about the harmful effects of low dose radiation. ALARA was based on the principle of both low dose and reduced cost. Very low doses can be achieved only at high costs. Everything we do to reduce doses costs money. However, dose

reduction should be pursued whenever possible and as much as possible, even when design criteria are met.

*Reasonableness* is a relative concept because the monetary cost depends upon social, political, industrial, and other factors. What is reasonable today may not be so in ten years. In order to exemplify the concept, let's take the original expected costs of the construction of nuclear plants. In the early 1970s the estimated cost of a nuclear plant was about 600 million dollars (a reasonable cost). Due to delays, design changes and backfits, the final cost of some plants reached about 2.5 billion dollars (an unreasonable cost). The "reasonableness" of cost in this example can be distinguished, for it seems that what one plans for and what one expects is reasonable, but unplanned cost is often denoted as unreasonable otherwise.

What is reasonable from one expert's point of view may not be reasonable from another's. It is because of this that human judgment varies from person to person. This is why there is a need for references. The concept of reasonable then depends on what reference an expert uses. This indicates that when we label or define the term *low dose*, we intuitively do so by using a set reference point. To define low dose we can use the reference value of 2.5 mrem/hr which corresponds to the occupational dose limit of 5.0 rem/yr [8]. During an evaluation of a radiation field, we would simply say that the dose rate is "low" if it falls below the reference limit. We would not make a distinction between say 1.0 mrem/hr and 1.5 mrem/hr. Since we use references, we leave an open area which becomes vague and imprecise and which can only be interpreted linguistically as "low." Furthermore, the doses that fall far below a limit are labeled "low low doses" in order to indicate that these doses are much lower than just low. This leads us to believe that there is a need to distinguish between various levels of low doses. If natural language makes a

distinction between two "low"s, it means there is a difference in levels of low. Our first approach to uncertainty is linguistic. Can we truly justify the use of "low low doses" ?

Another issue related to the way in which we see the dose levels we encounter, is the measurement in relation to its harmful effects. Even though we have a well-established measurement methodology for the detection of low doses, we still need to understand all possible harmful effects.

## **1.2 PURPOSE OF THE RESEARCH**

The purpose of this analysis is to assess radiation levels according to the ALARA principle. A new methodology is introduced to evaluate low doses in relation to cost constraints. In order to demonstrate this methodology a radiological assessment is performed while maintenance personnel access a compartment at a nuclear power plant during and after pipe rupture occurrences. In order to evaluate costs the methodology described in the ICRP publication 37 (cost benefit analysis) is used as a reference throughout a pipe rupture accident [1] [2]. This method is used as a reference in defining the meaning of the term reasonable. It is important to distinguish between the reasonableness and unreasonableness of costs in order to apply the ALARA philosophy. The air flow through a compartment model is used as a variable for the purpose of reducing airborne concentrations. An expert system called RAD (Radiation Assessment and Dose) was designed for the purpose of carrying this analysis.

Cost-benefit analysis is an optimization technique useful for determining the best solutions for radiation protection. Optimization principles applied in reactor operation, training, and plant maintenance can help evaluate radiological environments as well as

improving the interpretation of uncertain linguistic terminology. Cost-benefit analysis has successfully been applied in other disciplines such as pipe inspection, decontamination, reduction in the release of specific isotopes, and temporary shielding during maintenance. Optimization analysis is used in this research as a radiation protection guideline which assists the decision process in determining needed levels of radiation protection.

The International Commission on Radiation Protection Publication 26 (ICRP-26) recommends that exposure limits be kept below the prescribed limits and as low as reasonably achievable as long as economic and social factors are taken into account [1]. Furthermore cost benefit methodology can also be used to optimize equipment operations, shielding design and man-power requirements when performing maintenance. In general, cost benefit analysis can be used as a guide in the reduction of annual collective doses through the reduction of individual annual doses. Yet the use of more maintenance personnel to reduce individual doses is not always the best way to achieve this.

### **1.3 RADIOLOGICAL PROTECTION BACKGROUND**

Most of the annual collective occupational doses at nuclear power plants are received during refueling and outage maintenance. As a consequence there is an increased interest in the application of optimization principles in reactor operation, training, and plant maintenance. The ALARA philosophy is to apply all possible measures for radiological protection in design as well as practices in planning, training, material selection, equipment layout, shielding, equipment reliability, and all radiation protection related aspects of the nuclear industry.



The creation of the International Commission on Radiation Protection in 1928, had as an objective to establish standard radiation units [2] [9]. During the 1940's and 1950's, the biological effects were evident. The knowledge of the biological damage of radiation has evolved, since the early days, to what we presently know. This resulted in ICRP recommendations on limits of exposure. Before the forties, the effects of exposure to radiation were not well known. It was believed that a dose below some threshold (non-stochastic effects) did not cause any harmful effects. Doses below that threshold were regarded as "tolerable," and as a result of this concept the limit of exposure was stated as a "tolerable dose." Therefore the doses that were "tolerable doses" were not supposed to have any harmful effects. Even though progress was made after the forties and fifties, no such threshold could be demonstrated. This was because there were no noticeable signs of the biological effects of radiation. Malignant tumors were seen infrequently, only when considerable exposures occurred in large groups of people (data from Hiroshima and Nagasaki) [9]. In these cases observations of radiation effects were referred to as "stochastic effects" of radiation.

This statistical approach is connected to the concept of "acceptable risk." In this way maximum permissible doses were established which associate non-stochastic effects of radiation to risk levels that are negligible. The doses below the maximum permissible limit would correspond to the doses below the threshold for radiologically harmful effects. On the other hand the risks associated with stochastic effects of radiation would be small if compared with other occupational health hazards [9] [10]. In this manner a distinction can be drawn between dose limits to members of the public and occupational limits.

In 1955 the ICRP recommendations stated: "while the values proposed for maximum permissible doses are such as to involve a risk is small compared to the other

hazards of life; nevertheless, in view of the incomplete evidence on which radiation effects are irreversible and cumulative, it is strongly recommended that every effort be made to reduce exposure to all types of ionizing radiation to the lowest possible level." [9]. As a consequence of this, a "principle of tendency" was presented and consisted of reducing doses as far as possible below the limit recommended by the ICRP. Later in 1958, the ICRP in publication 1 stated that "It is emphasized that the maximum permissible doses recommended in this section are maximum values: the commission recommends that all doses be kept as low as practicable, and that any unnecessary exposure be avoided" [9].

Radiation exposures to personnel in the nuclear industry are influenced by many factors. These factors include the reliability of equipment, the station layout, and most importantly radiation protection programs. In addition, radiation protection guides must ensure that the radiation exposure received by equipment will not exceed levels that will hurt its performance. The effective design of facilities and the selection of equipment for systems that contain and store coolant sources that process radioactive waste also help reduce occupational radiation exposure (ORE).

Personnel access to contaminated areas for maintenance and inspection requires analysis and careful study of the contaminated environment to determine access limits. These analyses also require reliable monitoring data or radiation surveys to determine the levels of airborne contamination. A design objective of heating ventilation and air conditioning (HVAC) is to control air flows to restrict doses to onsite personnel such that doses do not exceed applicable limits of the 10CFR20. The philosophy of maintaining ORE low should be included in the conduct of all operation and maintenance procedures as well as design.

## 1.4 IMPORTANCE OF THIS RESEARCH

This section outlines the importance of various related aspects of the radiation protection programs in the industry in relation to the need for a more exact ALARA interpretation and implementation. The health physicist at a nuclear power plant is responsible for maintaining the radiation protection programs that ensure radiation exposure of the workers is kept at a safe level. One of the most important aspects of a radiation control program is monitoring controlled areas and personnel exposure.

Recent improvements in the nuclear industry have affected the design and operation of nuclear power plants. The measures introduced have made power plants safer. Due to ongoing maintenance requirements, however, there are activities where personnel may be exposed to radiation levels higher than planned. Also, there is an increasing desire among regulatory authorities for the reduction of public exposures due to release of contaminants. Since it is desirable to reduce public exposure and occupational radiation exposure, utilities operating nuclear power plants are looking at alternative ways to reduce occupational doses.

Thus, the nuclear industry in general has become more aware of the need to reduce ORE while maintaining all the operational safety requirements and minimizing cost. Optimization principles present an option that can be used during reactor operations and plant maintenance in order to reduce collective doses. There has also been strong emphasis on operations because safer operations not only reduce the probability of accidents but also result in reduced exposure for plant personnel and the public. ALARA programs in the nuclear industry require low levels of exposure for personnel performing maintenance activities because many places in the plant become contaminated after years of operation.

Nuclear safety covers a wide variety of aspects of the normal operation of a commercial nuclear plant. On the other hand, ALARA includes radiation measures for the protection of the personnel performing equipment maintenance and inspection. One objective of the utilities that operate nuclear power plants is to produce electricity at low cost with the highest possible availability, taking into account design requirements, operating specifications, and all health and safety requirements for normal operation

## **1.5 STATEMENT OF THE PROBLEM**

A multi-compartment model is used in this dissertation to analyze transient concentrations of the radioactive isotopes in order to assess the radiological levels after a postulated pipe rupture. Radiological assessments are sometimes required at nuclear plants because of piping leakage. The leaks create permanent sources of radioactivity because of subsequent contamination on the floor and equipment. A pipe leakage creates changing radioactive concentrations and time varying dose fields.

The air flow rate passing through a room is used as a control variable to reduce the airborne concentration of radioactivity caused by the pipe rupture leak. The dose rate inside a contaminated cubicle is a function of several factors that change down-stream from one room to another. The radiological analysis is performed from three points of view. The first is one of control by use of a fuzzy algorithm; the second is one of assessment or evaluation of the level of contamination resulting from the unexpected pipe rupture; and the third is analysis performed using the ICRP methodology introduced in Publication No.37 (cost benefit analysis) [2]. These three separate approaches are combined by a fuzzification technique described in section 4.3.

Selected reduction of collective doses can be achieved by increasing the air flow. This results in cost increases, for the total cost of radiation protection is a function of the desired radiation levels. When the flow rate is increased, the dose rates and integrated doses are reduced. The flow is then used as a variable to adjust the isotopic concentration when a pipe rupture occurs. The changing man-power utilization and varying environments during maintenance and inspection make an expert system a useful tool that can be applied when a radiological decision making process is required. The expert system utilizes a new fuzzy radiation algorithm.

In this dissertation, a radiological assessment is performed using a fuzzy logic algorithm. Fuzzy logic is used to define or quantify low doses and reasonable costs as stated in the ALARA philosophy. This process is carried out by balancing all costs, including detriment cost and the cost to lower doses required to implement ALARA. Cost benefit analysis balances all costs for the purpose of finding the optimal air flow rate to achieve high levels of protection while making a good distribution of resources.

The ALARA principle has two objectives: one is to reduce collective doses and the other is to save money. This two-goal objective seems conflicting, for it attempts to reduce collective doses and saving money at the same time. This implies that the allocation of resources must be carried out to balance desired levels of protection to a point in which further improvement in radiation protection would not be economical [10]. An important goal in radiation protection is to keep doses low. During contamination accidents at nuclear plants, it is necessary to perform radiological assessments of the environment in order to ensure that radiation levels are not harmful when access is required.

Furthermore the ALARA principle states that doses should be kept low but reasonable. It is important to point out that the reduction of collective doses depends greatly on planning because of the different radiation protection measures available. Consequently radiation protection is a multi-decision process performed *a priori*. Therefore, two types of problems are encountered in a radiation protection assessment. One is due to the variety of options available for radiation protection, and the other is due to the fuzziness in the ALARA terminology used in performing radiological evaluations.

This research explores a knowledge-based approach using fuzzy logic in order to reduce ORE at nuclear power plants. For a variety of reasons nuclear power plant personnel may be exposed to radiation levels less than the prescribed limit and yet higher than planned under normal conditions. RAD was designed to evaluate transient radiological data (dose rate, collective dose and radioactivity leakage). The expert system RAD contains forty six production rules which are intended to use expert knowledge to perform a radiological assessment. The rules represent heuristic knowledge about a contaminated environment. The knowledge base consists of rules which represent expert knowledge obtained from expert experience and knowledge of the operation of the system.

## **CHAPTER 2**

### **REVIEW OF LITERATURE**

#### **2.1 STUDIES RELATED TO THIS WORK**

In view of the importance of the early developments of expert systems, it is appropriate to review some of the fundamental ideas and methodologies of expert systems found in the literature. The expert systems presented in this section review the areas of development in which expert systems have been used. The use of expert systems such as RAD requires knowledge about specific problems where heuristics can be applied. The application of expert systems in specific fields depends on the knowledge base that has been incorporated into the system. The early uses of expert systems were in medical diagnosis, because there was a great deal of data and known symptoms of diseases [11]. This data could easily be incorporated into knowledge bases and through a pattern matching technique, prescribe specific treatments.

Expert systems contain accumulated knowledge in data bases. This knowledge represents a collection of information derived from experts' experience. Much of the information contained in the knowledge base comes from heuristics. Uncertainty and imprecision become part of the expert system because of the way in which heuristic knowledge is described. The imprecision and uncertainty comes from not being able to establish the exact meaning of linguistic operators used to describe heuristic information. As a result, expert systems have incorporated various methodologies for handling imprecision.

It is worth mentioning the three expert systems that repeatedly turn up in the literature, and are considered of major importance in the early development of expert systems: Dendral, Macsyma, and Mycin. Dendral combines instructions with rules within its knowledge base [12] [13] [14]. It is used in biology research to deduce the structures of organic molecules from mass spectrogram data [12]. Macsyma is designed to find solutions to calculus and algebra problems [13]. Mycin is an expert system used for medical diagnostics. It covers a wide variety of medical problems caused by bacterial infection and suggests treatment with antibiotics [14]. Mycin uses certainty factors to resolve the uncertainty and imprecision found in medical diagnostics [15]. The certainty factors are used to assign importance or weights to certain rules [16]. Mycin came about from research performed in the Stanford Heuristic Programming Project in which the objective was to establish a knowledge-based paradigm.

There are several expert systems presented in the literature that have mainly been used for medical diagnostics. Aside from Mycin, there is Puff which is employed to perform diagnosis in pulmonary dysfunction [17]. It was designed by using the Emycin shell, i.e. Mycin with the knowledge base removed. Another expert system is Guidon which makes use of Intelligent Computer Aided Instruction (ICAI) for the purpose of teaching medical students [18].

The architecture of early expert systems varied according to the purpose for which they were designed. For instance the structure of the expert system Hearsay allows for input from several sources through several processors [19]. The first expert system used for commercial applications was R1 [20] developed by John McDermot at Carnegie-Mellon [6]. The computer language OPS5 was derived from the second version of R1 called Xcon



[20]. This computer language sometimes referred to as an expert system building language, was used for the development of the expert system presented in this dissertation. Prospector is an expert system developed to aid in finding promising mining exploration areas [21]. An expert system designed to diagnose glaucoma is Casnet. This program uses models which contain semantic networks for speech understanding [22]. Two expert systems that introduced the concept of distributed expert systems are Hearsay I [23] and the improved version Hearsay II [24]. Distributed expert systems consist of various small expert systems connected to form a large one.

An expert system which uses fuzzy sets to represent imprecise data is Sperill-II. It performs damage assessment of existing structures [25]. FINDex was designed to forecast sales in the retail industry [26]. Flops is an expert system based on fuzzy production rules [27]. It has been used to distinguish localized areas in echocardiogram medical images. Another example is the expert system Casnet which handles imprecision by introducing "confidence values" in connection with "certainty factors." Confidence values between -1 and 1 are associated with rules and represent observations of states. The rules are applied if certainty factors and confidence values are above a predetermined threshold.

Expert systems are called fuzzy expert systems when fuzzy sets or fuzzy logic is used in their knowledge representation or reasoning strategy. Fuzzy set theory allows the representation of the imprecise linguistic variables used to describe control. The use of fuzzy sets in knowledge representation has been tested in various real applications [28]. An example of a fuzzy controller is the one used to control trains in Japan [29]. Another is the control of a cement kiln that also uses fuzzy control [29]. The theoretical foundation of fuzzy set theory is widely referenced in the literature [30] [31] [7].

Another advance in fuzzy expert systems is commercial application, for instance the code Reveal. This code is designed to handle judgmental information. It is intended to serve as a decision support and modeling system. The user provides descriptions of problems in natural languages in order to derive management policies. The modeling results from quantitative data interpretation [32].

There are many collections of papers in the literature that contain vast amounts of material on fuzzy expert systems [33]. The literature provides a good foundation for the introduction of fuzzy reasoning methods, mathematical formulations and applications of fuzzy expert systems. A reference which reviews several expert systems is a book by Donald Waterman, A Guide to Expert Systems [34]. This book reviews in depth some of the most important fuzzy expert systems, areas of application and the construction of expert systems. Another book written by Weiss and Kulikowski, A Practical Guide to Designing Expert Systems, introduces the basic concepts and tools needed to develop expert systems [35]. Along the same lines a book by Hayes-Roth, Waterman and Lenat, Building Expert Systems, gives a summary of the development of expert systems [36]. The book by Lenat and Davis explains two important expert systems: TEIRESIAS and AM [37] [38] [39]. The expert system Teiresias consist of multiple subprograms whose function is to assist the user in classification and describing problems in complex codes. The expert system AM, Automathed Mathematics, is used to model and conclude from insufficient data in number theory [37].

References [37] [38] [39] [40] [41] [42] provide a good description of some of the most important expert systems. The book by Kacprzyk, Multistage Decision-Making under Fuzziness, reviews basic concepts of decision making in fuzzy environments. It surveys the theory of fuzzy sets and fuzzy systems and also includes applications. In this

book fuzzy sets are introduced to connect "feelings with perception of decision makers with data in numeric decision model" [42].

L.A. Zadeh's work has had the most impact and has contributed considerably to fuzzy logic, fuzzy applications in the management of uncertainty and the fuzzy logic of semantics. His work appears in many papers [43] [44] [45] [46] [47] [48] [49] [50] [51] [52] [53] [54] [55] [56] [57]. Zadeh's contribution in possibilistic relational universal fuzzy systems presents a meaningful representational approach toward imprecise natural language terminology. However, the use of fuzzy numbers to represent linguistic qualifiers in premises and conclusions is attributed to Banisbonne [43]. Zadeh's idea of the proposition "John is tall," can be represented by a possibility distribution of the variable height [58].

The possibility distribution represents meaning in natural language. The truthfulness of this proposition is reflected in the values of possibility associated with it. The degree of truth is measured in a unit interval or fuzzy set, such as "very true," "not true" and "more or less true" [55] [53]. According to Zadeh, what we call common sense knowledge can be interpreted as an accumulation of "dispositions" or "propositions." A proposition of the type "tall men are not very agile" uses fuzzy linguistic variables and qualifiers that are vague. Fuzzy logic can be used to define such terms in fuzzy sets [59]. In the development of expert systems imprecision and uncertainty are found due to the linguistic descriptions used in heuristic knowledge. Therefore, the development of expert systems should include a method to handle such imprecision.

## 2.2 REGULATORY REQUIREMENTS

The regulatory authorities' purpose is to regulate all aspects of the nuclear industry. There are regulations and standards that oversee and control the design, construction, operation, and maintenance of nuclear power plants. These standards dictate the various permissible levels of radiation exposure of personnel allowed at commercial nuclear plants. The government agencies discussed below have issued and enforced all the regulatory requirements in the nuclear industry. The agency responsible for commercial reactors in the U.S. is the Nuclear Regulatory Commission (NRC).

The Nuclear Regulatory Commission requires utilities which operate commercial nuclear power plants to include radiological programs that guide and coordinate maintenance activities in these plants. The NRC's concern is to reduce public and occupational exposures to radiation. The NRC has established through the 10CFR part 20 (Code of Federal Regulations) guidelines relating to all aspects of the design and construction of nuclear plants [8]. NUREG-0578 is an additional document whose purpose is to provide guidelines for setting up programs to detect and to reduce leakage from systems outside the containment areas that have high concentrations of radioactivity.

In 1954, the National Commission on Radiation Protection (NCRP) recommended that radiation doses be kept as low as practicable. Later in 1965 the International Commission of Radiation Protection (ICRP) mandated that radiation doses be " kept as low as is readily achievable, economic and social considerations being taken into account." In 1971, the NCRP restated its original position by saying: "... it is... the intention to encourage protection practices that are better than any prescribed minimal level..." [1] [2]. At the same time the ALAP (As Low As is Practicable) term was also incorporated into the

10CFR20.1 (c). In 1973 the Atomic Energy Commission introduced Regulatory Guide 8.8 entitled "Information Relevant to Maintaining Occupational Radiation Exposure as Low as is Practicable." The current use of ALARA (As Low As Reasonably Achievable) appeared later in 1975 in Regulatory Guide 8.8 Revision 2. In 1986 the Nuclear Regulatory Commission (NRC) under a revised section of the 10CRF20.102 (a) (1) established that "... a radiation practice program including provision for keeping dose ALARA." [8].

Other related guidelines, in addition to Part 20 of the Code of Federal Regulations, include the following Parts containing radiological limits. Appendix A, Criterion 19 of 10CFR50 outlines the limits of doses from airborne contaminants in the control room during and after an accident. Part 100 limits offsite exposures due to airborne release during accident conditions. Part 20, Appendix B, Table I outlines the limits of airborne concentration so that the average concentration to which personnel are exposed will not exceed these limits [8]. There are two criteria commonly used as a basis for evaluating occupancy limitations at nuclear power plants during maintenance. One is the limit of 5.0 rem/year per employee, which corresponds to 2.5 mRem/hr ( 2000 hrs per year). The other limit is a quarterly limit of 1250 mRem per employee. The above limits are used to set concentration limits at nuclear power plants .

Since the whole body dose represents the sum of all doses (internal, external doses), there are other restrictions that apply to different parts of the body which may allow higher doses than 2.5 mrem/hr. In general the following documents and references are also common in the industry and contain information and instructions relevant to radiation protection: UPFSAR (Updated Final Safety Analysis Report), NRC regulations, Technical Specifications, State Regulations, Operating Procedures in specific systems, Operator

Procedures and Monitor Systems Manuals, and programs such as Health Physics programs and Leakage Reduction programs.

The main function of radiation protection design at nuclear power stations is to ensure that the radiation protection goals, which are established in Federal Codes and Regulations, will be met as well as to protect personnel operating nuclear power plants and the public. Regulatory Guide 8.8, for instance, requires utilities to develop an ALARA program to reduce occupational radiation exposure throughout all phases of the stations life: planning, designing, construction and operation.

## **2.3 CURRENT STATUS OF RADIATION PROTECTION MEASURES**

It is appropriate to review some of the radiation control measures used at nuclear plants because these provide information relevant to radiation protection. One of the most important aspects of a radiation control program is the monitoring of controlled areas and personnel exposure. Currently the instrumentation to measure radiation levels at nuclear power plants includes ARMs (Area Radiation Monitors), PRMs (Process Radiation Monitors) and CAMs (Continuous Air Monitors) located at selected locations in the plant [60]. Their readings are recorded and interpreted by trained personnel using set-point criteria. When the readings are higher than a prescribed limit the alarm is activated. Instrumentation calibration is part of the program for obtaining reliable dose readings. Another practice in planning that helps in dose reduction is dose estimate calculations before maintenance. This analysis establishes traffic patterns and layouts for proper access in order to reduce the time spent in radiation areas. Traffic patterns are important in minimizing the potential for spreading contamination.

In addition to the measures presented so far, the control of the spread of surface contamination is also important in the reduction of doses. Review of the design features that limit its spread is useful before entering radioactive areas. Some of these features may include mechanical penetration analysis, adequate air flow pattern control of airborne contamination, and analysis and interpretation of the dose rate resulting from maintenance.

It has been observed that as some nuclear plants age, some equipment becomes highly radioactive due to activation product accumulation. This results in high radiation doses for maintenance personnel [58]. Control of internal equipment contamination is important because it can be a contributor to occupational radiation exposure.

Heating ventilation and air conditioning design is also an integral part of radiation exposure control at nuclear plants, because flow patterns and confinement of contaminated air are used to control airborne radioactivity caused by leaks in contaminated equipment. The flow and amount of air in contaminated cubicles determines the concentration of radioactive sources present in areas of the plant. One design objective of the HVAC is to control airflow in order to restrict doses to on-site personnel such that doses do not exceed applicable offsite limits of the 10CFR20. However, low doses to on-site personnel can also be accomplished by improving plant design (plant layout), through the use of remote handling devices, better water chemistry, cleanup of equipment that requires regular maintenance, planning before maintenance activities, and training.

There are large potential risks of radioactive overexposure at nuclear power plants, for they contain a wide variety of radioactive contaminated equipment. All areas in the plant are classified according to relative radiation level, as well as access requirements such as controlled areas vs. general access areas [61]. The boundaries between these areas

incorporate monitoring equipment to serve as check-points to measure the levels of radioactivity.

Many systems in nuclear plants are interconnected and their operation depends on the functioning of several systems. Most radiation areas are maintained at negative air pressures to ensure that radioactive leaks stay in contaminated cubicles. Confinement is another practice to control radiological exposure and to keep clean air flow isolated from contaminated areas. The air-flow must be controlled to reduce radioactivity concentrations. The amount of air flow can effectively be used as a tool to reduce and control airborne levels and dose rates during maintenance.

All the areas in the plant are classified according to the relative radioactive level, as well as access requirements such as controlled area or general access area [62]. In Boiling Water Reactors (BWR) the major portion of doses comes from the maintenance of recirculating pumps and other BWR components of the primary circuit and the inspection and repair of associated components such as piping and maintenance of primary pumps. A large fraction of the total dose resulting from maintenance or inspection is not only due to the operation itself but in preparing for the operation (scaffolding, removal or construction of temporarily shielding) [58].

One objective of the safety measures incorporated into nuclear plants, is to prevent or mitigate unexpected releases from an accident and to protect plant personnel and the public. To reduce external releases, utilities must increase the storage and treatment systems thereby increasing occupational radiation exposure [8]. It has been observed that the reduction of flow rates due to the installation of filters in the HVAC to reduce releases results in an increase in the concentration of airborne radioactivity inside the plant. Job



rotation is another radiation protection measure used to reduce exposure of individuals, although this measure does not necessarily reduce the collective dose. On the contrary, it often increases the collective dose because the same task performed by several people slows the operation. The tasks may be also performed by less qualified personnel. By design, nuclear power plants have a variety of internal safety precautions which make them safe for the public, the surrounding environment and the nuclear plants' personnel.

## **2.4 IMPORTANT PRACTICES IN RADIATION PROTECTION**

This section outlines some of the procedures and common practices that help in the reduction of dose exposures. In general the selection of equipment is important because the safe handling of radiation in maintenance operations reduces collective and individual doses [2]. The design of nuclear power plants includes several features for the purpose of radiological protection. For instance, the design includes collection tanks and drain systems for the control of leaks due to pump seal failure, flanges, and valves. Personnel access to contaminated areas for maintenance and inspection requires analysis and careful study of the contaminated environment to determine access limits. These analyses also require reliable monitoring data or radiation surveys to determine the levels of airborne contamination. The health physicist at a nuclear power plant is responsible for maintaining the radiation protection programs that limit radiation exposure of workers to safe levels. Consideration of appropriate tools, protective clothing, personal protective equipment, selection of working methods, maintenance procedures, and the adoption of techniques are a major concern to keep doses ALARA.

Planning usually results in dose reduction. Optimization of maintenance procedures has a benefit, for planning prior to maintenance activities improves task efficiency as a

result of the increased attention paid to the details of the task. Training is part of routine maintenance. Training runs carried out prior to maintenance help select alternate techniques that will expedite the maintenance. There are programs that provide technical assistance and guidance to plant personnel in accordance with regulatory policies. Some of the responsibilities of such programs include: performing environmental radiological monitoring, effluent dose assessment, plant surveillance, measuring contamination levels (routine & emergency situations), and determining adequate protective clothing for personnel [9] [10].

Another important practice in radiation protection is to identify activities that contribute to the occupational dose. Dose reduction programs should identify repetitive high-dose tasks and circumstances related to the task to establish the techniques about the task that can help reduce the collective doses. The unexpected activities which contribute the most in collective doses for both BWR and PWR are in-service inspection and special maintenance. The purpose of in-service inspection is to examine the systems and components of the plant for possible deterioration. These inspections are performed visually inside the containment. This results in a significant radiation exposure for personnel performing this inspection. Planned activities for normal operation and routine maintenance that contribute the most are : waste treatment, refueling (which includes vessel opening & closing and fuel handling), control rod drive maintenance, pump maintenance, removal and installation of recirculating pumps in BWR, primary pumps in PWRs, fuel pool clean-up system maintenance, and steam generator maintenance (PWR). It should be noted, however, that the tasks in BWRs result in higher doses. As a consequence there is an increased interest in applying optimization principles in reactor operation, training, and plant maintenance to reduce personnel exposure [58] [62] [63] [68] [72].

In addition to the in service inspection, there are a number of systems that are periodically checked to determine leakage, i.e., residual heat removal (RHR) systems, safety injection (SI) systems and chemical and volume control systems (CVCS). A visual inspection is performed on the piping, valves, pumps, flanges, and fittings for any sign of external leakage. Because of these routine inspections, the health physicist at nuclear power plants must consider factors such as man-power requirements, time limits and man-hour expenditures to evaluate properly personnel access limitations.

## **CHAPTER 3**

### **RADIATION PROTECTION OPTIMIZATION**

#### **3.1 INTRODUCTION**

The goal of the as low as reasonably achievable philosophy is to apply measures for radiological protection for the purpose of reducing collective doses. There are many options available for radiation protection which may be applied at various phases of protection practices. Some of the practices and radiation protection measures include planning for maintenance, material selection, equipment layout, shielding, selection of protection equipment, and all radiological measures which reduce collective doses [2] [63] [64] [65] [66] [67]. The International Commission on Radiation Protection Publication number 37 (ICRP-37) has introduced a cost benefit methodology which can be used to optimize radiation protection measures [2].

This cost benefit analysis can be used as a guideline in the decision making process regarding radiation protection optimization [68]. For instance, radiation protection optimization may involve decision making in determining the number of people, the types of qualification required, type of radiation protection needed, work schedule, and type of monitoring equipment. Cost benefit analysis can be used to implement collective dose goals by allocating resources available for radiation protection. It attempts to determine optimal selection of related radiation protection parameters. Cost benefit analysis attempts to balance radiation protection costs with detriment costs. Optimization can also be applied during planning for equipment maintenance. The optimization process also requires value

judgment because radiological protection can be accomplished using various methods. Cost benefit analysis is applicable when radiation protection measures can be controlled.

The design of nuclear power plants includes a great deal of quantitative analysis performed at the early stage of design for the purpose of protecting the public and occupational personnel. The required level of radiation protection determines the design specifications of various radiation protection measures. Some of the protective measures include: shielding barriers, containment, ventilation systems, and operational features related to the maintenance of equipment. These protective measures are determined using various computational techniques during the design phase of nuclear power plants. The dose rates due to exposures of radiation can appropriately be designed at various areas of the plant. During maintenance activities of contaminated equipment or in-service inspections, optimization of radiation protection involves qualitative decision making [2]. Radiation protection involves the selection and decision of protective equipment, personnel qualifications, monitoring devices, and work schedules. Furthermore, the effectiveness of radiation protection depends on the decision process of selecting the most adequate or practical protection parameters. Thus radiation protection optimization would be more efficient if the decision process would depend on simple rules that reflect experience.

The amount of shielding is an example of protection which is permanent in the plant. Although temporary and removable shields are also selected protection measures during maintenance operations, other measures for radiation protection are: control of source activity through decontamination, distances between source and personnel performing maintenance, planning, exposure time (occupancy), and temporary or permanent shielding. Cost benefit methodology is primarily used to optimize controllable radiological variables such as ventilation air. The air flow passing through a compartment

which contains airborne radioactivity, reduces the concentration levels in the rooms. Although there are other radiological measures to control airborne radioactivity such as: source isolation, air cleaning, whole body protection, and respiratory equipment. However, the decision process can also rely on intuition and engineering judgment.

Planning plays an important role in the reduction of collective doses. Some of the factors that can be taken into account during planning may include: deciding how many personnel are involved in a maintenance practice, the type of qualification required, monitoring equipment used, length of time needed to perform an operation, protective equipment, and operating instructions [2]. However, deciding which of these to change, and determining the adequate combination of these factors, depends heavily on experience and value judgment. Radiation protection modifications due to the selection of protection parameters also modifies the radiation detriment costs.

In addition to the existing protective measures, there are also a number of operational features that influence collective doses such as: reactor fuel quality, fuel management procedures, percentage of fuel failure which leaks fission products into the primary coolant, plant chemistry, decontamination procedures and practices, plant maintenance, in service inspections practices, training of maintenance personnel, protective clothing, protective equipment, use of mock-ups, and health physics monitoring [1] [2]. Different combinations of these factors would result in different collective doses. Planning includes analysis of these factors and determining the ones that can appropriately be modified for the purpose of reducing collective doses. It should be pointed out that some of these factors depend on plant management. Practices in the water chemistry introduce uncertainty in the accumulation of radioactive sources. This in turn makes decontamination practices a factor important to radiation protection and reduction of exposures. A practice

which contributes to collective doses is in-service inspection. In order to reduce doses in this operation careful selection of radiation protection measures is required. The length of time and frequency of maintenance are also important. These activities may require a proper balance between the use of equipment and man-hour expenditures, in which case the cost is affected.

Another example is the use of protective equipment. For example, breathing equipment which may reduce mobility thus increasing the time it takes to perform a maintenance operation or inspection, and consequently increasing external collective doses. At the same time, the use of protective equipment reduces internal exposures. The use of more maintenance personnel beyond planned requirements also contributes to collective dose. This strategy could increase detriment and cost. Therefore, optimization of radiation protection requires a careful balance of protection parameters.

The International Commission on Radiation Protection outlined a cost-benefit methodology that relies on the optimization of selected radiological protection parameters. Accordingly with this methodology, the "as low as reasonably achievable" principle can be viewed as an optimization process [2]. This principle requires careful consideration of all radiological measures available for the purpose of reducing collective doses. This cost benefit methodology is used in this dissertation as a reference and compromise between the cost of radiation protection and the amount needed to achieve reasonable protection. The methodology outlined here is intended to be used as a guidance tool in the selection and levels of protective measures. However, intuition, judgment and most of all, experience plays an important role in radiation protection optimization.

### 3.2 RADIATION PROTECTION AS A DECISION PROCESS

The exposure of maintenance personnel usually results in an uneven distribution of radiation among the involved individuals. To ensure that exposures do not exceed the legal limit, sufficient protection is required [2]. The objective in the decision making process of radiation protection is to increase or combine the existing protective measures for the purpose of reducing the radiation exposure. Radiation protection has many options, some may not necessarily be cost effective. The reduction of collective doses may increase cost. In fact, higher levels of protection almost always cost more [2]. Furthermore, increasing radiation protection can also increase the operational risk or may inconvenience the physical operations not related to radiation protection. The best available combination of radiological parameter and the protection cost would characterize a reasonably achievable dose [69].

Therefore, the decision making process is a selection of the most adequate radiological protection of all the options considered. The best combination selected will have an impact on the levels of individual exposures and cost incurred. Furthermore the options selected impact the work schedule and may create unwanted difficulties. Thus, the decision making process directly affects radiation protection results.

The implementation of ALARA is a multi-decision process which one can follow for the purpose of optimizing of radiological protection management. A radiological cost assessment involves many factors which must be analyzed separately. These factors may include identification of the radiological problem under consideration, analysis of the negative impact of some options against other options, evaluation of all radiation protection options against their cost effectiveness and reduction of risk factor, as well as practicality.



Figure 3.1 shows an example of a decision process sequence in radiological assessments [10]. The ALARA objective is to reduce collective doses. In order to accomplish this, an identification of all alternative options must be considered. There may be options where it is best to reduce dose rates ( including shielding or source reduction). Other options might be to reduce the exposure time; this implies that training is important, because the use of mock-ups before the practice will reduce time. Other options can be to reduce the number of maintenance personnel taking part in the practice (i.e., they can be replaced by mechanical tools or robots), and yet another option is reducing the frequency of the tasks (e.g., with good design, or equipment that requires less maintenance). Furthermore, individuals in management who are responsible for the radiological protection decision process can have an influence at various levels on the ALARA implementation in the utility industry.

### 3.3 RADIATION PROTECTION CRITERIA

*Risk* and *detriment* are two concepts that quantify harmful effects of radiation [2]. Risk is related to the probability that an individual will incur specific effects of radiation as a result of exposure to radiation [2]. The *detriment* is referred to as "the mathematical expectation of the amount of harm in the exposed group of people, taking into account both the probability and the severity of the different possible harmful effects. Harmful effects include the stochastic and nonstochastic effects, as well as the concern and anxiety of the individuals at risk, and any adverse consequences for the comfort of these individuals due to restrictions imposed because of the occurrence of radiation exposure" [2]. According to ICRP-37 par. 22, [2], the magnitude of risk associated with radiation exposure is assumed to be proportional to the collective dose.

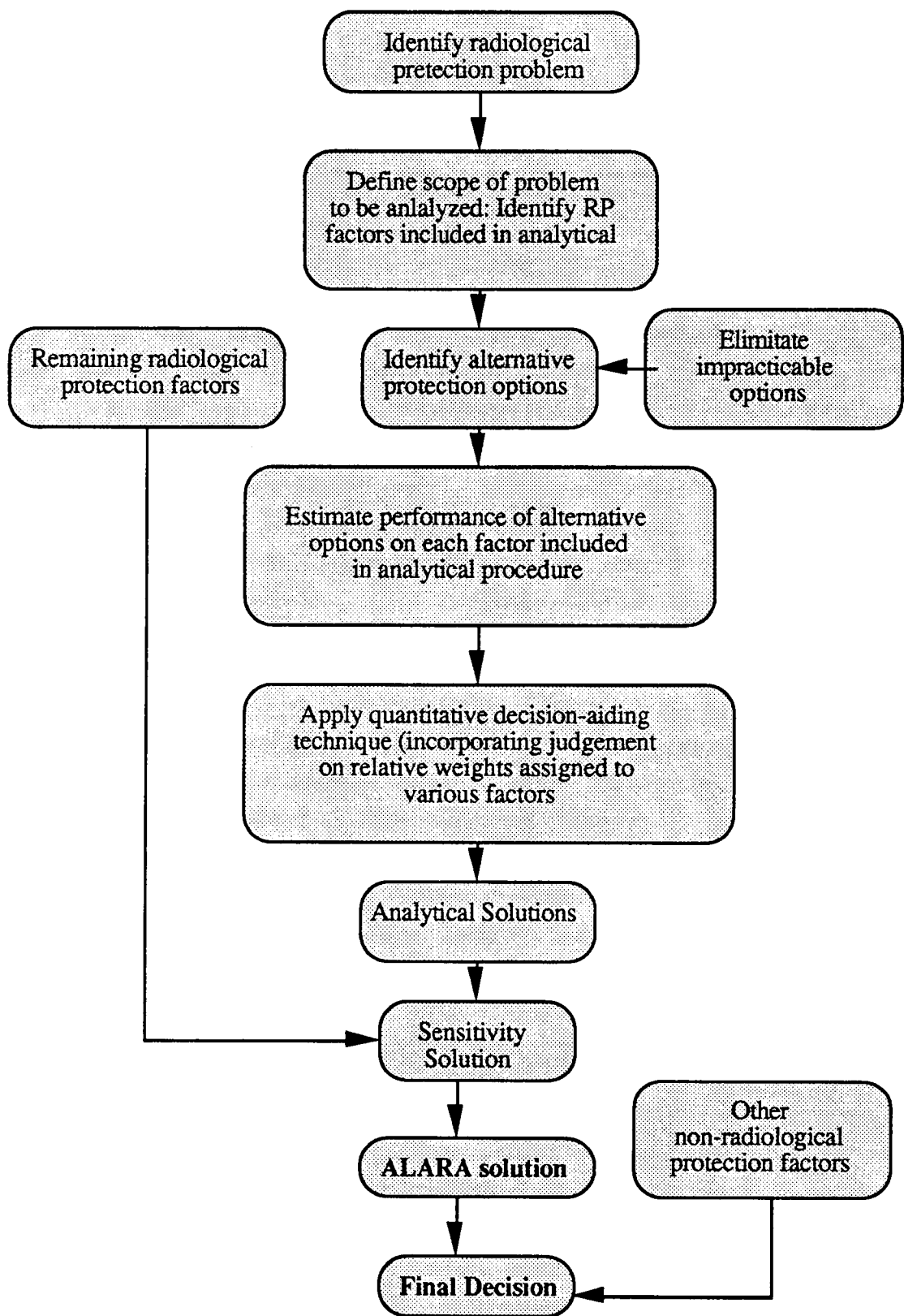


Figure 3.1 Example of an ALARA management decision process.

As a consequence of this assumption, a monetary value is associated with detriment Y. The detriment cost is the product of  $\alpha$  and S, where S is the collective effective dose equivalent resulting from a practice in a radiation field, and  $\alpha$  is the monetary cost assigned to the unit of collective dose. The cost of radiation protection includes all cost incurred to reduce collective doses. Any increase in the level of protection increases the cost. The cost function takes into account all costs, and its evaluation can sometimes be quite complex. Figure 3.2 illustrates the cost and detriment functions for cost benefit analysis. For the problem under consideration, cost is modeled to be a function of air flow.

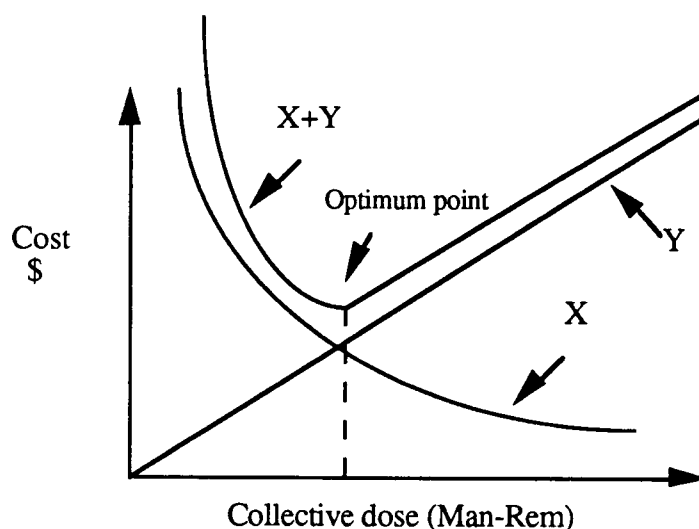


Figure 3.2 . ICRP cost-benefit analysis functions.

An optimum point in the process shown in figure 3.2 is reached when the total collective dose (x-axes) is calculated after a given task. When the air flow is increased for a given task the collective dose is reduced, and the radiation protection cost increases [67]. Cost benefit analysis helps us find the optimum air flow for radiation protection, cost being taken into consideration [1] [3]. The air flow is used as a control variable and a measure for radiation protection optimization.

The air flow reduces the radioactivity concentration as a function of time. The collective dose is obtained when the airflow is held constant for the entire analysis. A second data point in figure 3.2 would be obtained by increasing air flow then calculating, the reduced collective dose for the same task. The air flow is increased until it reaches an optimal value. This procedure provides an optimal flow rate for a constant pipe leakage. Accordingly with figure 3.2, the cost function is monotonically decreasing and the slope of  $X(q_i)$  is negative.  $Y(q_i)$  is a monotonically increasing function of individual dose  $q_i$ , with a positive slope.

### 3.4 THE COST OF RADIATION PROTECTION

According to ICRP-37, the optimization analysis requires quantification of the cost and detriment functions in consistent units. The cost function represents all costs in the implementation of radiation protection, including operating cost, maintenance cost, installation cost, protective equipment cost, and all additional radiation protection costs incurred in implementing radiological protection.

The total cost of heating ventilation and air conditioning in airborne radioactivity control includes the cost of installation, cost of equipment and cost of operation and maintenance. The cost of operation  $X_m$  when only air-flow is considered as a radiological protection measure [66] [67] is expressed as :

$$X_m = a b q F_t T \quad (3.1)$$

where:

a = cost of electricity used to move the air [\$/kwhr],

b = power required to move the air [kwh/ft<sup>3</sup>],

q = air flow-rate [Cfm],

F<sub>t</sub> T = time of operation.

F<sub>t</sub> is the time fraction of operating the systems, which is assumed to be one. Because cost benefit analysis depends on the cost function, it is appropriate to analyze the cost function. The cost function represents the cost incurred and takes into account materials, man power requirements, salaries wages, air conditioning and cooling costs, and any other costs used to meet required dose levels [70] [71] [72]. For example, the case under consideration utilizes 264 man-hours for the maintenance practice. If one were to assume a cost of \$50 per man-hour, the cost spent on salaries would be \$13,200.00. The total cost function, however, must include all costs incurred in radiation protection. In view of the fact that no data was available to model a cost function, a parametric study was used to try to determine a function that would represent the total radiation protection cost.

The parametric study consists of finding the equation that best represents the variation of the radiation protection cost with the air flow. A polynomial equation of degree  $n$  was selected to represent the total radiation protection cost. The magnitude of radiation protection cost is adjusted by varying the parameters  $\delta_1$ ,  $\delta_2$  and  $n$  in equation (3.2)

$$X(q) = \delta_1 q + \delta_2 q^n \quad (3.2)$$

The first term of this equation represents the operational cost of the HVAC. Therefore, equation (3.1) can be included into equation (3.2) by setting the factor  $\delta_1$  equal to the operational cost

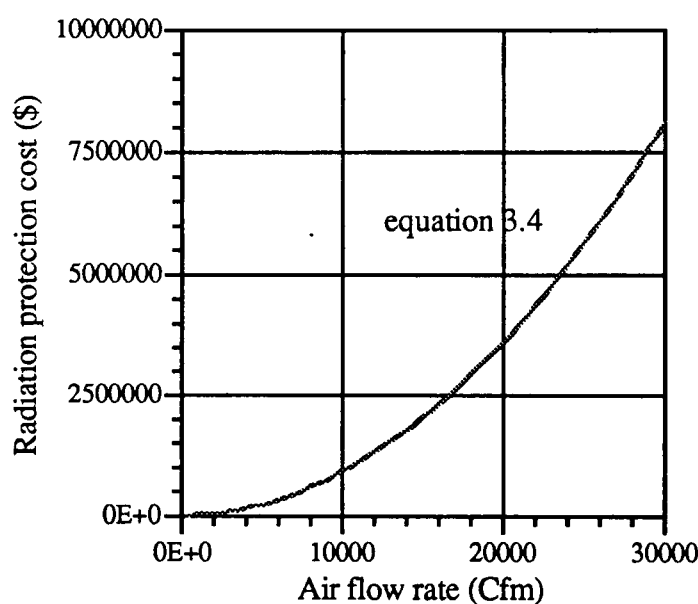
$$X(q) = a b q T + \delta_2 q^n \quad (3.3)$$

To obtain the cost function for the ICRP-37 analysis, two values of  $n$  were considered. The first value was  $n = 2$ , and the second was  $n = 1.2$ . The factor  $\delta_2$  was also adjusted according to the magnitude of the radiation protection cost (in this case  $\delta_2 = 0.1$ ).

$$X(q) = a b q T + \delta_2 q^2 \quad (3.4)$$

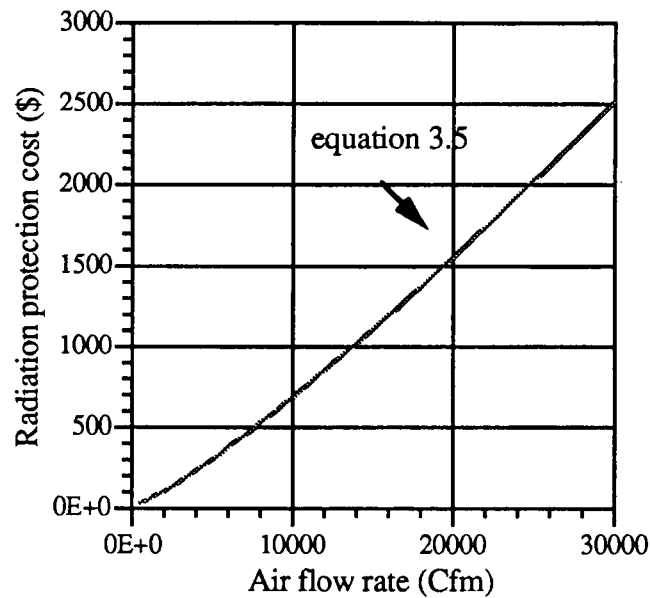
$$X(q) = a b q T + \delta_2 q^{1.2} \quad (3.5)$$

Before the cost functions were selected, these two cases were plotted to determine the cost functions. The first case is illustrated in figures 3.3 (a) and represents an upper limit of cost when  $n = 2$ . On the other hand, equation (3.5) shown in figure 3.3 (b) represents a lower value of the radiation protection cost.



(a)

Figure 3.3 Radiation protection cost .



(b)

Figure 3.3 Radiation protection cost (continued).

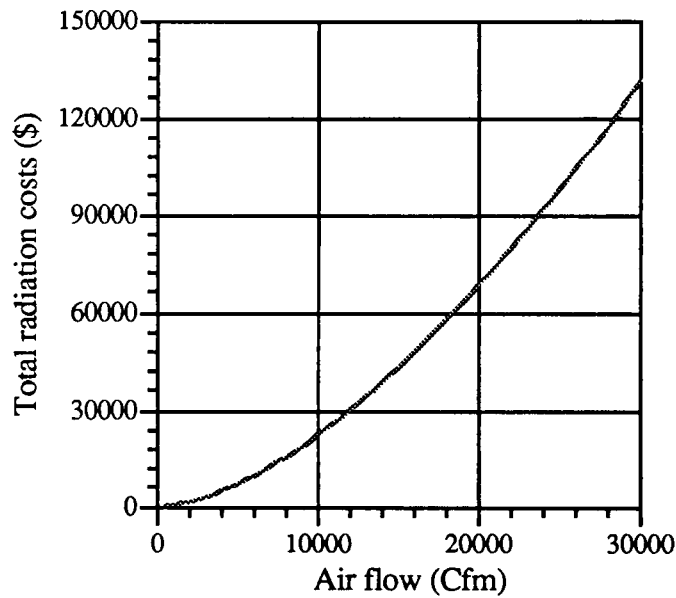
In order to select the cost function for the first, second and third compartment, cost benefit was first applied to the two above cases. Equations 3.4 and 3.5 marked an upper and lower limiting costs. After the parametric study, the selected values of  $n$  were  $n = 1.6$  and  $\delta_2 = 0.09$  for the first cubicle. For the second cubicle  $n = 1.4$  and  $\delta_2 = 0.1$ , and for the third cubicle  $n = 1.3$  and  $\delta_2 = 0.1$ . The value of  $n$  decreases to reflect a decreasing radiation protection cost for the second and third cubicle. The following equations modeled the assumed total costs incurred in the reduction of dose in the first, second and third compartment model correspondingly.

$$X_1(q) = a b q T + \delta_2 q^{1.6} \quad \text{(First cubicle)} \quad (3.6)$$

$$X_2(q) = a b q T + \delta_2 q^{1.4} \quad \text{(Second cubicle)} \quad (3.7)$$

$$X_3(q) = a b q T + \delta_2 q^{1.3} \quad (\text{Third cubicle}) \quad (3.8)$$

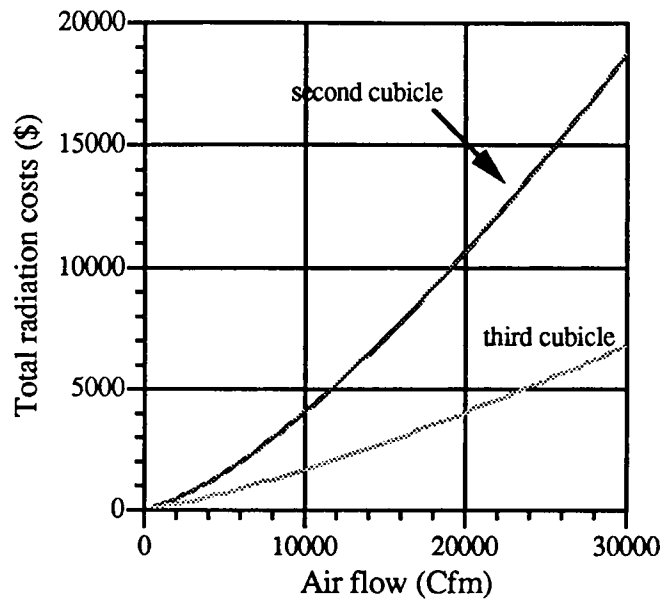
Figure 3.4 (a) represent the total radiation protection cost as a function of air flow rate for the first compartment as given by equation (3.6). Figure 3.4 (b) for the second and third compartment as given by equations (3.5) and (3.6). These cost functions are used to determine the optimal air flow rate using the ICRP analysis. For a given radioactive leakage rate and air flow, the cost would correspond to the air flow that would be used during the entire period of forty hours. But since the leakage increases, cost benefit analysis is performed at each time leakage increase. Since the dose rate on the second and third compartments are lower than the first compartment, the costs of radiation protection are less. Lower doses result in lower collective doses and less radiation protection.



(a)

Figure 3.4 Radiation protection cost for the single compartment.





(b)

Figure 3.4 Radiation cost for the second and third compartment model (continued).

It is important to point out that these equations can be modified to include the other costs of radiation protection if they are known. These equations were selected after a parametric study of various costs. Furthermore, the purpose of this research is to show that a fuzzy radiological algorithm can be used when different costs are incurred. The selected cost functions cover a wide range of costs.

### 3.5 RADIATION DETRIMENT COST

The evaluation of detriment cost entails assigning monetary value to human health factors. Detriment measures harm to an exposed individual after performing a task in a contaminated environment. Detriment is a way to measure all inflicted harm to the exposed individual. This dissertation research utilizes the ICRP-37 methodology [2], in which the detriment cost is directly proportional to the collective dose:

$$Y = \alpha S$$

(3.9)

where  $\alpha$  is the "dimensional constant expressing the cost assigned to the unit collective dose for radiation protection purposes" [2]. This linear assumption is critical and practical to assess radiological effects within an economical context. This is based on the premise that: "there is no threshold in the relationship between dose and the probability of induced stochastic health (cancer or genetic damage)" [10].

The dollar value attached to detriment is a convenient way to perform cost-benefit analysis, even though the radiation protection cost involves several components that could be analyzed separately. There are various values of  $\alpha$  which cover a wide range of values [2]. Furthermore,  $\alpha$  represents the cost per unit collective dose, and this, in turn, includes all types of radiation. It is obvious that  $\alpha$  does not make a distinction between types of radiation. The value  $\alpha$  assigns a monetary value to all health detriment resulting from radiation exposures, including any type of harm created as a result of radiation exposure.

As a logical consequence of this argument one may conclude that there may be different applicable values of  $\alpha$  for different circumstances. For instance the type of task in the nuclear industry, the health and age of the personnel performing the job, type of source and quantity of radiation involved, length of time for specific protection, and location. Therefore, evaluation of  $\alpha$  may require a more detailed study to determine all factors involved which may also include administrative judgment. Detriment should include all economic cost estimates and all complexities involved to place a monetary value on adverse effects on human life [65].

The suggested value found in the literature ranges from \$100 to \$1000 per man-rem, but the value used may have to be established by regulatory authority. The analysis performed in this dissertation has used  $\alpha = \$ 100$  per man-rem. Although, the International Commission on Radiation Protection Publication 22 has suggested the value of  $\alpha = \$ 250$  per man-rem. On the other hand, the 10CFR20 [1] [2] [10] has suggested the value of  $\alpha = \$ 1000$  per man-rem. The detriment should reflect current economic conditions and public concerns. However, it has been acknowledge [2] that assigning monetary value on human life is a controversial issue because of the complexity involved in measuring unknown effects of radiation; for instance, anxiety and the shortening of life expectancy.

Furthermore, distribution problems may arise as a consequence of variations in cost due to location in different countries. For example, problems may arise when crossing international boundaries especially if the values of  $\alpha$  in one country are different from the source country (such as the cases when radioactive clouds cross international borders) [2]. The problem can be even more complex if dispersion is due to accidents that affect the environment with contamination by long-lived radioisotopes, in which case the future health of the population may be at risk [2].

### **3.6 ICRP-37 METHODOLOGY**

The objective of cost benefit methodology introduced by the International Commission on Radiation Protection is to keep all exposures as low as reasonably achievable [2] [58] [64] [73]. Cost benefit methodology is used in this research to define low doses and their cost reasonableness. ICRP-26 recommendations suggest that exposure limits be kept below the prescribed limits and as low as reasonably achievable as long as

economic and social factors are taken into account [1] [2] [74] [75]. Reduction of doses may require a step by step process. The application of ICRP-37 cost benefit analysis methodology is based on three principles. These are interrelated and can be interpreted as follows:

a) The first principle is intended to justify the use of ICRP-37. This indicates that the application of cost benefit must produce a positive net benefit.  $B > 0$  (i.e. the gross value of the radiation protection practice  $V$  should be higher than the cost of input  $P$  plus the cost of protection  $X$  and the cost of detriment  $Y$ ). In radiation protection "an option is selected if the resulting net benefit exceeds that of the next best alternative and not otherwise" [2]. The net benefit to society can be expressed as:

$$B = V - P - X - Y, \quad (3.10)$$

where:

$B$  = net benefit to society from the introduction of the practice

$V$  = gross value of the practice,

$P$  = cost of input, all production cost excluding radiation protection cost

$X$  = cost of radiation protection,

$Y$  = cost of radiation exposure detriment,

b) Optimization is understood in the sense that exposures should be kept as low as reasonably achievable, economic and social factors being taken into account. Doses should be kept as low as reasonable, indicating that an evaluation of the radiological impact of exposure is made in relation to economic and social gain when a reduction is achieved. This implies that the sum of the cost of protection  $X$  and the cost of social detriment  $Y$  be minimized with respect to collective dose.

c) Doses should not exceed those recommended by the International Commission on Radiation Protection.

The International Commission on Radiation Protection Publication No. 37 is primarily concerned with the second premise, which attempts to establish what is reasonably achievable in the control of radiation exposures. In ICRP-37 the optimum value associated with levels of radiation protection  $\omega$  is obtained by finding the minimum value of equation (3.10). Optimization means finding the lowest point of the sum of cost and detriment (figure 3.2).

$$X(\omega) + Y(\omega) = \text{minimum} \quad (3.11)$$

where the cost of protection  $X(\omega)$  and the cost of detriment  $Y(\omega)$  are functions of the protection parameter  $\omega$ . The protection level  $\omega$ , represents optimum radiological variables that reduce collective doses. Since the air flow  $q$  is used as a radiological variable the optimization can be performed by minimizing the sum of  $X + Y$  as a function of air flow.  $X$  and  $Y$  are also referred to as "constraining functions," for  $X$  reflects cost limitations, and  $Y$  represent the collective dose constraints.

The selection of optimal values of radiation protection are obtained by maximizing the net benefit  $B$ . Mathematically the optimum point of a function can be found by taking the first derivative of the function with respect to the radiation protection parameter  $\omega$ . The lowest point in figure 3.2 is found by taking the derivative of equation (3.10) with respect to air flow  $q$ . This is accomplished with the assumption that the gross value  $V$ , and the

cost of input P, are not dependent on the protection parameters  $\omega$ . According to premise b, the objective is to maximize the net benefit B.

$$\frac{dB}{d\omega} = \frac{dV}{d\omega} - \frac{dP}{d\omega} - \frac{dX}{d\omega} - \frac{dY}{d\omega} \quad (3.10)$$

This is referred to as "objective function" or "optimization function." In equation (3.10), X and Y vary according to the levels of protection because collective dose is dependent on the radiological variable q. The optimization is best represented as a function of the air flow q. Since V and P are constants with respect to the air flow q, equation (3.12) is reduced to:

$$\frac{dX}{dq} = - \frac{dY}{dq} \quad (3.13)$$

The cost function X, represents the total cost incurred to achieve a given collective dose. The dose limits are considered to be the limitations for optimization analysis. This is expressed as:

$$H_c(\omega) < H_1 \quad (3.14)$$

This equation is referred to as a limiting equation, where  $H_c(\omega)$  is the individual effective equivalent dose received by individual c at a radiation protective level  $\omega$ , and  $H_1$  is the applicable dose limit [2]. This analysis must be developed under the limiting conditions of individual doses. Today, just operating below the dose limits is not good enough. As low as reasonably achievable means to reduce dose rates below the required limits. In the nuclear industry an important constraint in the decision process is the reduction of individual doses so that doses remain below the limit. In order to achieve optimum levels

of radiation protection, cost benefit analysis balances total costs with collective doses. In summary, "the Commission has concluded that the phrase as low as reasonably achievable can be interpreted by a process of cost-benefit analysis which establishes optimum levels of radiation protection" [2].

### 3.7 COST-BENEFIT ANALYSIS FORMULATION

In this analysis, the reduction of exposure is accomplished by introducing clean air into the contaminated area, reducing the airborne concentrations. In order to find the optimal air flow according to ICRP-37 analysis, the dose rate is required. For example, in the single compartment model, the concentration  $c_1$  [ $\mu\text{ci/cc}$ ] is found using the following equation [76]:

$$c_1 = \frac{x_1}{v_1} = L c p \frac{(1-e^{-at})}{q} \quad (3.15)$$

And the dose rate  $d(t)$  is :

$$d(t) = \omega L \frac{(1-e^{-at})}{q} \text{ rem/sec} \quad (3.16)$$

where:

$$a = 472 \frac{q}{v_1}, \quad b = 472 \frac{q}{v_2}, \quad c = 472 \frac{q}{v_3}$$

$q$  = air flow [cfm]

$p$  = partition factor = 0.1

$$\frac{x_1}{v_1}, \frac{x_2}{v_2}, \frac{x_3}{v_3} = \text{activity concentration } [\mu\text{ci/cc}]$$

$L$  = radioactive leak rate into the compartment [Gpm]

$v_1 = 3.0E+10$  cc,  $v_2 = 1.33E+09$  cc,  $v_3 = 6.852E+08$  cc

$c$  = radioactive concentration of the leak [ $\mu$ ci/cc] 20 for I-131

$F$  = conversion factor to obtain mrem/hr per  $\mu$ ci/cc =  $8.33E+06$

$\omega$  = conversion factor to obtain (rem/sec) =  $\frac{k F c p}{3.6E+06}$

$k$  = conversion factor to obtain [ $\mu$ ci/cc] = 0.13372

In order to obtain  $\mu$ ci/cc, one must multiply the  $at$  factor by 472 and the concentration by 0.13372; this is then multiplied by  $8.333E+08$  to obtain mrem/hr.

The integrated dose is:

$$D = \int d(t) dt. \quad (3.17)$$

and the collective dose is:

$$S = \int n(t) d(t) dt \quad (3.18)$$

where  $n(t)$  is the occupancy requirements. The collective dose is also defined as the product of:

$$S = D T N f \quad (3.19)$$

In this case  $D$  is the mean dose rate,  $T$  is the mean exposure time per task,  $N$  is the number of workers involved, and  $f$  is the frequency of performing the task. The reduction of any of these factors results in reduction of the collective dose. Sometimes tasks require



fixed values of  $N$  and  $T$ , thus the remaining factor  $D$  can be reduced using a variety of techniques such as protective equipment, temporary shielding, segregation of equipment, moving high maintenance equipment to lower dose rate areas, and varying the air flow. On the other hand, the resulting collective dose using equations (3.16) (3.18) and occupancy  $n(t)$  is:

$$S = n(t) D = \int \frac{n(t) L c (1 - e^{-at}) dt}{q} \quad (3.20)$$

and the detriment:

$$Y = \frac{L \omega \alpha}{q} \int n(t) (1 - e^{-at}) dt \quad (3.21)$$

The cost of radiation protection follows from equation (3.4)

$$X = a b \tau q + \delta q^{1.6} \quad (3.22)$$

Cost is a function of the air flow; therefore, increasing the air flow increases the cost of the radiation protection. It is worth mentioning that the operating cost of ventilation units in homes are lower (because the air flow is low) than installation costs. However, ventilation units at nuclear power plants or mines, have operating costs that are higher than installations costs [2]. The total cost is a function of  $a$ ,  $b$ ,  $T$ , and  $q$ . The cost is also a function of dose because the isotopic concentration is a function of air flow rate, and as  $q$  increases the collective dose is reduced.

The collective dose shown by equation (3.20) is inversely proportional to the flow rate. According to equation (3.11) to optimize protection means mathematically to minimize the sum of  $X + Y$  with respect to collective dose. The optimal point is obtained by taking the derivative of equation (3.21) and (3.22) and setting them equal to each other. For a given maintenance activity, the optimal value of flow rate  $q$  is reached when the sum of  $X$  and  $Y$  is at a minimum value, therefore:

$$\frac{\partial X}{\partial q} = a b \tau + \delta 1.6 q^{0.6} \quad (3.23)$$

and

$$\frac{\partial Y}{\partial q} = -\frac{L \omega \alpha}{q^2} \int n(t) (1-e^{-at}) dt \quad (3.24)$$

According to equation (3.12) and (3.13) the optimal air flow is obtained from:

$$\frac{\partial X}{\partial q} = -\frac{\partial Y}{\partial q} \quad (3.25)$$

And finally, the optimal air flow is obtained by substituting equation (3.23) and (3.24) into equation (3.25) and solving for  $q$ :

$$a b \tau + \delta 1.6 q^{0.6} = \frac{L \omega \alpha}{q^2} \int N(t) (1-e^{-at}) dt \quad (3.26)$$

For the double compartment model, the concentration is:

$$c_2(t) = k \frac{x_2}{v_2} = \frac{L c p}{q} (1 - e^{-bt}) + k \frac{L c p v_1}{(v_1 - v_2) q} (e^{-bt} - e^{-at}) \quad (3.27)$$

The dose rate as a function of time in rem/sec is:

$$d_2(t) = \frac{L \omega}{q} (1 - e^{-bt}) + \frac{L \omega v_1}{(v_1 - v_2) q} (e^{-bt} - e^{-at}) \quad (3.28)$$

According to equations (3.9) and (3.18) the detriment is defined as:

$$Y = \alpha \int n(t) d(t) dt. \quad (3.29)$$

or

$$Y = \alpha \frac{L \omega}{q} \int n(t) (1 - e^{-bt}) dt + \alpha \frac{L \omega v_1}{(v_1 - v_2) q} \int n(t) (e^{-bt} - e^{-at}) dt \quad (3.30)$$

The derivative with respect to the air flow is:

$$\frac{\partial Y}{\partial q} = -\frac{L \omega \alpha}{q^2} \left\{ \int n(t) (1 - e^{-bt}) dt + \frac{v_1}{(v_1 - v_2)} \int n(t) (e^{-bt} - e^{-at}) dt \right\} \quad (3.31)$$

The cost function, according with equation (3.7) is :

$$X = a b \tau q + \delta q^{1.4} \quad (3.32)$$

From this equation, the derivative with respect to the air flow is given by:

$$\frac{\partial X}{\partial q} = a b \tau + \delta 1.4 q^{0.4} \quad (3.33)$$

Where the optimum air flow is obtained by solving for q in:

$$a b \tau + \delta 1.4 q^{0.4} = \frac{L \omega \alpha}{q^2} \left\{ \int n(t) (1 - e^{-bt}) dt + \frac{v_1}{(v_1 - v_2)} \int n(t) (e^{-bt} - e^{-at}) dt \right\} \quad (3.34)$$

For the triple compartment model concentration in  $\mu\text{m/cc}$  is:

$$c_3(t) = k \frac{v_1 v_2 L c p}{(v_1 - v_2)(v_2 - v_3) q} (e^{-bt} - e^{-ct}) + k \frac{(L p c)}{q} (1 - e^{-ct}) + k \frac{v_1^2 L c p}{(v_1 - v_2)(v_1 - v_3) q} (e^{-ct} - e^{-at}) \quad (3.35)$$

The dose rate in rem/sec is given by:

$$d(t) = \frac{v_1 v_2 L \omega}{(v_1 - v_2)(v_2 - v_3) q} (e^{-bt} - e^{-ct}) + \frac{L \omega}{q} (1 - e^{-ct}) + \frac{v_1^2 L \omega}{(v_1 - v_2)(v_1 - v_3) q} (e^{-ct} - e^{-at}) \quad (3.36)$$

And by use of equations (3.9) and (3.18) the detriment is given by:

$$Y = \frac{v_1 v_2 L \omega}{(v_1 - v_2)(v_2 - v_3) q} \alpha \int n(t) (e^{-bt} - e^{-ct}) dt + \frac{L \omega}{q} \alpha \int n(t) (1 - e^{-ct}) dt + \frac{v_1^2 L \omega}{(v_1 - v_2)(v_1 - v_3) q} \alpha \int n(t) (e^{-ct} - e^{-at}) dt \quad (3.37)$$

In this case, the derivative of the detriment with respect to the air flow is:

$$\frac{\partial Y}{\partial q} = -\frac{L \omega \alpha}{q^2} \left\{ \frac{v_1 v_2}{(v_1 - v_2)(v_2 - v_3)} \int N(t) (e^{-bt} - e^{-ct}) dt + \int N(t) (1 - e^{-ct}) dt + \frac{v_1^2}{(v_1 - v_2)(v_1 - v_3)} \int N(t) (e^{-ct} - e^{-at}) dt \right\} \quad (3.38)$$

The cost function, according with equation (3.8) is

$$X = a b \tau q + \delta q^{1.3} \quad (3.39)$$

For this compartment, the derivative of the cost function with respect to the air flow is given by:

$$\frac{\partial X}{\partial q} = a b \tau + \delta 1.3 q^{0.3} \quad (3.40)$$

The optimum ICRP air flow is obtained by substituting equating equations (3.38) and (3.40) into equation (3.25), and solving for q

$$a b \tau + \delta 1.3 q^{0.3} = \frac{L \omega \alpha}{q^2} \left\{ \frac{v_1 v_2}{(v_1 - v_2)(v_2 - v_3)} \int n(t) (e^{-bt} - e^{-ct}) dt + \int n(t) (1 - e^{-ct}) dt + \frac{v_1^2}{(v_1 - v_2)(v_1 - v_3)} \int n(t) (e^{-ct} - e^{-at}) dt \right\} \quad (3.41)$$

## CHAPTER 4

### FUZZY RADIATION PROTECTION

#### 4.1 INTRODUCTION

The quantities involved in ALARA are inherently fuzzy because they depend on a variety of factors specific to a plant environment and maintenance practices. In computer science there has been a great interest in developing techniques to encode human knowledge into mathematical algorithms for the purpose of analyzing data derived from computers to aid in the decision process of control environments. Traditionally the interpretation of data processed by computers is done by experts in specified fields. The expert knowledge that is described by vague linguistic terminology is often difficult to represent in precise mathematical terms. The branch of computer science that attempts to resolve this problem is an area known as "fuzzy expert systems." Expert systems intend to make computers intelligent systems that can make human interpretations of their own using data derived according to the problem solving environment. An expert system is a computer code that simulates in some measure human deductive reasoning [77] [78]. Expert systems attempt to provide the same answers just like an expert would in a given situation [11].

In recent years fuzzy logic has been applied in a number of disciplines such as: medicine, management, computer and system science, and meteorology for the purpose of resolving imprecision [79] [80] [81]. Fuzzy sets theory can be used to quantify and define vague semantic linguistic concepts that represent expert knowledge. Approximate

reasoning in fuzzy logic is the process of deriving conclusions from facts that are represented in rules which use fuzzy variables. An advantage of the use of fuzzy logic in approximate reasoning is that it uses exact representation of syntax as is used in natural language [11]. Problem solving strategies in science can be encoded into heuristic knowledge. With such representation an expert can encode knowledge into rules. The verbal description of instructions for the control of systems may contain or may use imprecise words that are not accurately defined. The imprecision and vagueness of such terms can be resolved by the use of fuzzy logic which makes use of membership functions (membership functions) to encode inexact meanings of words. In this way fuzzy set theory allows a representation of heuristic knowledge to be manipulated by mathematical models.

Fuzzy logic can help in the definition of linguistic variables used to describe complex processes such as those found in radiological control problems. In this case linguistic variables are used in human reasoning to described information and instructions about specific control. These instructions are described through verbal descriptions. The verbal descriptions represent knowledge that experts have acquired about complex processes. In control theory, instructions are used to control processes which must have precise statement descriptions of processes to accomplish good control. Therefore, by use of fuzzy logic we can represent the semantic of expressions mathematically.

The linguistic terms used in the "as low as reasonably achievable" principle are vague and imprecise. When applied to radiation protection they have different expert meanings. For instance, "reasonably low" can have various levels of low which cannot be handled with current conventional certainty or confidence factors. The terms "low" and "reasonable" belong to the same category as tall, good or hot which are part of the linguistic terms used in common language and their values are not numerical but linguistic. Since

*low* and *reasonable* are linguistic variables, fuzzy set theory can help in handling difficulties encountered when defining vagueness and imprecision.

Fuzzy logic provides a mathematical structure to represent vagueness and imprecision found in linguistic terminology used in ALARA during radiological assessments. The evaluation of low and reasonable dose rate is an example of an imprecise evaluation of a radiological environment. Radiological assessments of this type reflect a meaning of the words used in the environment in which they are applied. A radiological assessment entails a careful study of all available options for radiation protection. This procedure is carried out through a decision process for the purpose of selecting the best option in radiation control that reflects expert knowledge.

The mathematical approach used in fuzzy set theory has been used to design an expert system to handle the imprecision associated with ALARA terminology. Fuzzy set theory can be used to quantify the imprecision in linguistic hedges. Therefore, it brings about a practical formalism to deal with the imprecision found when using vague terminology. Fuzzy logic can be used to clarify the decision process when trying to evaluate radiological environments [78]. "Low" and "reasonable" are subject to human judgment and are imprecise because of the question "how low is low ?" and "how reasonable is reasonable ?" The use of such terminologies adds uncertainty when trying to assess the adequacy of design or levels of contamination. The uncertainties are non-probabilistic and *fuzzy* in nature [67]. In conclusion, fuzzy set theory provides the mathematical means to deal with the imprecision found in terminology commonly used in decision-making.



## 4.2 FUZZY SET THEORY AND SEMANTICS

In radiation protection, fuzzy logic can be applied to distinguish between various levels of dose, such as low, medium, and high. Each of these terms can be defined by a corresponding fuzzy set or membership function. The basic representation of linguistic variables in fuzzy logic is fuzzy sets [82]. A fuzzy set is a collection of points between zero and one. These sets are represented as membership functions for the purpose of distinguishing degrees of "truth". A set of points represents the degree of truth of the concept to distinguish vagueness [45] [83] [84]. In radiological assessments, the linguistic variables are vague due to the interpretation given in natural language. The level of truth in linguistic variables can be measured by assigning a membership function as shown in figure 4.1. The membership function value or degree of truth determines if a variable belongs, or if it does not belong, to the assigned meaning [82]. For instance, the membership function of "false" and "true" in figure 4.1, can be used to distinguish the concept of a high from a low number. Then if the number fifty is declared as high, the highest value on the x-axes in figure 4.1 is fifty (the ordinate of figure 4.1 is normalized) and fifty has a membership value of one for the "high" and zero for "low" or not true.

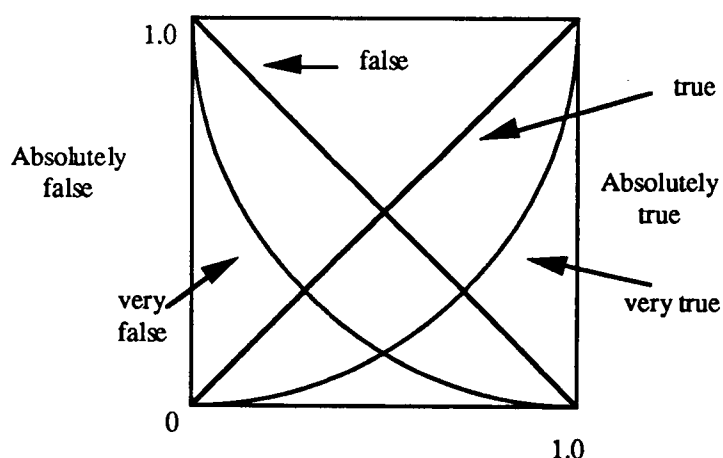


Fig 4.1 Degree of "truth" and "false" represented as degree of membership.

The degree of truth is the membership value between zero and one. This number indicates the truthfulness of a meaning described by a membership function. According to figure 4.1 the fuzzy set, represented as a membership function, defines and distinguishes true and false concepts. In this way one can assign degrees of "truth or false". A degree of membership of a number is given by the value of the membership function which reflects the degree of truth. Let us take for instance the real number "seven". One can define a membership function that represents the linguistic meaning of "about seven" as illustrated in figure 4.2. In this manner one can find degrees of truth to any number in the vicinity of the real number "seven." The linguistic variable "about" is a modifier or operator which in natural language is vague and imprecise. This implies that a number for example 7.3 has a degree of membership of 0.98 as degree of truth and corresponding degree of truth of seven is one as assigned by the membership function "about seven" [49] [85].

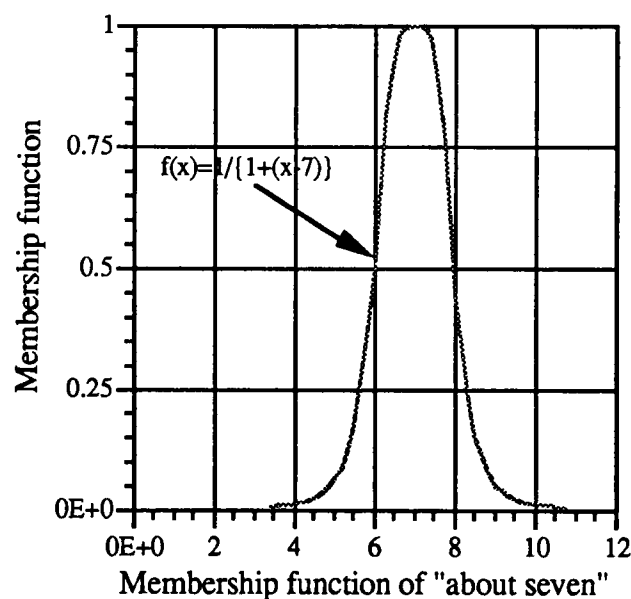


Figure 4.2 Degree of membership for the meaning "about seven."

Another example of a linguistic variable is *age*; figure 4.3 represents the membership value on the y-axis of an age on the x-axis. Age can have various linguistic values such as *young*, *old*, *very old* or *very young*. "Very" and "quite" are operators which modify the meaning of their operand to some degree and modify the concept of age according to categories given in natural language. The linguistic descriptions have values defined in natural languages only.

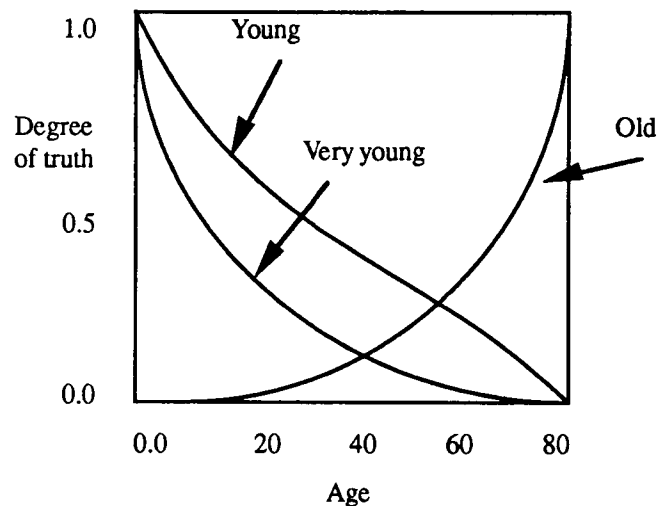


Figure 4.3 Membership functions for young and old.

The fuzzy algorithm developed in this research distinguishes between three levels of dose rate (low, medium and high) which were approximated by linear membership functions. Figure 4.4 defines the normalized membership function of the fuzzy value dose rate (x-axes).

An example of the applications of heuristic knowledge is in aircraft control. In landing an aircraft the function of a pilot is to monitor various parameters for the purpose of maneuvering the aircraft to a safe landing. Some of these parameters include the trajectory

or glide path which provides a glide slope, airspeed, rate of descent, and elevator angle change. A heuristic rule describing the control of landing can be of the form :

" If rate of descent is normal and airspeed is moderate and glide-slope is positive medium then the engine speed should be changed to positive medium and elevator angle change should be insignificant" [5].

This rule uses imprecise terminology such as "normal", "positive" "medium" and "insignificant", and their meaning of which can be encoded in fuzzy sets.

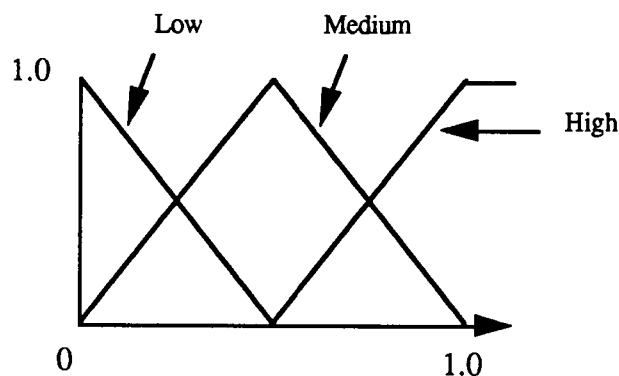


Figure 4.4. Membership functions of dose rate.

### 4.3 NEW FUZZY RADIOLOGICAL APPROACH

The objective of the *extension principle* is to find a connection and relationship between non-fuzzy functions and their fuzzy equivalent [84] [85]. The purpose of the application the extension principle in this dissertation is find the fuzzy equivalent of radiological equations used in RAD for the purpose of quantify ALARA terminology. The *extension principle* in fuzzy set theory "allows the domain of the definition of a mapping as

a relation to be extended from points in  $U$  to fuzzy subsets of  $U$ " [31], where  $U$  is the universe of discourse composed of real numbers. For instance, in functions such as equation 4.1, one would be interested in finding its fuzzy equivalent when one or several of these variables  $x_1$ ,  $x_2$ ,  $x_3$ , and  $x_4$  are fuzzified:

$$y = f(x) = f(x_1, x_2, x_3, x_4) \quad (4.1)$$

A new approach utilized in this research is the use of *parameterization* to derive accurate membership functions from physical equations describing radiological environments [7]. The objective of the development of the ALARA fuzzy methodology in radiological assessment is to parameterize exact functions or relations which relate an exact physical behavior to the variables describing radiological environments. The purpose of these fuzzy relations would be to derive the membership function from physical functions that relate non-fuzzy variables. For instance, one can relate (in an equation form) the amount of shielding in terms of shielding thickness needed to obtain desired dose rates. This function determines how much shielding is needed to provide an adequate dose rate reduction or *low dose rate*. By use of the parameterization procedure one is able to find the corresponding membership function for *adequate shielding derived from low dose rate*.

The important contribution of this approach is the derivation of a concept, such as "adequate shielding," from a physical equation when one or more of the variables in such an equation are fuzzified. In this fashion one can connect or combine a linguistic concept (via parameterization) from functional relationships, and thus, derive the corresponding membership function. The membership function would represent the mathematical value of the meaning associated to the "concept" involved.

Typically in fuzzy control theory, the range of values the fuzzy variables take is determined by a knowledgeable engineer or an expert, so are the numbers of fuzzy variables and their shapes. The expert system RAD uses fuzzy variables that are interrelated and dependent on dose rate, for instance, in the single compartment model:

$$d(t) = \frac{L c (1 - e^{-at})}{q}, \quad (4.2)$$

The objective of RAD is to reduce and control the dose rate by increasing or decreasing the air flow rate by forced circulation into a contaminated cubicle. RAD contains sets of fuzzy conditional statements which represent expert knowledge about the safety and the desired operation of the heating, ventilation, and air conditioning system. The expert system is designed to demonstrate this new approach by utilizing three state fuzzy variables:

- (1) **leakage** of radioactive liquid into the room
- (2) **dose rate**
- (3) **collective dose**

The control variable is the **air flow** passing through the room. The known linguistic variables or fuzzy values for these variables are presented on Table 4.1. In this manner, fuzzification of radiological variables, which is of importance in the control of contaminated environments, provides a way of quantifying the various meanings of terms involved in radiation optimization. Figure 4.4 shows the three membership functions of dose rate which have been approximated by a linear function. For example, the linear equation of the membership of low is represented by:

$$\mu_{low\ dose}(x) = 1 - 2x \quad 0 < x < 0.5 \quad (4.3)$$

This equation can be considered a first approximation to the meaning of "low dose rate." In fact, in fuzzy control one may use trapezoidal or triangular membership functions to approximate the meaning of linguistic variables. One may also make a similar approximation about other fuzzy variables. The range of values of each fuzzy value is determined by a knowledgeable engineer or expert. However, it should be noted that the linear representation of the membership functions of dose rate are approximations, because linguistics modifiers such as "low" probably have non-linear membership functions. The universe of discourse of the fuzzy values of dose rate can be defined if the extent of possible values are known. In the development of fuzzy expert systems there is a great deal of tuning, because the range of values depends on how fuzzy variables are defined.

Table 4.1 Linguistic values of the fuzzy state variables.

| leak rate                        | dose rate & collective<br>dose | air flow                    |
|----------------------------------|--------------------------------|-----------------------------|
| <i>lower than expected (low)</i> | <i>low</i>                     | <i>below normal</i>         |
| <i>expected</i>                  | <i>medium</i>                  | <i>normal (design rate)</i> |
| <i>higher than expected</i>      | <i>high</i>                    | <i>higher than normal</i>   |
| <i>high</i>                      |                                | <i>high</i>                 |
| <i>pipe rupture (accident)</i>   |                                | <i>accident level</i>       |

The "as low as reasonably achievable" principle states that dose rates must be kept "low but reasonable", meaning at a reasonable cost. This double goal objective brings

about a new concept, which can be define as a double fuzzy variable. This would represent an extension to a fuzzy *double operator* or modifier of the control variable "*low but reasonable dose rate*". Previously, figure 4.4 and equation 4.5 show the quantified fuzzy low dose rate only.

Part of this research is to extend the meaning of a double qualifier of a fuzzy variable when they have different universes of discourse. At first it may seem that these two concepts contradict each other. In fact very low doses can be achieved only when the cost of radiation protection incurred increases. However the objective of the ALARA principle is to stay within a reasonable cost (constraint) and low dose rate (goal), i.e. to reduce dose rates as long as the *reasonable* and *acceptable* qualifiers attached to cost and detriment are in agreement with the established current definition of such a concept. The ALARA principle consequently entails a referenced meaning of terms. The linguistic modifiers of low and reasonable are common natural language, because they have been coined through their repetitive usage within specific contexts. One does not question if the meaning of such terms is correct, or if they have an exact mathematical representation. Such terms become imprecise because of their unclear boundaries, although accepted in natural language. The results of this research show that with the methodology of parameterization, one can derive membership functions of double qualifiers, which have opposite objectives.

As explained in chapter 3, ICRP-37 introduced a cost benefit methodology that can be used to define the concept of "reasonable cost" (See section 3.6 for ICRP-37 details.) The new approach of this research is demonstrate by the use of a cost benefit methodology as a reference for the purpose of fuzzify the air flow through a cubicle and a means of reducing personnel exposure to radiation. Therefore, the fuzzification of the air flow rate



obtained for the ICRP-37 methodology defines and distinguishes between three concepts of cost which are necessary in the ALARA principle when performing radiological assessment.

By applying cost benefit methodology analysis, one obtains optimal air flow rates, which from the ICRP-37 point of view, represents an allowable air flow because the radiation protection costs are taken into account. The three derived concepts of cost are: *reasonable, more or less reasonable and, not reasonable*. The "more or less reasonable" concept is defined as a way of distinguishing the region between "reasonable" and "not reasonable". Figure 4.5 shows the resultant air flow (ICRP air flow) from applying this methodology for the single compartment model. The air flow resulting from applying cost benefit analysis follows the leakage response illustrated in figure 4.6.

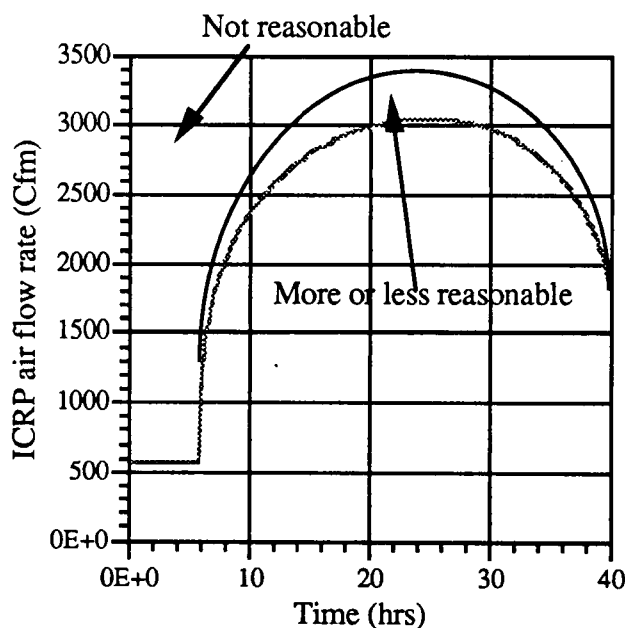


Figure 4.5 ICRP-37 air flow reference for the first compartment.

The concept of "reasonable" cost would correspond to the operational air flows below the ICRP air flow. In order to derive the concept of "more or less reasonable," the area between 110% and 100% of the ICRP air flow is used as a reference to represent and derive "more or less reasonable" cost. The air flow above the "more or less reasonable" area defines a "not reasonable" cost. Equation 4.2 describes the change in dose rates as a function of air flow, leakage rate, and time. The dose rate is directly proportional to the leakage rate and inversely proportional to the air flow. (The equations for the multi-compartment model follow the same reasoning) From this equation one can derive three ensuing concepts of dose rate by use of the parameterization procedure. Therefore, when the operational air flow is below the optimal ICRP-37 level, the dose rate is *high*. The "more or less reasonable" cost region derives *medium* dose rate, and when the air flows are higher than this line, the dose rates are *low*. A meaning that was vague, now is referenced. This is the double qualifier in radiation protection. The concept of low dose and reasonable cost has been connected through the fuzzification of air flow. In this fashion one is able to derive and connect two opposite goals of the ALARA principle.

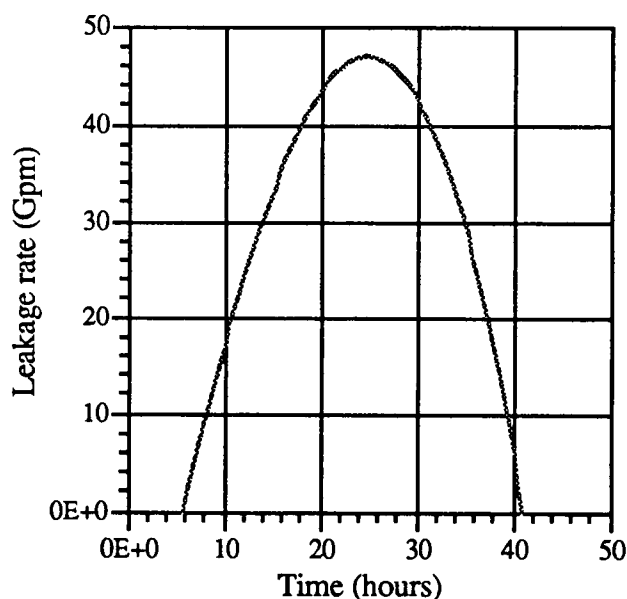


Figure 4.6 Leakage rate as a function of time.

#### 4.4 FUZZY PARAMETERIZATION PROCEDURE

The parameterization of dose rate from the ICRP air flow results in three different membership functions of dose rate (low, medium, and high). These regions of figure 4.5 in turn derive the three membership functions of "dose rate" according to equation 4.2 for the single compartment. The three regions in figure 4.5 represent the three referenced costs; reasonable, more or less reasonable, and not reasonable. The parameterization procedure consist of subdividing the fuzzy variable air flow  $q$ , into three more concepts derived from the reference ICRP results of cost. The dose rate is given by:

$$d(t) = k c_1 = k L c p \frac{(1-e^{-at})}{q} \quad (4.4)$$

The paramentrization of the air flow is accomplished by solving for the membership functions in the equations of the three regions defined in figure 4.5 [7] [86]. Equations (4.5) to (4.8) correspond to the four lines of figure 4.7.

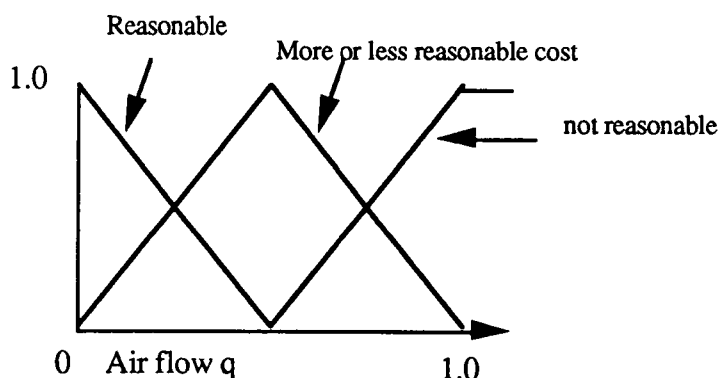


Figure 4.7 Membership functions of the fuzzyfied air flow  $q$ .

Then, four normalized equations cover the entire range of ICRP flow as shown in figure 4.7. The "reasonable" portion corresponds to  $q_1$  equation (4.5), the first portion of the "more or less reasonable" corresponds to  $q_2$  equation (4.6). The second part of the "more or less reasonable" is given by equation (4.7), and the "not reasonable" area is given by equation (4.8). RAD passes the upper limit,  $\Phi$  to the routines. The value  $\Phi$ , corresponds to the highest ICRP air flow from figure 4.5.

$$\mu_{\text{reasonable}} = 1 - 2x = 1 - 2\left(\frac{q_1}{\Phi}\right) \quad 0 < x < 0.5 \quad (4.5)$$

$$\mu_{\text{more or less reasonable}} = 2x = 2\left(\frac{q_2}{\Phi}\right) \quad 0 < x < 0.5 \quad (4.6)$$

$$\mu_{\text{more or less reasonable}} = 2 - 2x = 2 - 2\left(\frac{q_3}{\Phi}\right) \quad 0.5 < x < 1.0 \quad (4.7)$$

$$\mu_{\text{not reasonable}} = 2x - 1 = 2\left(\frac{q_4}{\Phi}\right) - 1 \quad 0.5 < x < 1.0 \quad (4.8)$$

The membership values  $\lambda$ , vary from zero to one and four values of the flow derive four membership functions of dose rate are:

$$q_1 = \frac{\Phi}{2} (1 - \lambda) \quad (4.9)$$

$$q_2 = \frac{\Phi}{2} \lambda \quad (4.10)$$

$$q_3 = \frac{\Phi}{2} (2 - \lambda) \quad (4.11)$$

$$q_4 = \frac{\Phi}{2} (\lambda + 1) \quad (4.12)$$

From these equations four different membership functions are derived

$$d_1(t) = k L c p \frac{(1-e^{-at})}{q_1}, \quad \mu_{\text{high}} = k 2 L c p \frac{(1-e^{-at})}{\Phi(1-\lambda)} \quad (4.13)$$

$$d_2(t) = k L c p \frac{(1-e^{-at})}{q_2}, \quad \mu_{\text{medium}} = k 2 L c p \frac{(1-e^{-at})}{\Phi\lambda} \quad (4.14)$$

$$d_3(t) = k L c p \frac{(1-e^{-at})}{q_3}, \quad \mu_{\text{medium}} = k 2 L c p \frac{(1-e^{-at})}{\Phi(2-\lambda)} \quad (4.15)$$

$$d_4(t) = k L c p \frac{(1-e^{-at})}{q_4}, \quad \mu_{\text{low}} = k 2 L c p \frac{(1-e^{-at})}{\Phi(1+\lambda)} \quad (4.16)$$

Using the same procedure, one can also derive the membership of cost. For instance, in the first compartment:

$$X_1 = a b \tau q + \delta q_1^{1.6} \quad (4.17)$$

Then: 1.6

$$\mu_{\text{reasonable}} = \Phi \frac{ab\tau}{2} (1-\lambda) + \delta \left( \frac{\Phi(1-\lambda)}{2} \right) \quad (4.18)$$

$$X_2 = a b \tau q + \delta q_2^{1.6} \quad (4.19)$$

Then 1.6

$$\mu_{\text{more or less reasonable}} = \Phi \frac{ab\tau}{2} \lambda + \delta \left( \frac{\Phi\lambda}{2} \right) \quad (4.20)$$

$$X_3 = a b \tau q + \delta q_3^{1.6} \quad (4.21)$$

Then

$$\mu_{\text{more or less reasonable}} = \Phi \frac{ab\tau}{2} (2 - \lambda) + \delta \left( \frac{\Phi(2 - \lambda)}{2} \right) \quad (4.22)$$

$$X_4 = a b \tau q + \delta q_4 \quad (4.23)$$

Then

1.6

$$\mu_{\text{not reasonable}} = \Phi \frac{ab\tau}{2} (1 + \lambda) + \delta \left( \frac{\Phi(1 + \lambda)}{2} \right) \quad (4.24)$$

The values of the membership functions are obtained by varying  $\lambda$  from zero to one. The methodology to obtain the membership function of detriment is the same, for example, for the single compartment:

$$Y_1 = \frac{L \omega \alpha}{q_1} \int N(t) (1 - e^{-at}) dt \quad (4.25)$$

where  $q_1$  comes from the equation:

$$q_1 = \frac{\Phi}{2} (1 - \lambda) \quad (4.26)$$

$$\mu_{\text{acceptable}} = 2 \frac{L \omega \alpha}{\Phi(1 - \lambda)} \int N(t) (1 - e^{-at}) dt \quad (4.27)$$

where:

$x$  = Normalized value of the air flow

$\Phi$  = Upper limit of the ICRP reference air flow

$\lambda$  = Variable representing the membership function (from zero to one)

$q$  = Air flow rate

## 4.5 FUZZY RADIATION PROTECTION OPTIMIZATION

In natural language, to optimize means to do the best one can under a given set of circumstances. In this context "best" is to maximize or minimize. The purpose of fuzzy optimization is to find the best answers or solutions by finding the intersection of goals and constraints, thus finding solutions in a multi-criteria environment [3] [11] [87]. The constraints and goals (objective functions) can be represented as fuzzy sets. These fuzzy sets must define and quantify the linguistic concept used for optimization purposes. The fuzzy set of a constraint represents a restriction or limitation. The fuzzy set of the goal represents desirable results [11]. This qualification is reflected on the values of the corresponding universe of discourse. We can deduce conclusions from these objective functions by applying fuzzy optimization principles. Fuzzy optimization allows mathematical manipulation of subjective linguistic descriptions used in control theory.

Radiological assessments entail an evaluation of resultant dose rates and collective doses. From the point of view of the ALARA principle, the goals are to reduce dose and dose rates. On the other hand, cost is a constraint. An ALARA assessment thus is a process of selecting the best combinations of radiological parameters. These parameters depend on a variety of conditions such as cost (budget constraints) and collective dose requirements. In the application of fuzzy optimization in radiation protection, the objective function (dose and detriment) and constraint (cost) have a range of values that depend on the extent of their meaning. This meaning can be represented by membership functions. These membership functions represent the numerical values to distinguish the various levels of imprecision found in cost and detriment. In decision theory, we would like to simultaneously satisfy the objective function and constraints [49] [88]. A decision in a

fuzzy radiological environment which satisfies both objectives and constraints, corresponds to the intersection of fuzzy constraints and fuzzy objective functions.

The cost depends on the monetary value of man-hour expenditure plus cost of additional equipment to expedite the operation for a given maintenance operation. The man-hours take into account the number of personnel and the time of task. In fuzzy optimization, a decision set results from the intersection of the membership functions of the fuzzy goal dose and fuzzy constraint cost. This intersection forms another membership function of the fuzzy decision set.

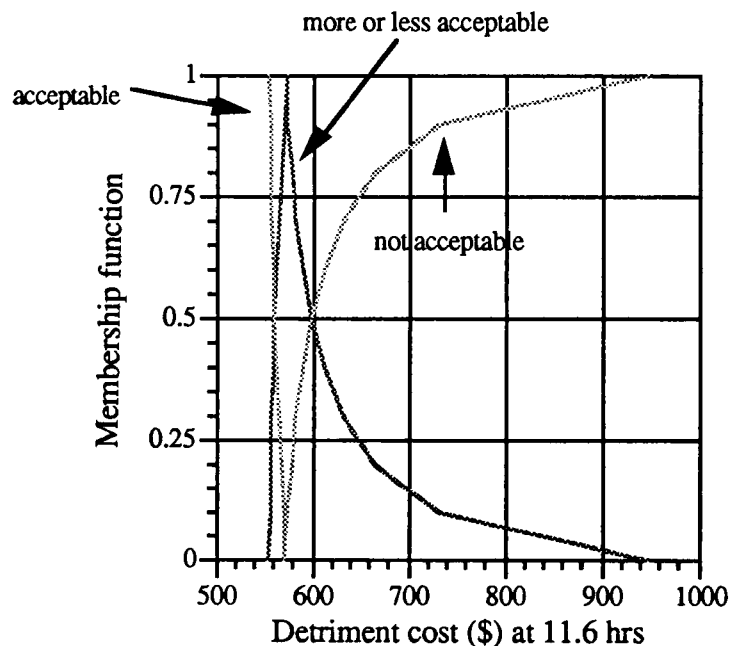
The variable cost constraint can have various linguistic interpretations when operators or modifiers are applied to it. For instance, the cost of a task is reasonable or fairly reasonable. Reasonable and fairly reasonable are vague terms, which from a fuzzy theory point of view can be represented as fuzzy sets. The same would be the case for the fuzzy goal dose rate, low dose rate (the dose rate should be in the vicinity of 2.5 mrem/hr). In the context of fuzzy radiation protection, detriment is dependent on dose rate, from which one can also derive the corresponding meaning from the already defined dose rate in the previous section. For example, if dose is low, then detriment is acceptable. The different meanings of dose, detriment, and cost can be represented by membership functions. In the case under consideration, the fuzzy variables are *cost* and *detriment* which are subdivided into the fuzzy values presented in table 4.2. Figure 4.6 represents the membership functions of detriment at different times (these are the results obtained from applying the parameterization procedure explained in section 4.4).



Table 4.2 Fuzzy values of the cost constraint and goal detriment.

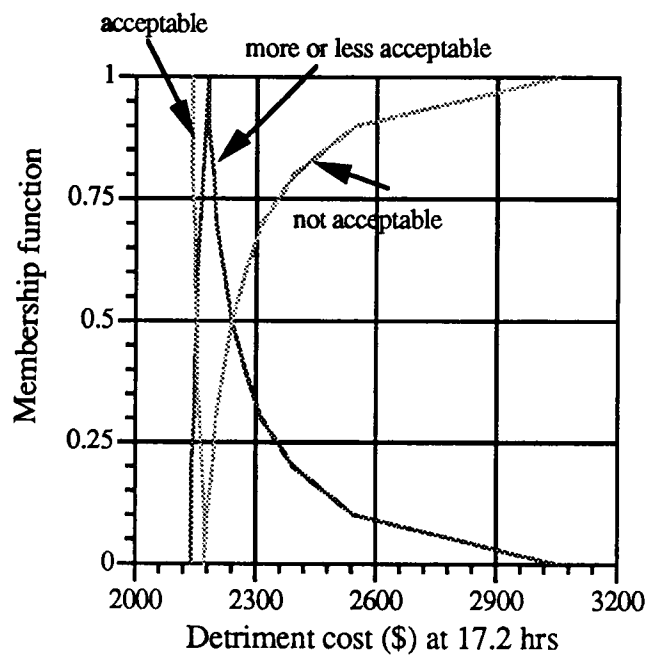
| COST             | DETRIMENT               |
|------------------|-------------------------|
| reasonable       | acceptable              |
| about reasonable | more or less acceptable |
| not reasonable   | not acceptable          |

The degree of truth for each fuzzy value is reflected in a corresponding fuzzy membership function  $\mu_{\text{detriment}}(x)$ ,  $\mu_{\text{cost}}(x)$ . The three different meanings represented in the membership functions were derived by use of the parameterization procedure. The fuzzy variable cost represents the constraint to which a given task is subjected. Dose rate and detriment represent the fuzzy safe goal or objective function, and the two are related by equation (3.7).

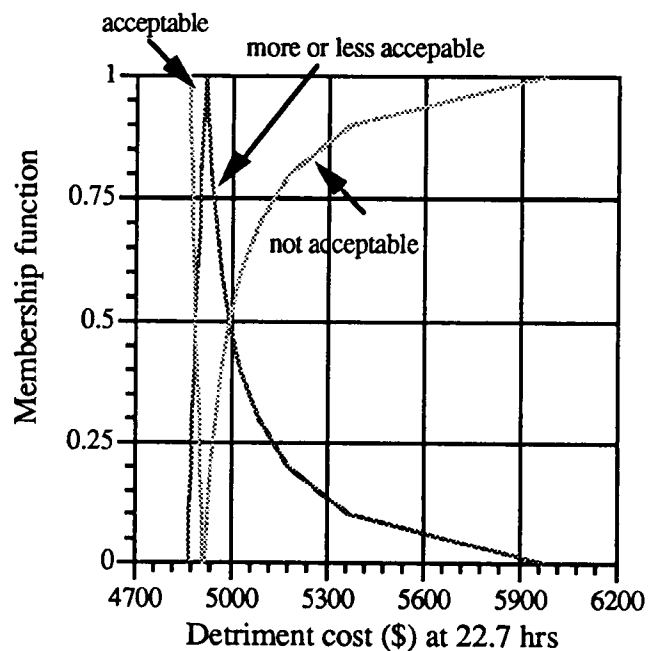


(a)

Figure 4.6 Membership functions of fuzzy goal detriment.



(b)



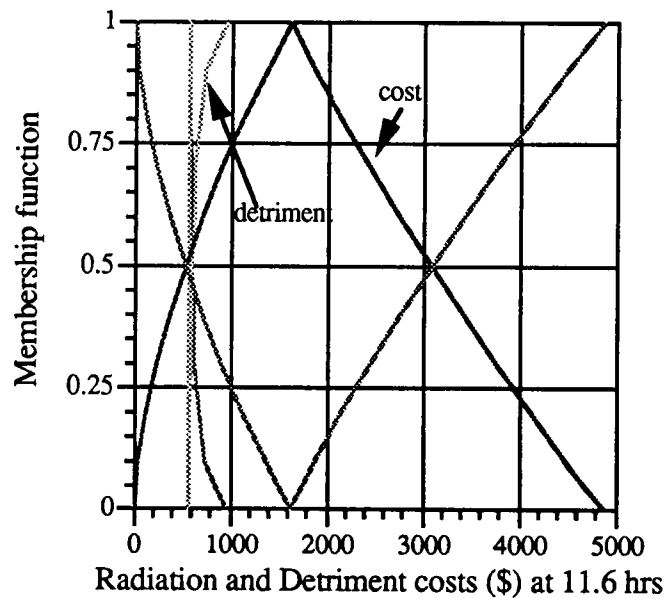
(c)

Figure 4.6. Membership functions of fuzzy goal detriment (continued).

The fuzzy safe goal detriment membership function  $\mu_{\text{detriment}}(x)$  can be combined with the fuzzy constraint cost membership function  $\mu_{\text{cost}}(x)$  to form a *fuzzy decision set* which results from the intersection  $\Lambda$  of their membership functions [3]

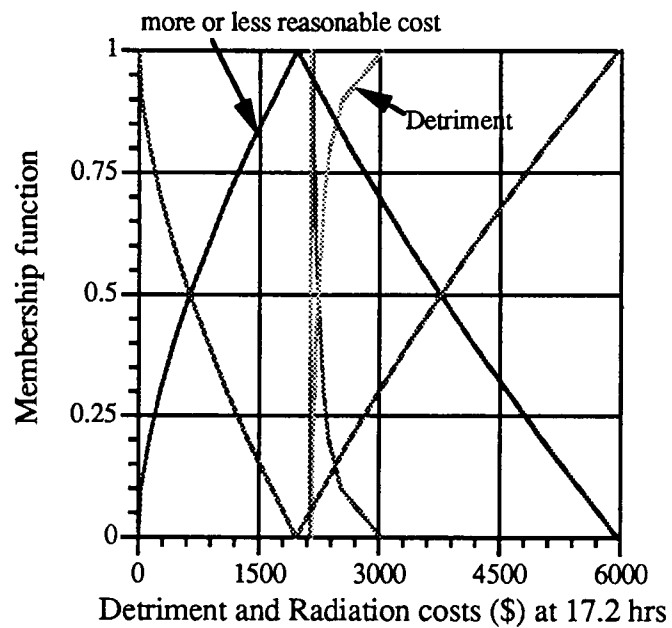
$$\mu_{\text{decision}}(x) = \mu_{\text{cost}}(x) \Lambda \mu_{\text{detriment}}(x). \quad (4.28)$$

The decision set is characterized by several constraints and goals. Therefore, one may generalize to  $n$  fuzzy detriment goals  $D_1, D_2, \dots, D_n$  and  $m$  fuzzy cost constraints  $C_1, C_2, \dots, C_m$ . Fuzzy optimization is represented by the membership function  $\mu_{\text{decision}}(x^*)$ , in the space of alternatives  $x$ . The optimal decision is the maximum value  $x^*$  of the intersection [3] [49]. Figure 4.7 shows how the intersection of cost and detriment yield optimal values at different times.

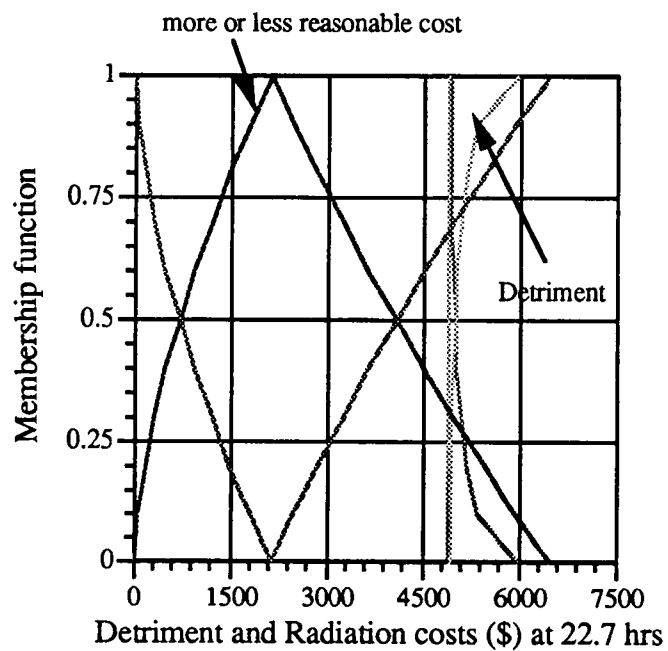


(a)

Figure 4.7 Optimization of fuzzy cost constraint detriment goal.



(b)



(c)

Figure 4.7 Optimization of fuzzy cost constraint detriment goal (continued).

## CHAPTER 5

### EXPERT SYSTEM ARCHITECTURE

#### 5.1 OVERVIEW

An expert system called **RAD** was written in the OPS5 (Official Production System) and was designed to test the fuzzy algorithm presented in section 4.3. The objective of the fuzzy algorithm is to define (from a fuzzy point of view) and utilize radiological variables which are necessary in a radiological assessment. The expert system is designed to control the air flow for the purpose of reducing dose rates and minimize occupational radiation exposure. It performs a radiological evaluation when a pipe leakage takes place. RAD analyzes data reflecting the changing intensity of the radiation field, and determines the optimum flow rate in contaminated cubicles where access is anticipated.

OPS5 is utilized to represent expert knowledge in the form of production rules while external subroutines perform various numerical computations as required by the problem. The computer language OPS5 is a good expert system building tool [6] [89]. One of its desirable features which made it practical is the combination of numerical and symbolic manipulations. The symbolic capability is used for knowledge representation in production rules. Numerical computations are performed by interphasing with external subroutines and functions.

Furthermore, when mathematical algorithms are used to describe physical behavior of systems (as in this case, calculating the isotope concentration in a multi-compartment

model) the solution to these type of problems can employ several rigorous mathematical methodologies which vary in complexity and a requires computer language capable of performing numerical computations easily and rapidly. For instance, FORTRAN is a computer language well suited for this purpose.

The computer language OPS5, on the other hand, due to the rule-base structure capability, can encode knowledge into heuristic rules, and is also able to perform numeric computations in FORTRAN by interphasing the external subroutines and functions. The difficulty of complex mathematical problems can be bypassed by solving all computations in the external functions and obtaining solutions which can be returned to the rule base code. In this manner the OPS5 rule based structure can remove some of the complexity involved in finding a solution which may require complex mathematical formulas. Another feature that makes OPS5 desirable is the capability to handle constantly changing data coupled with a rule base. The advantage of symbolic manipulations in OPS5 is that it can easily structure rules that come from heuristic knowledge.

## **5.2 DESCRIPTION OF THE PROBLEM**

The purpose of the expert system RAD is to analyzed a pipe rupture from a radiological point of view. A radiological assessment consists of determining dose rates and collective doses while controlling (by use of the fuzzy algorithm) the air flow rates in various compartment models shown in figure 5.1. A radiological assessment is carried out by using the methodology described in the International Commission on Radiation Protection Number 37 and described in Chapter 3. This methodology is utilized as a reference for the definition of the "reasonableness" of cost. This analysis is also coupled

with the fuzzy radiological algorithm for the purpose of quantifying and defining the "as low as reasonably achievable" principle in relation to the environment under consideration.

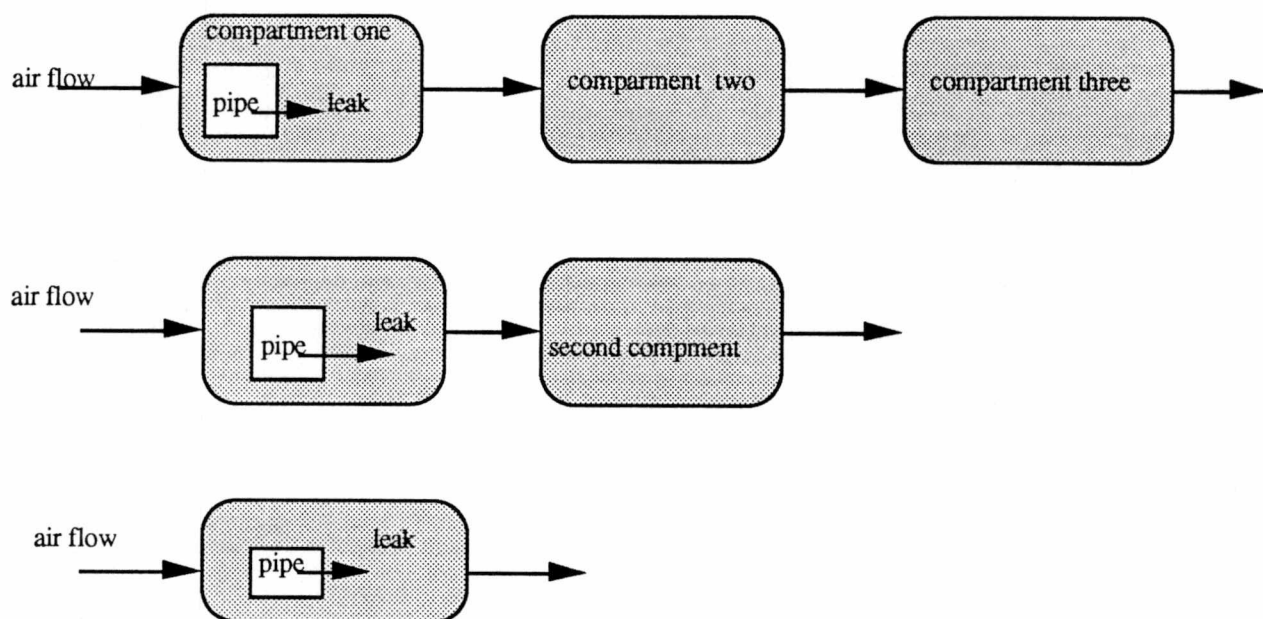


Figure 5.1 Compartment model.

When the air flow rate passing through the room is increased the dose rates and integrated doses are reduced. RAD calculates the integrated dose and the dose rates as a function the increasing air flow rate,  $q$ . Initially,  $q$  is assumed to be constant. The flow is then used as a variable to reduce the isotopic concentration when a pipe rupture occurs or equipment leakage higher than normal takes place. A leak in compartment one for instance, (Figure 5.1) will set a pattern of concentrations in each of the compartments down stream, which is different for every increase in  $q$ . High doses would be present due to the airborne radioactivity and also due to the radioactive sources in the water as well, even though for

this problem only the airborne of Iodine-131 is considered. By use of the prescribed air flow the airborne concentration is reduced. Fuzzy rules are used to calculate the prescribed air flow, rules which represent expert knowledge about a given radiological environment. They are grouped in what is known a *fuzzy algorithm* described in section 5.2.1. Figure 5.2 outlines the way in which the working memory serves as a dynamic data storage. The working memory or global memory is where data and informations about the state of the problem is stored.

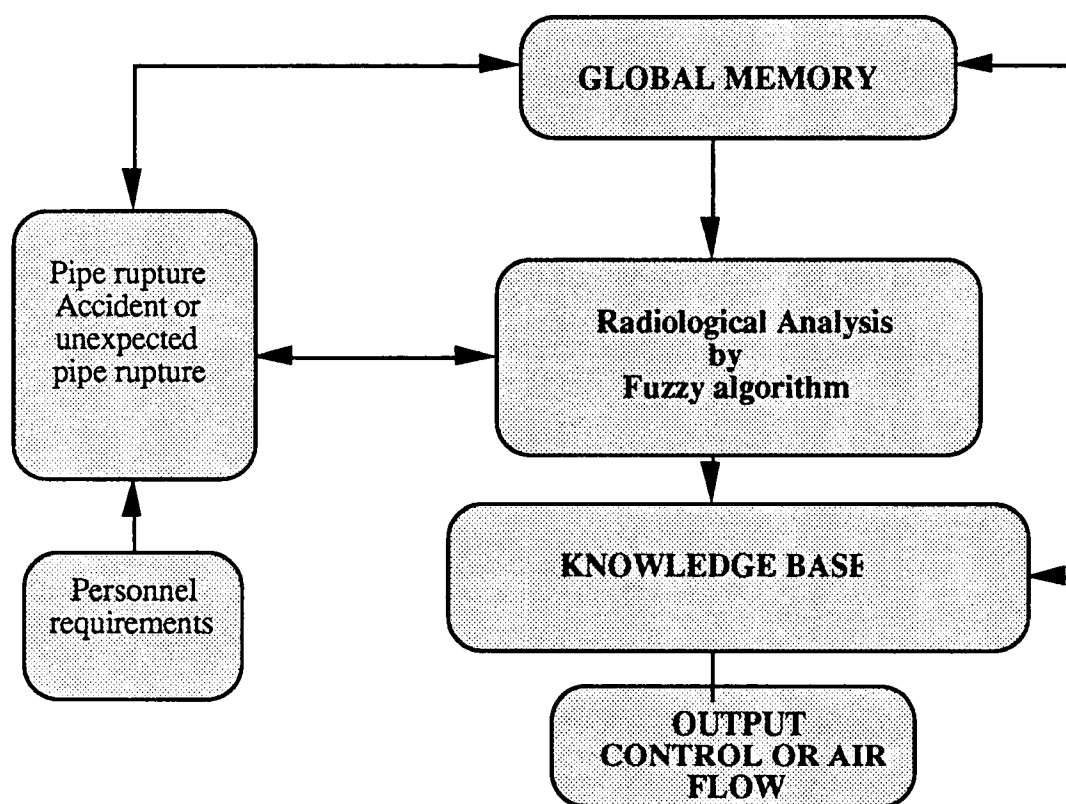


Figure 5.2 Expert system problem description.



This analysis combines two methods, a fuzzy radiological algorithm and a cost benefit analysis. From the point of view of fuzzy logic, one can use the fuzzification process to subdivide the vague meaning in terminology. Traditionally, in fuzzy control, fuzzy variables are defined with one modifier only. As described in section 4.3, the purpose of the combination of these two methods is to obtain a unique membership function which would represent the combined meaning of "low and reasonable dose rate." In order to accomplish this task, RAD was designed to interface with multiple external subroutines. The external subroutines and functions are designed to perform specific tasks. There are several tasks relegated to the subroutines and functions. One is to find the optimum air flow for a given leak in a compartment, and another is to provide membership functions to support the fuzzy algorithm. The optimization routine is based on the methodology outlined in reference [2] and consists of defining a cost-function and finding the optimum air flow rate for the combination of all cost and collective doses  $S$ , as described in Chapter 3.

### **5.3 THE OPS5 LANGUAGE AND EXPERT SYSTEMS**

The objective of an expert systems is to simulate the expertise experts use in specific fields for the purpose of deriving conclusions and solutions about problems. The knowledge base in an expert system contains sets of rules which represent knowledge about specific situations. The structure of an expert system has three basic components: first it must have a set of facts (data to be analyzed); second a set of rules which are applied to those facts; and third, an inference engine. The inference engine is a built-in algorithm which by pattern matching recognizes the facts [11].

The structure of the expert system RAD is of conditions which derive actions that change the state of the environment under analysis. The expert system written in OPS5 contains a set of production rules or "condition-action rules" statements which are operated on by known facts in cycles [90] [91]. In each cycle the known facts are matched against the condition, and if the conditions are matched, then a prescribed action is applied. The action changes the state of the system, matching other production rules.

Fuzzy logic allow the representation of linguistic models with words by representing linguistic variables with numbers, qualitative analysis are possible with a quantitative representation of verbal variables. This is the case in fuzzy control in which linguistic expressions are used in conditions that utilize fuzzy verbal models to represent, define, and quantify linguistic meaning. Approximate reasoning in expert system means to represent semantics into useful mathematic equations for computer manipulations [42] [11]. With an "IF-THEN" structure, one can prescribe instructions in a cluster of rules. For instance, in driving a car, a rule of thumb is "if it is raining or is snowing, then drive slowly." A set of rules like these form a knowledge-base.

For the radiological model described in section 5.1.1, the expert system utilizes fuzzy linguistic representations. The fuzzy variables used in this analysis are: **leak rate**, **dose rate**, and **collective dose**. The production rule system attempts to assess contamination levels as a function of time. Particular rules are applied if the conditions are matched or instantiated, in which case an action follows. The prescribed controlled variable is **air flow** which dictates new dose rates and collective doses. On the other hand, **detriment** is another radiological variable which is needed to evaluate harm from radiation. Fuzzy logic is also used to define and determine the uncertainty found in

detriment. In fuzzy logic, detriment may take on various meanings such as: acceptable or more or less acceptable.

#### 5.4 DESCRIPTION OF THE EXPERT SYSTEM RAD

The expert system RAD analyzes transient radioactive concentration for the cubicles shown in figure 5.1. It should be pointed out however, that the fuzzy expert system **RAD** is a very specialized program; thus it is only applicable in the environment for which it was designed (see section 5.3 for details). OPS5 is a data driven programming language [76], that requires a precise rule structure and knowledge-base for execution. This knowledge-base utilizes heuristics encoded into rules or productions rules. These rules evaluate the state of the system for the purpose of prescribing air flows. RAD's knowledge-base contains forty six rules, and in order for the rules to fire data is required. This data is provided from groups of subroutines and functions which are recalled from within OPS5 in a well coordinated and timely manner.

RAD was divided into three main subprograms: fuzzy-ops (1), fuzzy-ops (2) and fuzzy-ops (3). Each subprogram is designed to perform separate tasks. One is data collection and updating, the task is the application of the fuzzy algorithm, fuzzyfication and defuzzyfication, and the last is the estimation of ICRP reference air flow and fuzzy optimization. The first and second tasks are connected sequentially and cycle once one is completed; the last one is optional. The first subtask purpose is to collect and calculate relevant information about the type of compartment. Once a string of data (membership functions) is collected from the external subroutines, the rule base analyzes this data through pattern matching technique. For instance, at each time step the **dose rate**, **dose**, and **leakage** are necessary for rule firing. The second subtasks is the fuzzyfication and

defuzzification of crisp data. Once this is completed, RAD saves the data on files for the last task, fuzzy optimization analysis. In order to fuzzify the crisp values of leakage, dose rate and dose, a production rule is designed to collect this membership values and another to defuzzify and delete them according to the fuzzy algorithm.

The OPS5 language uses three main components: the rule base, working memory, and the rule interpreter. The working memory represents data which describes the radiological environment. The rule interpreter or inference engine is an algorithm by which the program executes the analysis of data through a pattern matching cycles. The process by which data is analyzed in OPS5 is referred to as the forward-chaining method. In this method conclusions and solutions are derived from analyzing large amounts of data, (i.e. the name indicates the direction of the methodology). The inference engine in OPS5 is capable to analyze data in a forward and backward chaining method.

Data in RAD is stored in the working memory whose components are called working memory elements (WME). Strings of data are represented as "classes" with attribute. The heading of this structure has a class name and subsequent names of relevant components related to the class are called attributes. This structure allows RAD to form a symbolic strings of data. For instance, RAD distinguishes dose rates in three different compartments which are represented as:

(literalize comp\_one            dose\_rates)

where the working memory creates a space that contains a class called "comp\_one" for the first compartment whose attribute is "dose\_rate." The second compartment class name is "comp\_two." The "literalize" statement is used to define or declare the existence of

a class. This is the structure of the information stored in RAD. The attributes have values which can be either numbers or symbols, and are called atoms.

Production rules follow a IF-THEN structure which contains a left hand side (LHS), and a right hand side (RHS). The elements of both are of "class-attribute" format. The LHS elements represents a conditions, and the RHS represents the conclusion or action that may be executed. A rule is applied only when the LHS matches data from the Working Memory elements. A rule in RAD is of the form :

```
(p get_membership_funct_comp_1
      (comp_one    ^dose_rate <dose> )
-->
      (modify comp_one    ^dose_rate 4.0 ) )
```

Where " (p " indicates the beginning of a rule, "get\_membership\_funct\_comp\_1" is the name of the rule and "(comp\_one ^dose\_rate <dose> )" represents a condition. If the condition is matched, the dose rate in comp\_one is modify to 4.0. In which <dose> represents a variable (variables are enclosed in angle brackets). The action part of the rule plays a very important role in the determination of the solution to specific problems. The action permanently can modify, create, and remove working memory. In addition to these command, printing data and terminating the execution the program are also performed on the RHS. Another feature used in RAD is the "call" action. This action is used to bring in data from external subroutines. RAD makes use of various subroutines written in FORTRAN. For example:

```
(call  fuzzyl-for <leak>)
```

This declaration is made on the RHS of the rule and is used to invoke the external subroutine "fuzzyl-for" (fuzzy-leak) by passing the variable <leak>. In this case RAD passes the variable to the subroutine which in turn returns four values directly to the working memory (the subroutines fuzzydr-for, fuzzyd-for and fuzzyf-for have the same function). The fuzzyl-for is used to estimate the degree of membership of a crisp value of the leakage rate according to the model of figure 5.3. For each crisp value of leakage corresponds a degree of membership (DM1 and DM2) and a "label" (L1 and L2) refereeing to where it falls on the universe of discourse. Figure 5.3 shows the transfer of variables in the subroutines.

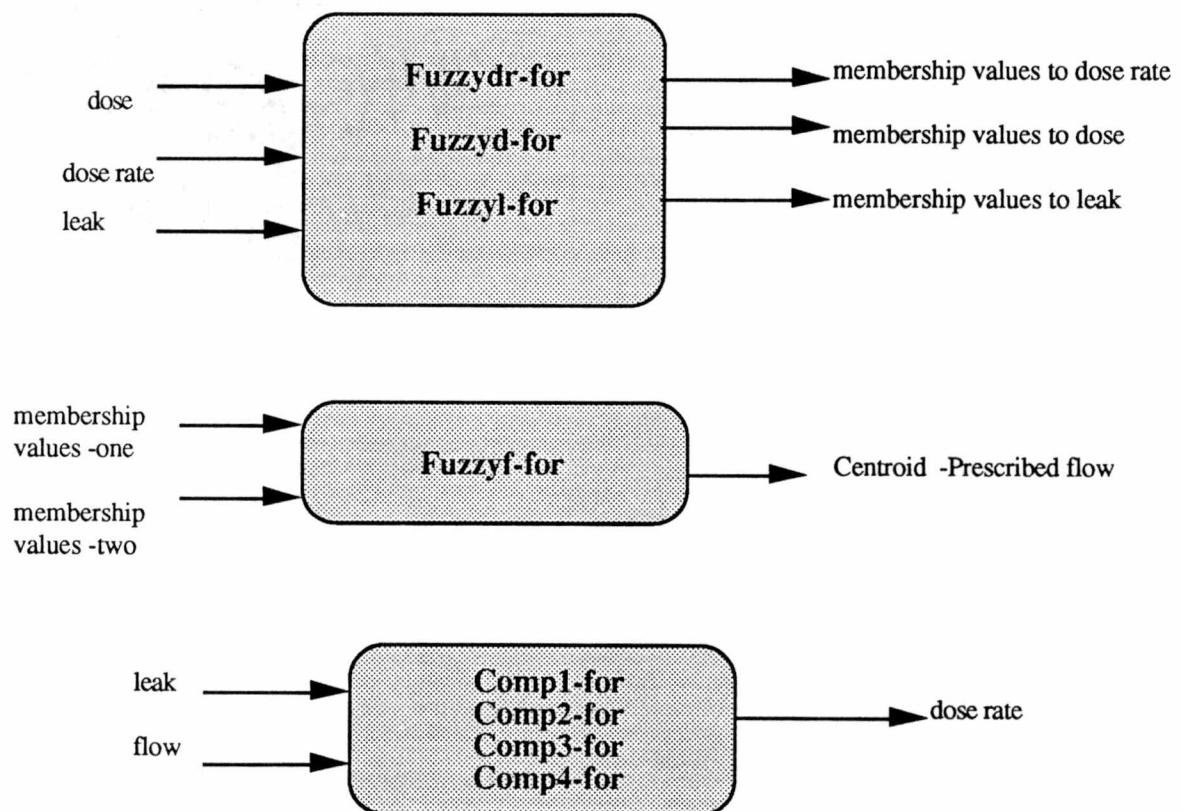


Figure 5.3 Subroutine variable interchange.

RAD also makes use of "integer functions," in which only one value can be returned, not to the working memory but to the RHS of the rule which called it, as illustrated in figure 5.4. For example:

```
( bind <occup> (occup-for <time>) )
```

In this rule, the variable <time> is passed to the subroutine "occup-for" which returns the occupancy or number of working personnel in a given compartment at the time <time>. Even though the "integer functions" and "subroutines" perform all necessary mathematical computations outside the knowledge-base, there are some basic numerical computations that can be performed in OPS5 by use of the "compute" function. OPS5 was designed to represent expert knowledge via rules, and it would not be efficient to use OPS5 as a number crunching code (the external subroutines are well suited for this purpose).

The function of the rule interpreter or inference engine is to match working memory elements with rules. This process is referred to as a "recognize-act cycle." Sets of working memory elements which match a rule are selected to form a "conflict set." This set of working memory elements is called "instantiations."

Newly created working memory elements are identified from old WME by placing a "time tag." A time tag is a number associated to all WME that indicates the time of its creation [114]. OPS5 contains two "conflict resolution strategies" for the selection of the most likely match or "instantiation" which resides in the conflict set. One is called lexicographic-sort (LEX) and the other is referred to as the means-ends-analysis (MEA) strategies.

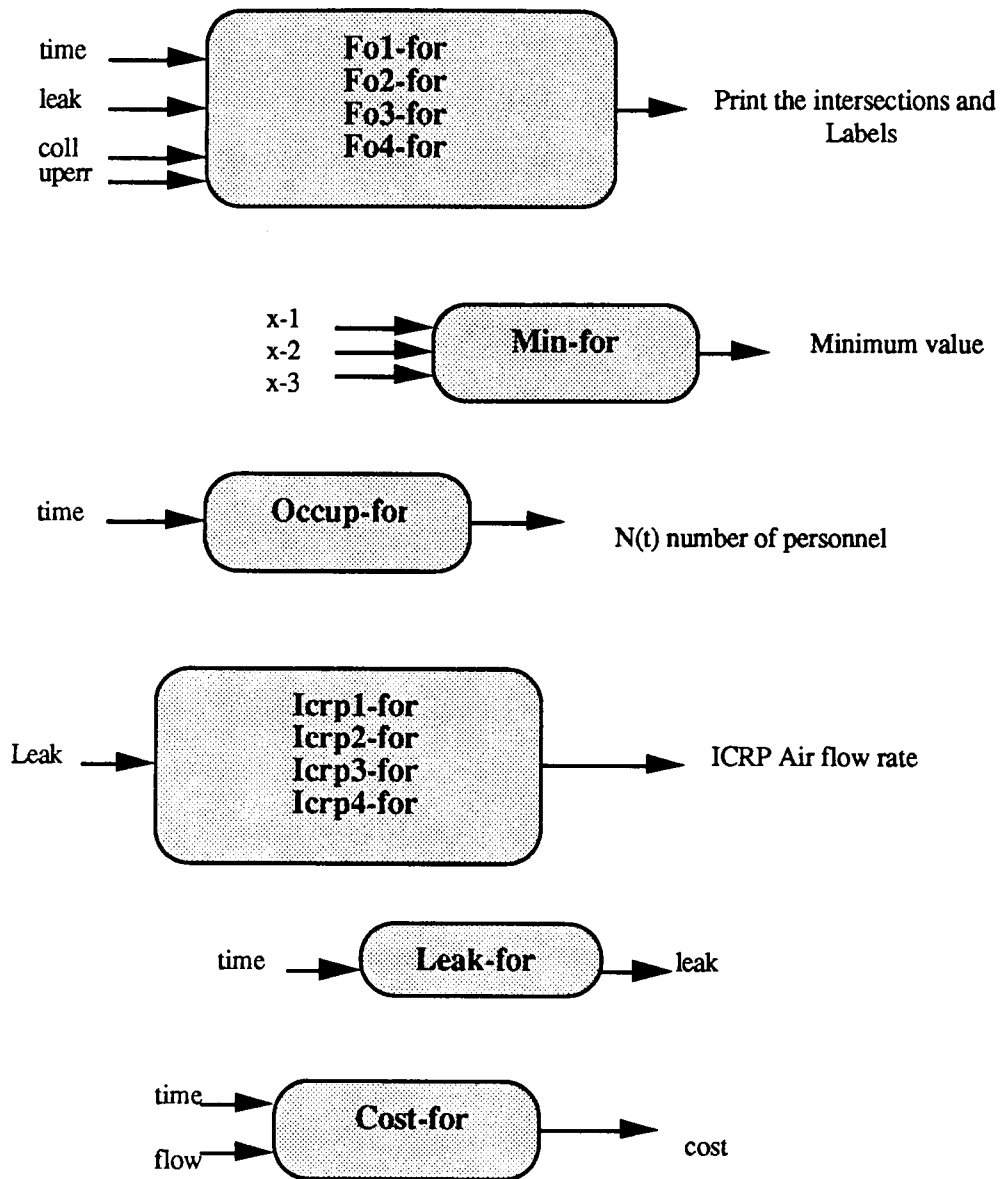


Figure 5.4 Integer function variable interchange.

Without giving further details about the conflict resolution, the criteria of these two strategies is based on refraction, recency, and specificity (details can be found in reference 89). RAD makes use of the MEA conflict resolution method, because it contains additional steps in the solution process that favors recency, and it is more suited for large codes that analyze continuously changing data. When an instantiation is selected, an action or "act"



executes all the commands on the RHS of the rule. The main mode of control in RAD is what is referred to as the "pop-subtask" method, which consists of removing all the working memory elements after each cycle [76]. The conflict resolution strategy selects one rule. The action of the rule in turn determines the prescribed air flow.

An advantage of OPS5 is the flexibility it allows in directing tasks to different rule clusters for different subtasks functions. The rules are applied to the data which produce an air flow rate that represents the defuzzify value from the fuzzy algorithm fuzzyf-for. The subroutine leak-for simulate leakage as a function of time. Figure 5.5 shows the leak model selected for this problem. The leak produces a dose rate and dose, which increase or decrease according to the leakage and air flow. This is what makes RAD a dynamic program because it prescribes the air flow according to its knowledge base. Here an integer function provides a simulated leakage rate; however, this leakage rate could be supplied from monitor sensors. The same applies to the subroutines comp1-for, comp2-for and comp3-for in which dose rates are calculated.

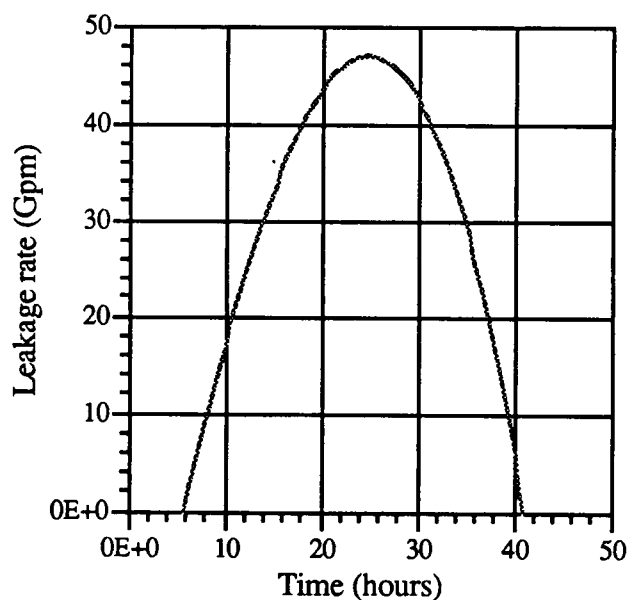


Figure 5.5 Leakage rate as a function of time.

### 5.4.1 RADIOLOGICAL FUZZY ALGORITHM

A radiological fuzzy algorithm is a set of instructions which contain fuzzy defined variables which, when evaluated, result in an approximate solution to specified problem. In general conditional fuzzy statements are conditional expressions that relate fuzzy variables that are of the form: if A (antecedent) and B (antecedent), then C (consequent). Where A , B and C are given a meaning in fuzzy set theory that defines the range in which that meaning is applicable [77][31]. A set of rules or "rules of thumb" that encode instructions of operation of a specific task about a system constitutes a fuzzy algorithm. Fuzzy algorithms can be used to describe complex behavioral systems which are difficult to understand and assess [31]. Conditional fuzzy rules is used in the fuzzy expert system, whose purpose is to control, maintain, regulate desired air flows by monitoring state variables, and making adjustments according to the fuzzy algorithms. **Dose rate**, **leakage**, and **collective dose** are the state variables, and air flow is the control variable.

The function of the heating, ventilation, and air conditioning system is to control radioactivity levels by increasing or decreasing the air flow. Instructions about the operation of the air flow can be describe in rules. These rules reflect a precise description of control. The linguistic terms used in these rules may be vague and imprecise or fuzzy in nature. The expert knowledge can be expressed in "rules of thumb," for instance:

1. If **radioactive leakage** is *lower than expected*, AND **dose rate** is *low*, AND **dose** is *low*, THEN the **air flow** should be *below normal*

These rules represent knowledge about the operation. Figure 5.6 illustrates the membership functions used for this analysis. The accuracy of the knowledge base depends highly on the accuracy of the knowledge acquisition. This knowledge should reflect the control of a system, and knowing how to control systems obviously requires understanding [11]. Therefore, the shape and value of the membership function depends upon an expert's knowledge which in turn reflects the understanding of the system.

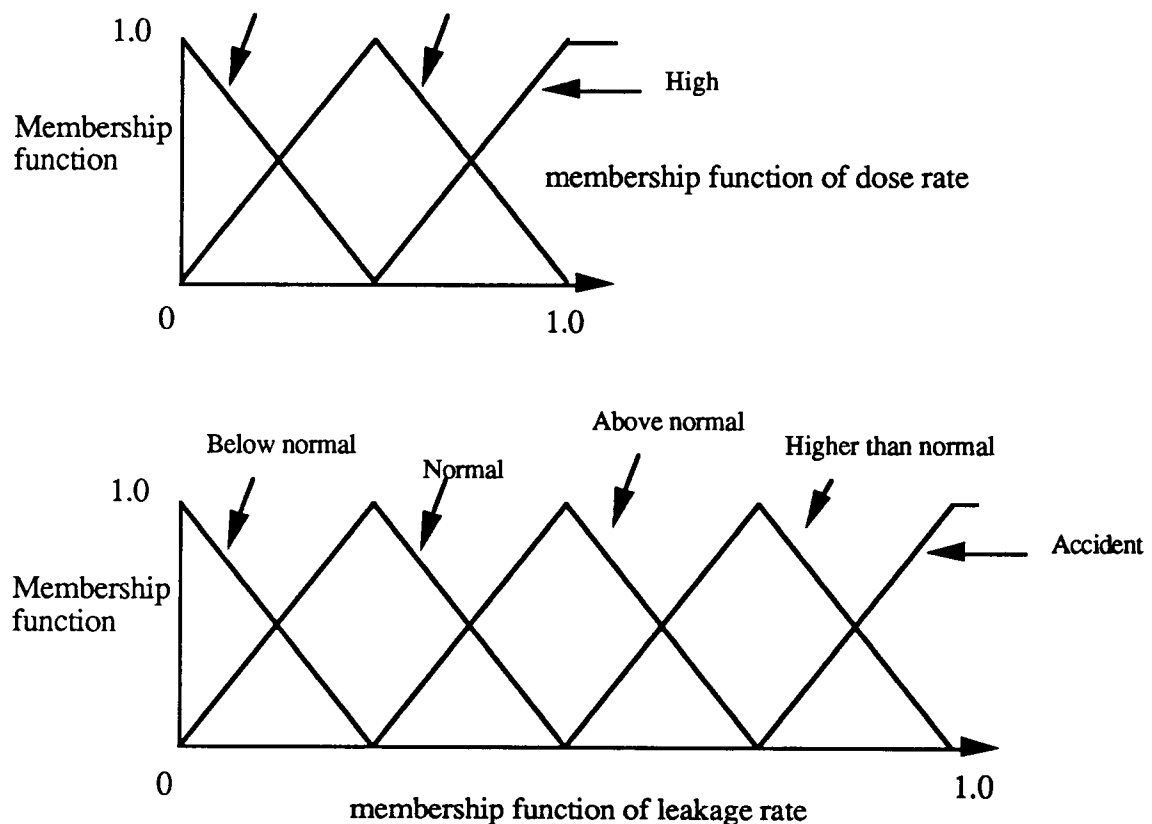


Figure 5.6 Membership function of leak rate and dose rate.

The amount of radioactive contamination determines the dose rate in a given compartment, which in turn determines access to the compartment. The dose rate also

determines integrated doses to personnel entering the compartment. In this situation there are three state variables that dependent on the value of the air flow, because air flow reduces radioactivity concentrations. The fuzzy algorithm can be represented as a cluster of fuzzy conditional statement. The rules analytically model the relationship between the variables that influence radiation protection.

The set of rules that characterize the operation of air flow approximates a desired optimal operation (A copy of the expert system RAD is in Appendix). The important feature of this approach is that the "rules of thumb" dictate a specific operation or air flow when fuzzy variables are defined with their corresponding membership functions. A fuzzy algorithm of this type provides a way to handle mathematically linguistic vagueness when describing a complex process with multi-fuzzy variables.

The expert system RAD was designed to demonstrate the approach introduced in section 4.3. This expert system analyzes data obtained from the subroutines. Simulated data such as leak and occupancy are evaluated by the fuzzy algorithm. The defuzzification process of the resulting prescribed flow is obtained by finding the centroid of the total flow. The total flow is the collection of truncated fuzzy flows after all applicable rules have been evaluated. A truncation point is determine by the type of connector in the fuzzy algorithm, **AND** selects the minimum of the three degrees of membership, and **OR** selects the maximum degree of membership. The value being selected truncates the corresponding shape of the fuzzy flow [31] [44] [48] [51]. A rule is applied only if incoming data falls into the category required by the rule. Once all applicable rules have been evaluated, the defuzzification of air flow (control variable) is found. This methodology is applied for every new string of data , and only those rules that apply yield results.

### 5.4.2 ICRP IMPLEMENTATION

This section outlines the method by which the cost benefit analysis (introduced in chapter 3) is used by RAD to obtain optimum air flow rates when cost is taken into consideration. According to section 3.6 of the *ICRP-37* methodology seems to be justifiable if the costs of radiation protection are comparable to the detriment costs. This type of analysis can be made if there is a cost incurred in radiation protection to improve the radiological environment which is comparable to the resulting equivalent detriment cost. The collective dose and cost are calculated in each compartment accordingly. The methodology used to obtain the optimum air flow is described in section 3.7. The collective dose results from entering a cubicle of the model with occupancy requirements as described in figure 5.7. Before cost benefit was applied the air flow passing through the room is at a normal rate, and there is no cost involved in radiation protection.

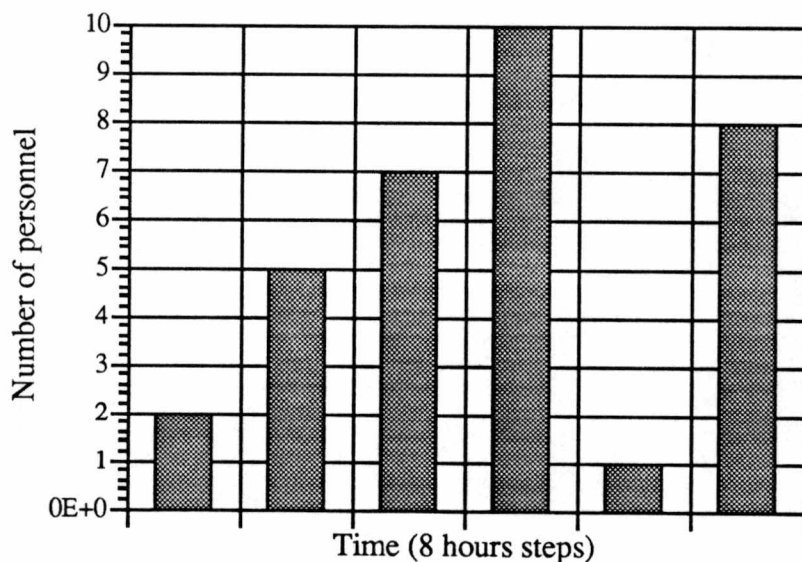


Figure 5.7 Occupancy requirements as a function of time.

Cost benefit analysis is applied when the air flow is increased. The increase in air flow induces a corresponding cost in radiation protection. The resulting collective dose is reduced. The detriment can also be estimated because the value of the collective dose is known. Note that the collective dose is dependent on the occupancy requirements  $N$  and is given by the subroutine occup-for. On the other hand, the cost function is composed of all costs incurred to reduce dose rates. The subroutine icrp-for provides a model of cost which includes: operational cost, maintenance cost, cost of all additional protective equipment and all the unexpected costs. The cost functions for first, second, and third cubicle models are prescribed by equations (3.6), (3.7) and (3.8), and explained in section 3.4. The operational cost represents the cost of running the HVAC system (electricity consumption).

The optimum air flow is obtained by taking the derivative of the detriment and cost function with respect to the air flow, setting them equal to each other, and solving for the air flow. The optimal value is reached at the lowest point of the sum of cost and detriment. This analysis is performed for a constant leakage. According to ICRP methodology one can estimate an optimal value of air flow for every leakage increase. A different air flow corresponds to each leakage at each time step. There is one allowable air flow for a given leakage. If leakage changes so does the allowable air flow.

The subroutine icrp-for is integrated into the RAD program which estimates the optimum air flow at each leakage increase. The optimal point is found by assuming that leakage is constant at a given time step. The collective dose is calculated assuming the occupancy requirements as given by occup-for, figure 5.7. In improving the radiological environment, a cost must be incurred due to the protective measures taken.

### 5.4.3 DESCRIPTION OF SUBROUTINES

The purpose of the subroutines is to generate numerical data that represents a decreasing or increasing air flow rate, as well as leak rate in the compartment model. The subroutine comp-for calculates the concentration as a function of time in a selected cubicle. In addition to the isotopic concentrations, the external subroutines calculate the dose rates, collective dose, cost, and detriment at each time step.

Figure 5.8 shows the overall program structure, the individual subroutines, and functions used by RAD. This program analyzes the simulated pipe rupture given by the subroutine leak-for. Production rules in RAD are applied to the transient data provided by leak-for. These rules try to prescribe the air flow according to the knowledge encoded into the rules. The prescribed air flow is different from the allowable air flow predicted by icrp-for. The ICRP air flow rate corresponds to the air flow that comes from balancing predetermined costs functions and detriment.

Fuzzy rules or fuzzy conditional statements are used to analyze the radiological environment in the compartment model. The subroutines that obtain the degree of membership for the leak, dose rate and dose are fuzzyl-for, fuzzydr-for and fuzzyd-for correspondingly. The subroutines provide a "label" or name and the grade of membership that corresponds to the crisp values of each variable.

The program RAD passes crisp values to the subroutines. For instance, to obtain the degree of membership of the dose rate, RAD first obtains the dose rate from the subroutine comp-for, then it passes it to fuzzydr-for.

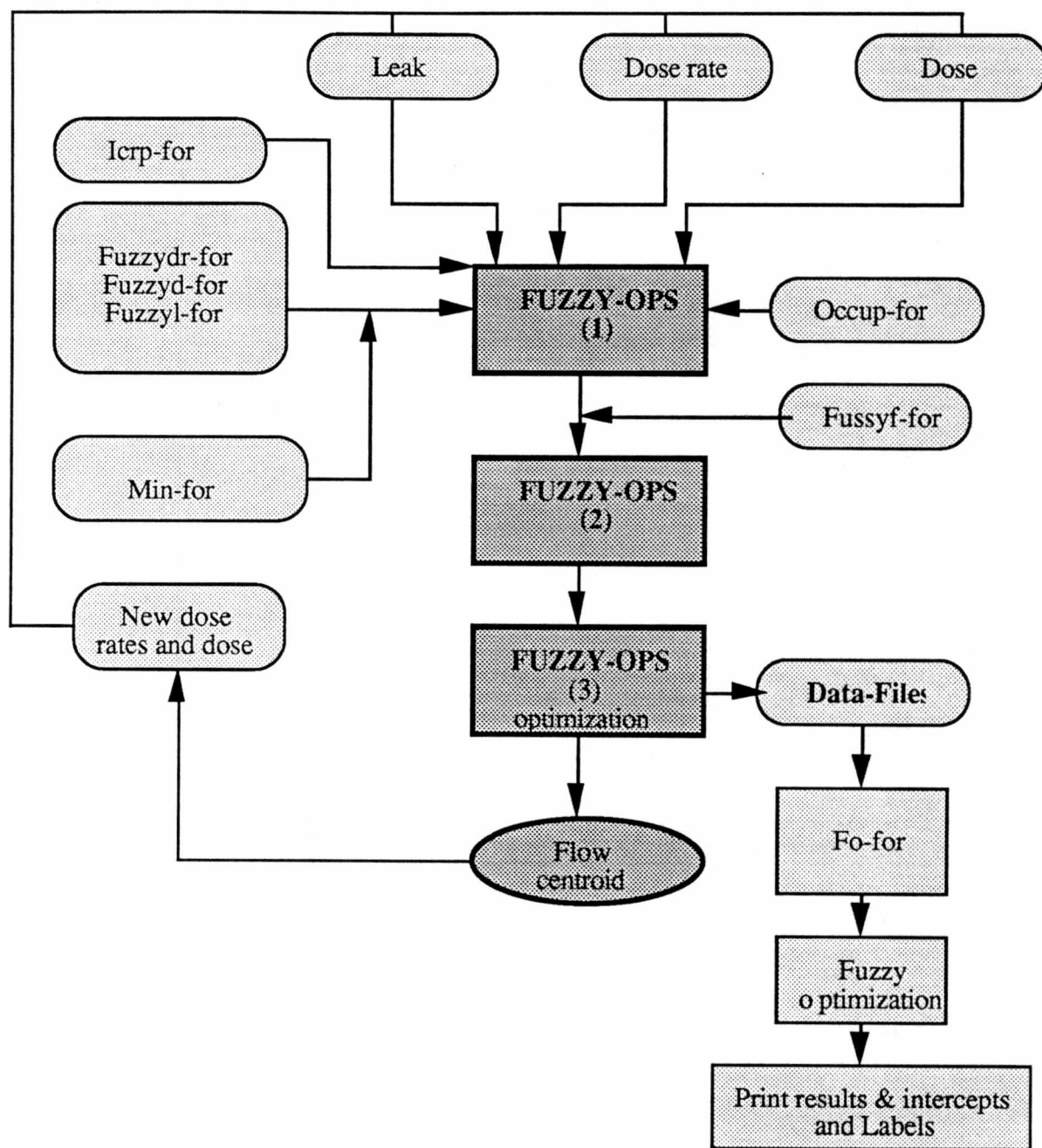


Figure 5.8. Subroutines interfaced with RAD.



The subroutine icrp-for is integrated into the RAD program by estimating the optimum air flows. As new data becomes available, the rules apply accordingly. The environment will change as the leak changes (increase or decrease). A fuzzy prescribed air flow rate is obtained when the rules are applied to the transient data. Leakage and occupancy data is supplied to the program which in turn is used by the applicable production rules so that conclusions can be drawn as indicated in figure 5.9. The rules relate those variables which influence the control variable.

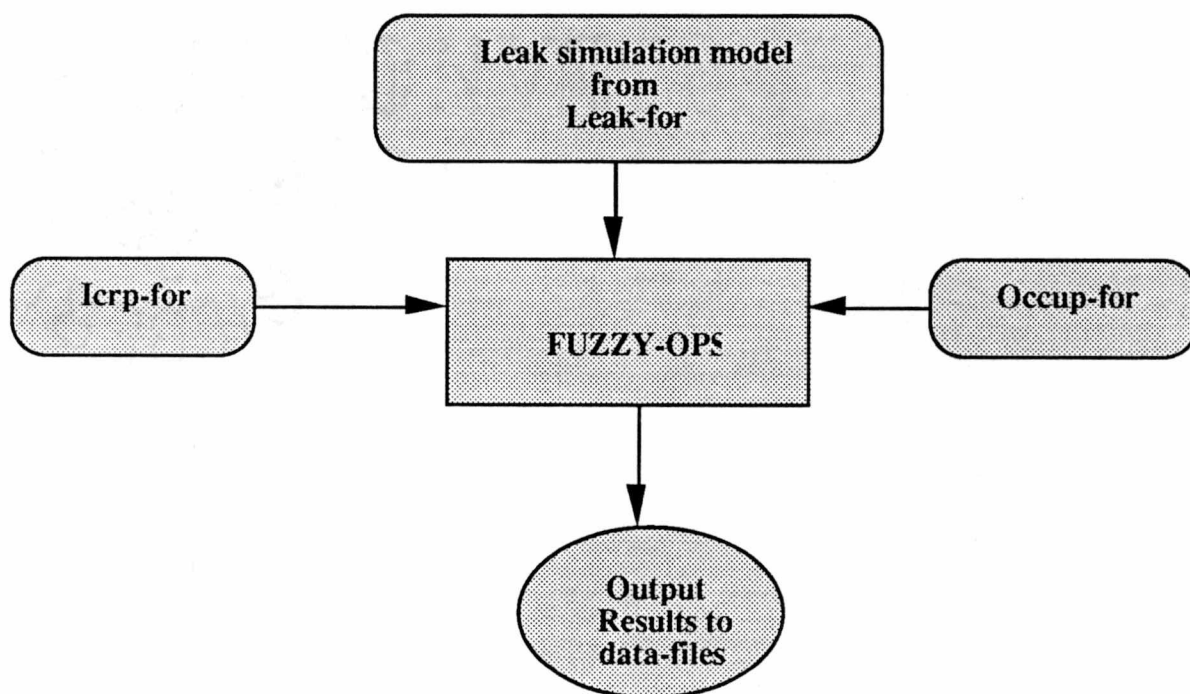


Figure 5.9. Subroutine simulation models.

The external subroutines: comp1-for, comp2-for, comp3-for, comp4-for are written in FORTRAN to calculate the concentrations and dose rates as a function of time. The data about specific states can be deleted and added to reflect the transient generation of new

information. The leak-for subroutine provides a leak at each time step, and occup-for subroutine provides the occupancy as shown in figure 5.9.

Finally the min-for subroutine obtains the minimum value of the degrees of membership functions passed from the RAD program to obtain the prescribed air flow.

#### **5.4.4 EXPERT SYSTEM ASSUMPTIONS**

The radiological assessment is performed by a simulation of a radioactive pipe rupture accident at a nuclear power plant. In order to model the rupture, the following assumptions were made:

1. Immediately after the pipe rupture, access is required in the contaminated cubicle (given by the subroutine occup-for).
2. The dose rates were estimated from the airborne concentrations of I-131 gamma sources only. A more realistic dose will reflect the contribution of various other sources (i.e. airborne from additional isotopes, radioactive piping), as well as sources accumulated in the water, collected on the floor, and additional sources due to the radioactive liquids in the piping going through the room. These three last components were not taken into account.
3. A partition factor of 10% is assumed for I-131 (i.e., the partition factor is the percentage of radioactivity in the water that becomes airborne).
4. It is assumed that the airborne contamination becomes uniformly distributed immediately after it comes in contact with the room's atmosphere.

5. It is assumed that due to the severity of the accident, there is a high cost incurred on radiation protection. This cost is assumed to be a function of air flow as given by equations 3.6, 3.7 and 3.8. When the harshness of the environment becomes unacceptable, the air flow increases and, so does the cost of radiation protection.

6. The operational cost is given by equation 3.1. This cost is a function of **b**, the energy per unit volume capacity of the HVAC and the time **T** of operation.

### 5.2.5 EXPERT SYSTEM RULE-BASE

The following rules are part of the expert system RAD rule-base presented in Appendix. These rules were obtained from table 4.1 by relating the fuzzy variables of leak rate, dose rate, and collective dose with the control variable air flow. These rules represent the fuzzy algorithm described in section 5.1.2. These rules directly relate leak rate to air flow only, however, RAD rule-base includes not only this cases but all the other modes of the desired operation which relate the variables described in table 4.1.

1. If **radioactive leakage** is *lower than expected* AND **dose rate** is *low* AND **dose** is *low* THEN the **air flow** should be *below normal*

2. If **radioactive leakage** is *as expected* AND **dose rate** is *medium* AND **dose** is *medium* THEN the **air flow** should be *normal rate*.

3. If **radioactive leakage** is *higher than expected* AND **dose rate** is *medium* AND **dose** is *medium* THEN the **air flow** should be *higher than normal*

4. If radioactive leakage is *higher than expected* AND dose rate is *high* AND dose is *high* THEN the air flow should be *high*.

5. If radioactive leakage is *high* AND dose rate is *high* AND dose is *high* THEN the air flow should be *at the accident level*

## 5.5 MATHEMATICAL IMPLEMENTATION

In order to obtain the dose rate at each time step, the isotopic concentration was calculated from the equations:

$$c_1(t) = \frac{x_1}{v_1} = L c p \frac{(1-e^{-at})}{q} \quad (5.1)$$

$$c_2(t) = k \frac{x_2}{v_2} = \frac{L c p}{q} (1 - e^{-bt}) + k \frac{L c p v_1}{(v_1 - v_2) q} (e^{-bt} - e^{-at}) \quad (5.2)$$

$$c_3 = k \frac{v_1 v_2 L c p}{(v_1 - v_2)(v_2 - v_3) q} (e^{-bt} - e^{-ct}) + k \frac{(L p c)}{q} (1 - e^{-ct}) + k \frac{v_1^2 L c p}{(v_1 - v_2)(v_1 - v_3) q} (e^{-ct} - e^{-at}) \quad (5.3)$$

where,  $c_1(t)$  = concentration of the airborne on the first compartment,

$c_2(t), c_3(t)$  = concentration in the second and third compartment,

$L$  = leak rate in the first compartment ,

$p$  = partition factor

$k$  = conversion factor

$v$  = volume of room ,

$q$  = flow out of compartment ,

and

$$a = \frac{q}{v_1}, b = \frac{q}{v_2}, c = \frac{q}{v_3}$$

Comp1-for is used to perform the mathematical computations to obtain the isotopic concentration and provides data to support transient analysis.

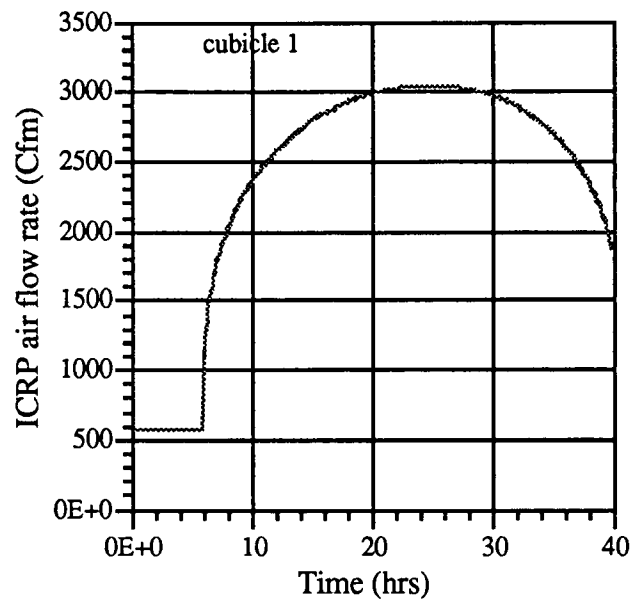
## CHAPTER 6

### RESULTS

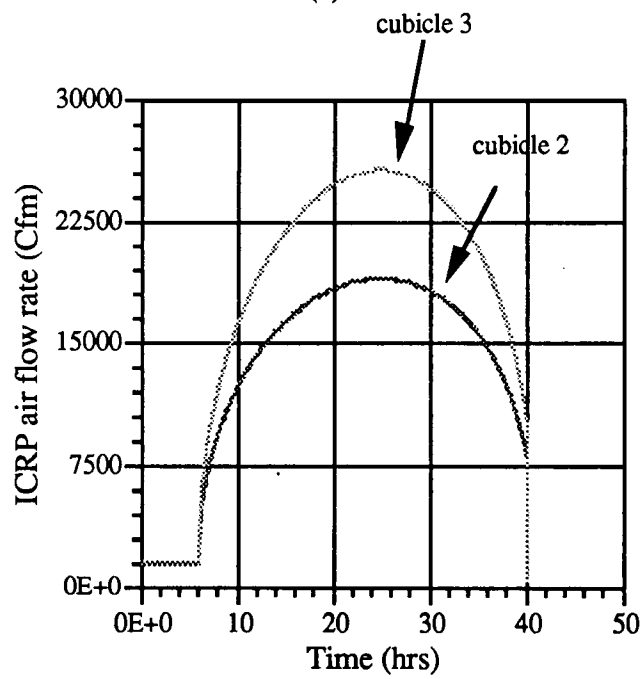
#### 6.1 RADIATION OPTIMIZATION RESULTS

The cost benefit analysis introduced by the International Commission on Radiation Protection has served as a reference in the definition of reasonable costs. The air flow rate obtained from applying the cost benefit analysis results in an allowable air flow rate (or ICRP air flow) when the radiation protection cost function is taken into consideration. Figure 6.1 shows the ICRP air flow rate as a function of time at each compartment. The ICRP air flow rate is less in the first compartment and increases in the second and third compartments, figure 6.1 (b) ; in all cases the allowable air flow also increases or decreases according with the leakage increases or decreases. The reason for the increase of the ICRP air flow rate in the second and third cubicles is because the dose rate decreases (according to equations 5.1, 5.2 and 5.3). As a result of this, the collective dose is also less in the second and third cubicles.

Based on these results, the following observations can be made. The radiation protection cost and operations costs increase as the air flow increases. The value of  $\alpha = \$100$  per man-rem was selected for this analysis because it results in minimum detriment cost. The effect of increasing  $\alpha$  from the low value of \$100 to \$1000 man per rem would bring about the following effect. When  $\alpha$  is increased from the low value to high, the total collective dose is reduced at any leakage level. It seems that a higher  $\alpha$  ensures lower total collective doses because higher air flows are obtained from cost benefit analysis.



(a)



(b)

Figure 6.1 ICRP air flow as a function of time for the second and third cubicles.

For a given  $\alpha$  or leakage increase, a higher air flow was reached to achieve optimum levels. This indicates that higher air flow results in higher costs. Yet when  $\alpha$  is high and leakage constant, it takes a higher air flow to reduce total costs. When leakage increases, the collective dose increases (the collective dose rate of increase starts high and starts to decrease as air flow increases); furthermore, if the collective dose is high, so is the detriment cost.

On the other hand, the fuzzy algorithm employed in RAD results in a prescribed air flow which reduces the collective dose by reducing the dose rate. Figure 6.2 presents the prescribed air flow resulting from applying the RAD fuzzy algorithm. The rule base in RAD was designed to decrease the collective dose by reducing the dose rate. As the pipe leakage starts to increase the airflow increases in an attempt to keep dose rates low. The resulting dose rates, as shown in figure 6.3, increase as pipe leakage increases, obviously not as high as if the air flow were not increased. The dose rate decreases in the second and third cubicles. The collective dose, presented in figure 6.4, resulting from the occupancy requirements of figure 5.7, decreases in the second and third cubicles.

Based on the resultant dose rate, one can conclude that the air flow should be able to reduce dose rate even further and make the contaminated environment more acceptable. This can be accomplished by modifying the rule base and the corresponding universe of discourse.

The resulting collective dose (man-rem), after the radiological assessment under this postulated accident, is about a third the average annual collective dose at many nuclear plants. This result depends on the rule base used in RAD which obviously can be modified to reduce the dose rate and make the compartment safer.



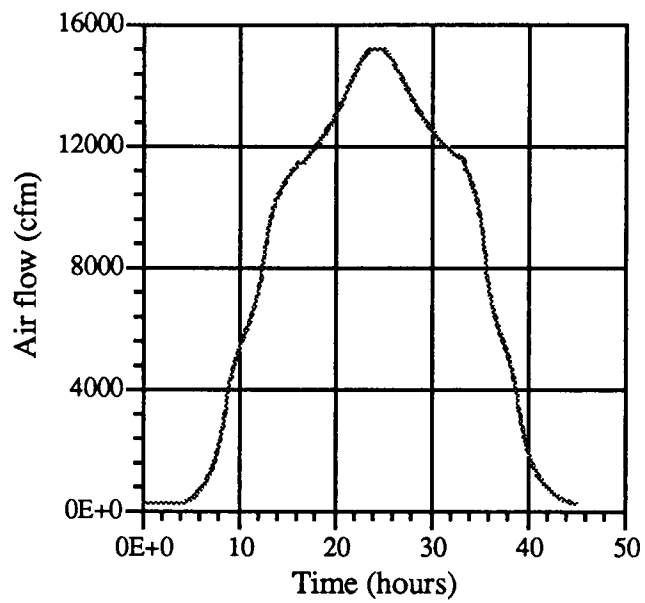


Figure 6.2 Prescribed air flow as a function of time.

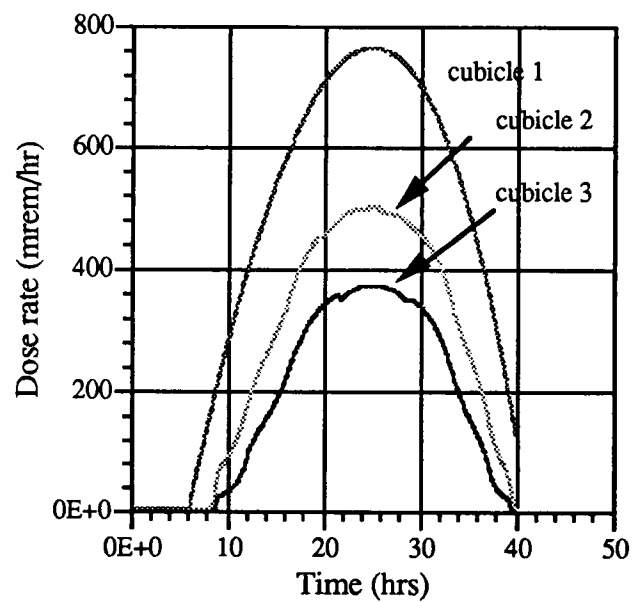


Figure 6.3 Dose rate as a function of time.

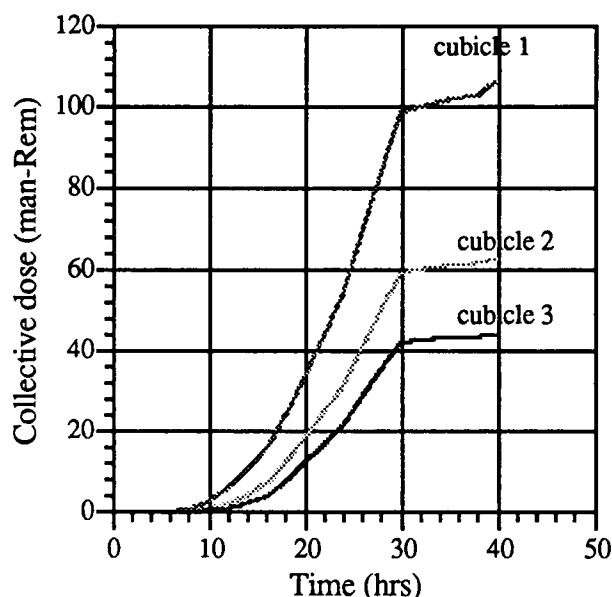
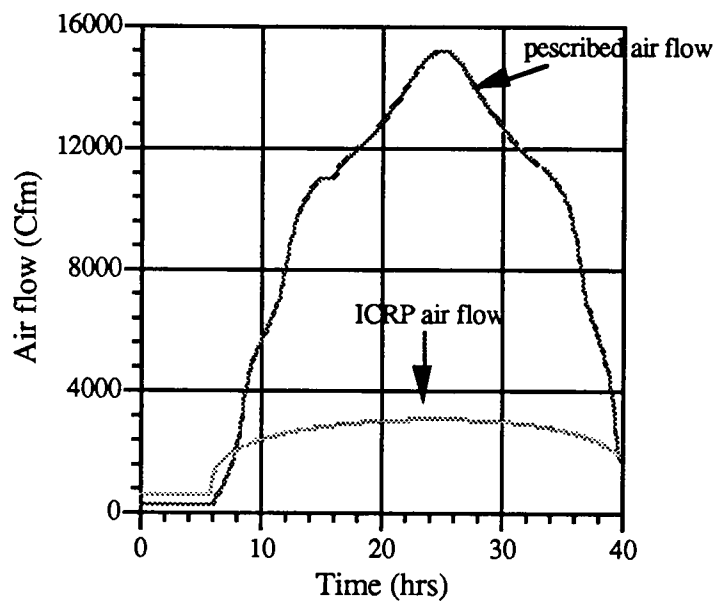
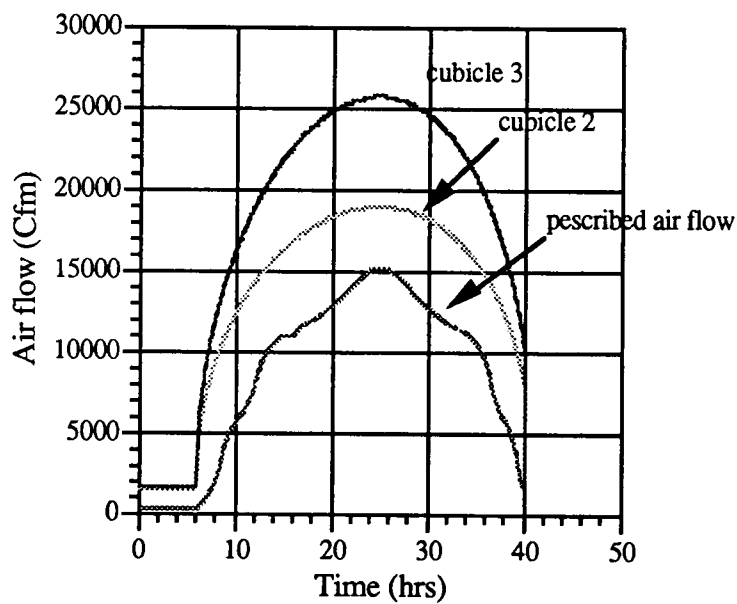


Figure 6.4 Collective dose as a function of time.

Based on this, the resulting ICRP flow rate for the first compartment is less than the prescribed air flow as illustrated in figure 6.5 (a). The reason for this is that the prescribed air flow does not consider radiation protection cost. Figure 5.6 (b) illustrates the comparison of the ICRP air flow in the second and third compartment; the increase is due to the reduced cost of radiation protection. The reduction of the collective dose and dose rate is the primary objective in the fuzzy algorithm. Whereas, the allowable ICRP air flow rate in the first compartment results from applying the radiation protection cost function of equations 3.2, figure 6.1. The radiation protection cost are less in the second and third compartments. This results in a higher allowable ICRP air flow in the second and third compartments as presented in figure 6.5 (b).



(a)



(b)

Figure 6.5 Comparison of ICRP air flow with the prescribed flow rate.

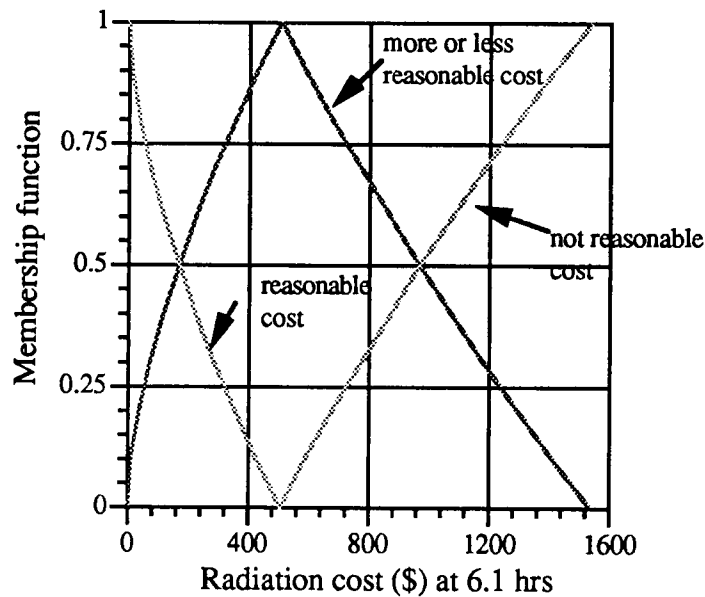
## 6.2 FUZZY RADIOLOGICAL RESULTS FOR THE FIRST CUBICLE

The parameterization procedure (introduced in section 4.4) was used to derive the membership function of cost, detriment, and dose rate. The concept of reasonable cost was as explained in section 4.3. The parameterization procedure, by use of the fuzzification of the "allowable ICRP air flow," derives the membership function from equations presented in sections 3.7 and 5.5. Since the total cost is a function of air flow, the fuzzification of the ICRP air flow subdivides three regions which represent the three concepts of cost: reasonable, more or less reasonable, and not reasonable. Therefore from the three regions of the allowable ICRP air flow three membership functions of cost and dose rate were derived.

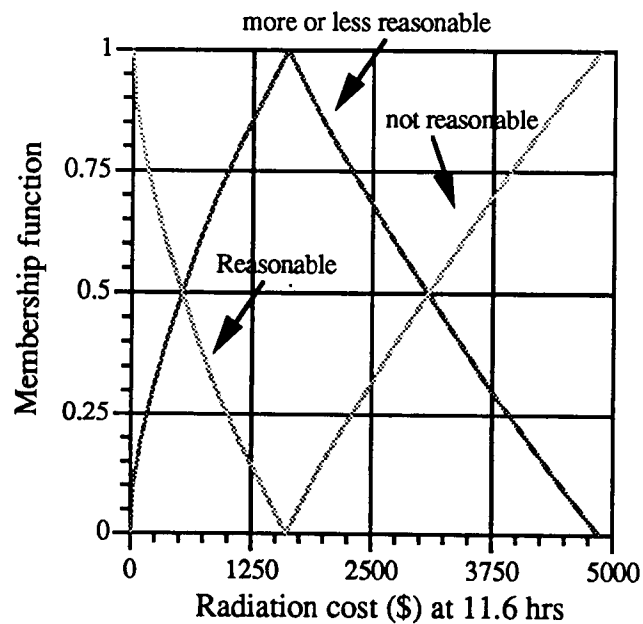
Figure 6.6 presents the derived membership functions of cost at various time intervals when the leakage increases, and figure 6.7 presents the results when leakage decreases. The ICRP air flow increases and decreases throughout the pipe leak, the three derived membership functions also increase and decrease. This effect is shown in the three dimensional figure 6.8. These figures show the elastic action reflected on the membership function of cost, as leakage increases with time on the x-axes. The universe of discourse also increases on the y-axes. The value of the membership function or degree of truth is shown on the z-axes.

More or less along the same lines, figure 6.9 presents the derived membership functions of dose rate at various times for the first part of the leak and figure 6.10 for the second compartment at various times. As in the previous results due to the ICRP reference

increases and decreases, the membership function of dose rate also increases and decreases as is shown in figure 6.11.

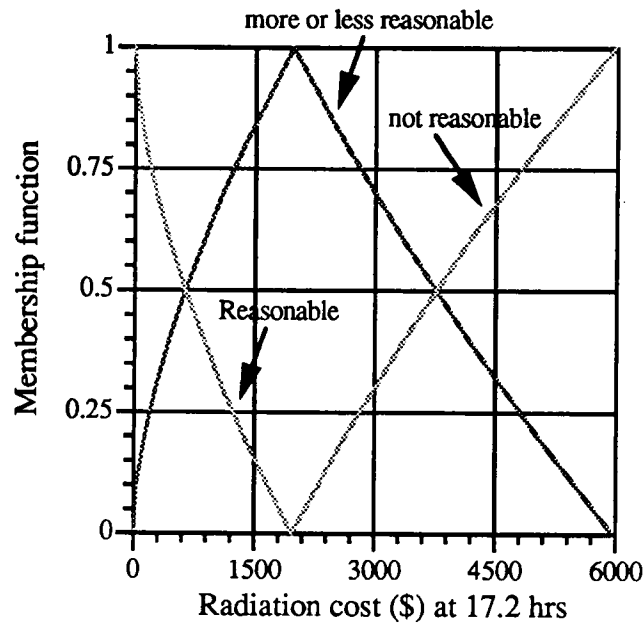


(a)



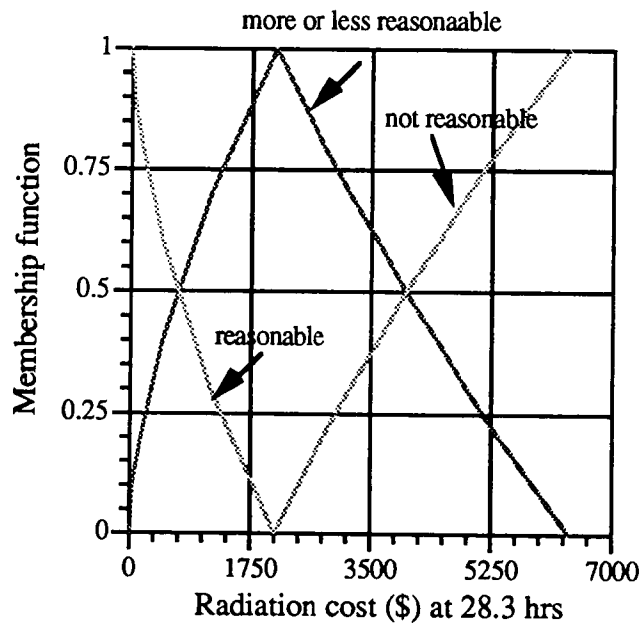
(b)

Figure 6.6 Cost membership functions as leakage increases.



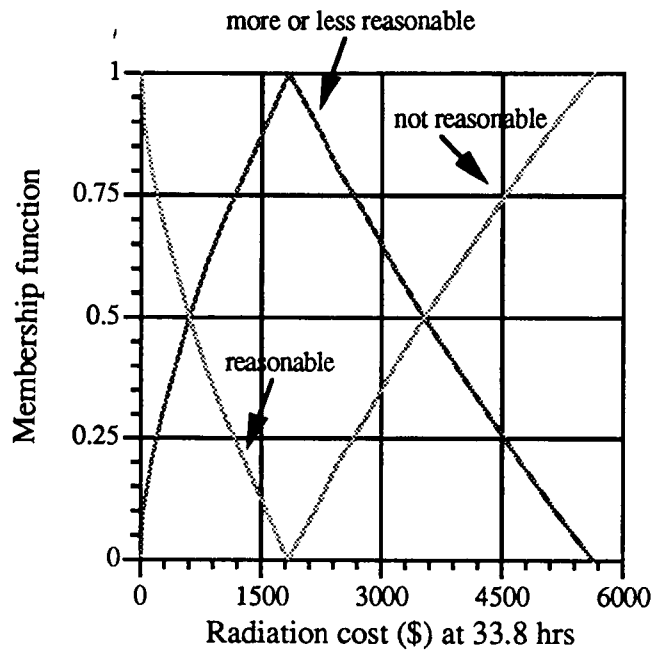
(c)

Figure 6.6 Cost membership functions as leakage increases (continued).

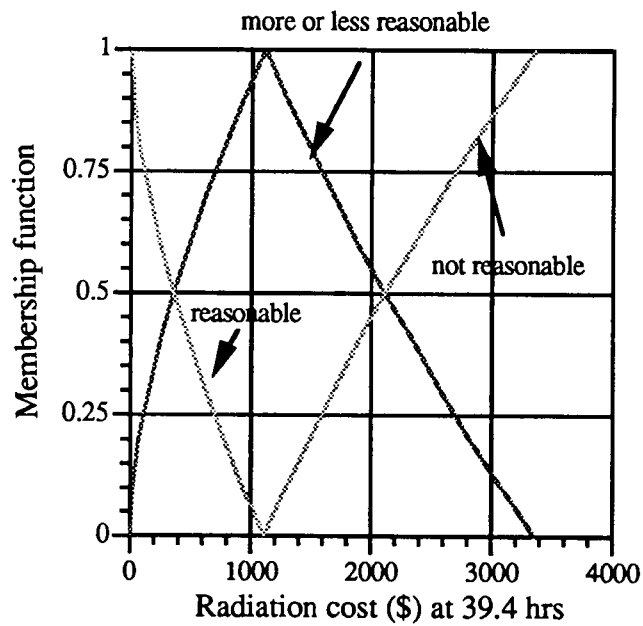


(a)

Figure 6.7 Cost membership functions as leakage decreases.

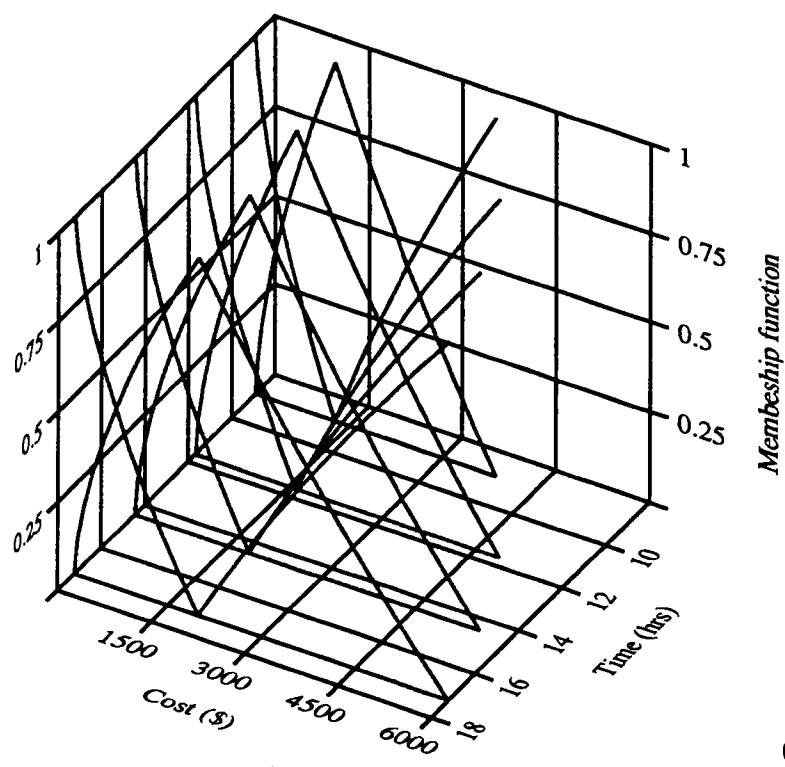


(b)

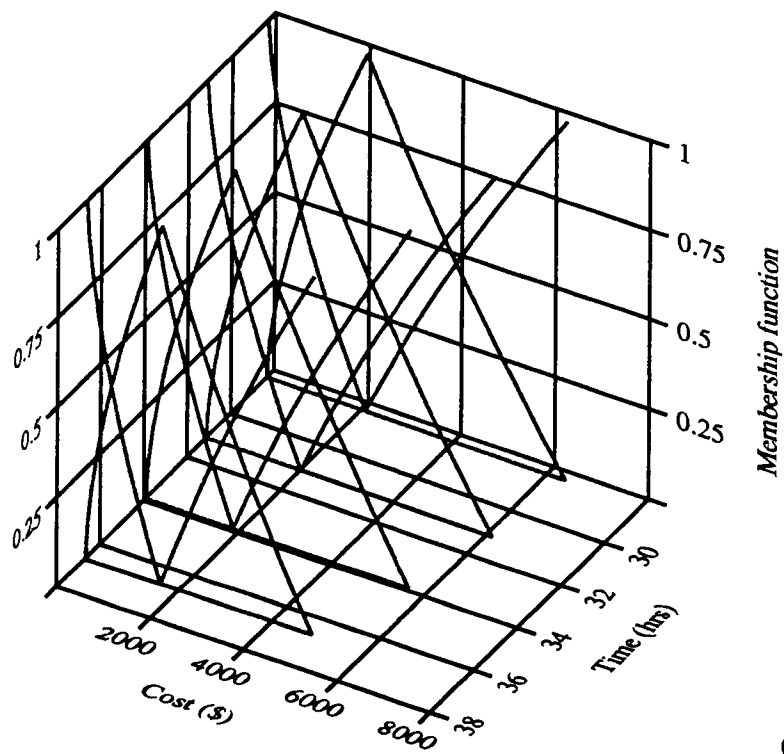


(c)

Figure 6.7 Cost membership functions as leakage decreases (continued).



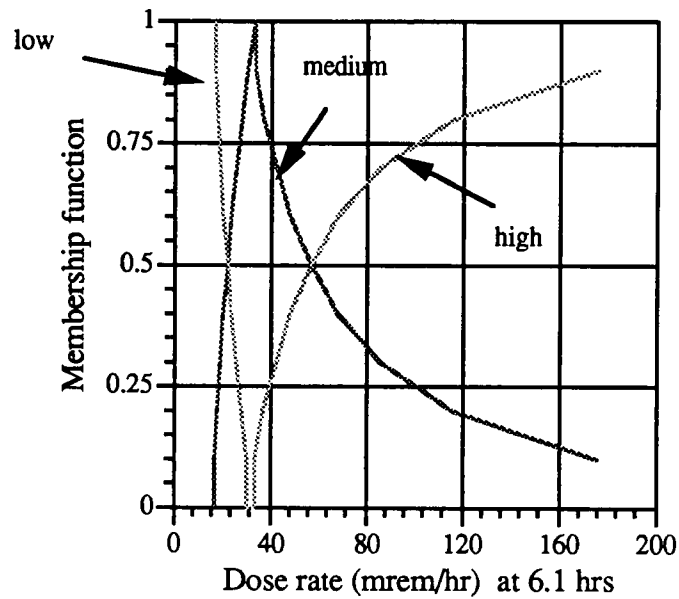
(a)



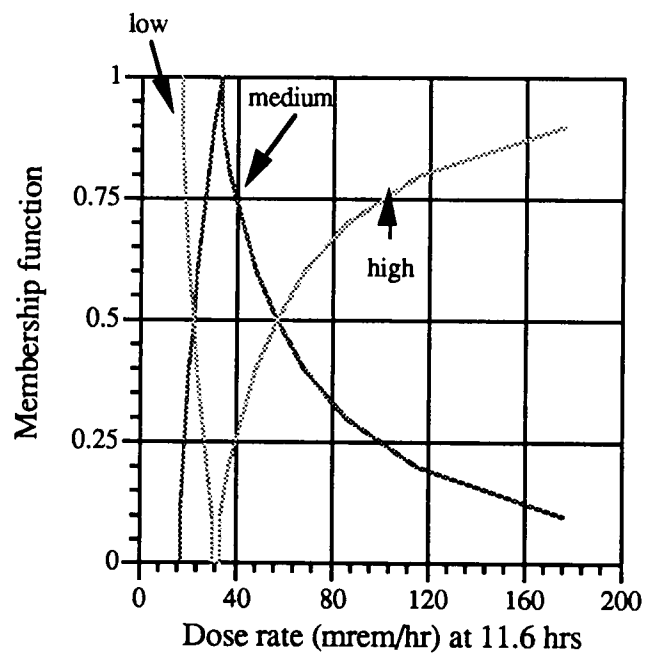
(b)

Figure 6.8 Three dimensional view of the cost membership functions as leak increases (a) and decreases (b).



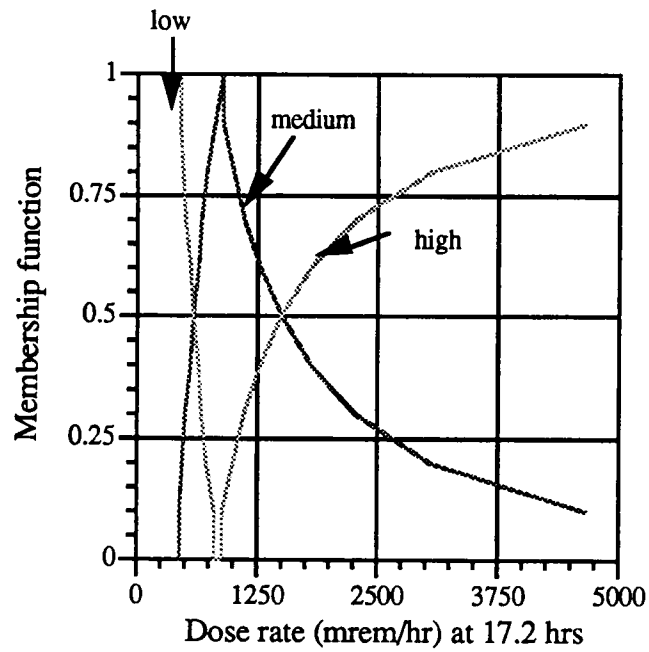


(a)



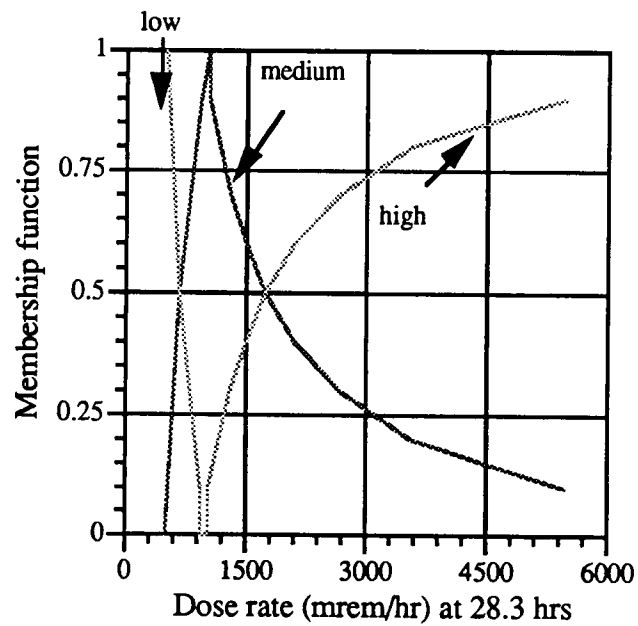
(b)

Figure 6.9 Membership functions of dose rates as leakage increases.



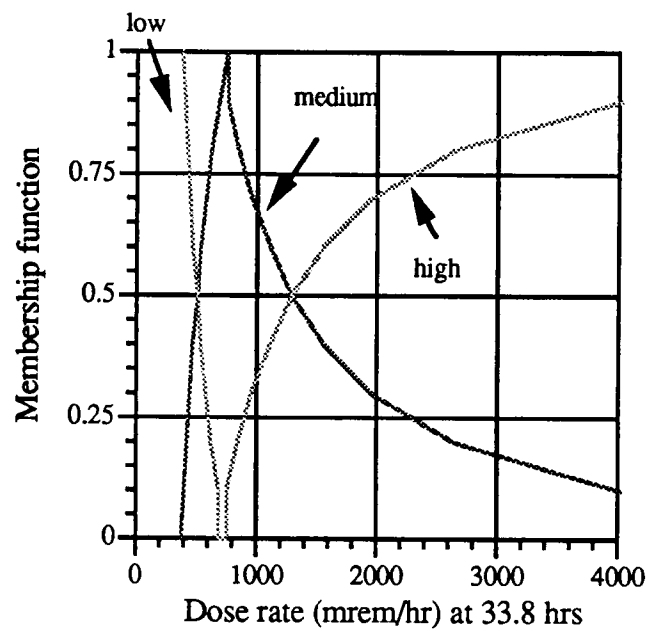
(c)

Figure 6.9 Membership functions of dose rates as leakage increases (continued).

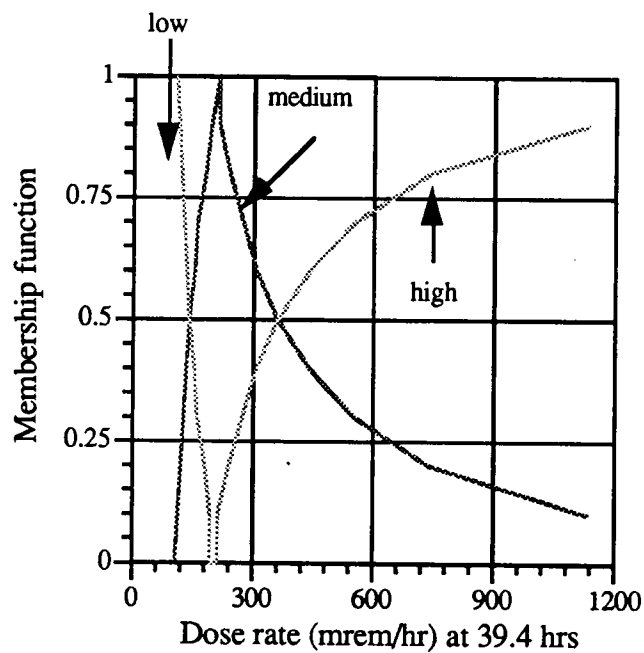


(a)

Figure 6.10 Membership functions of dose rates as leakage decreases.

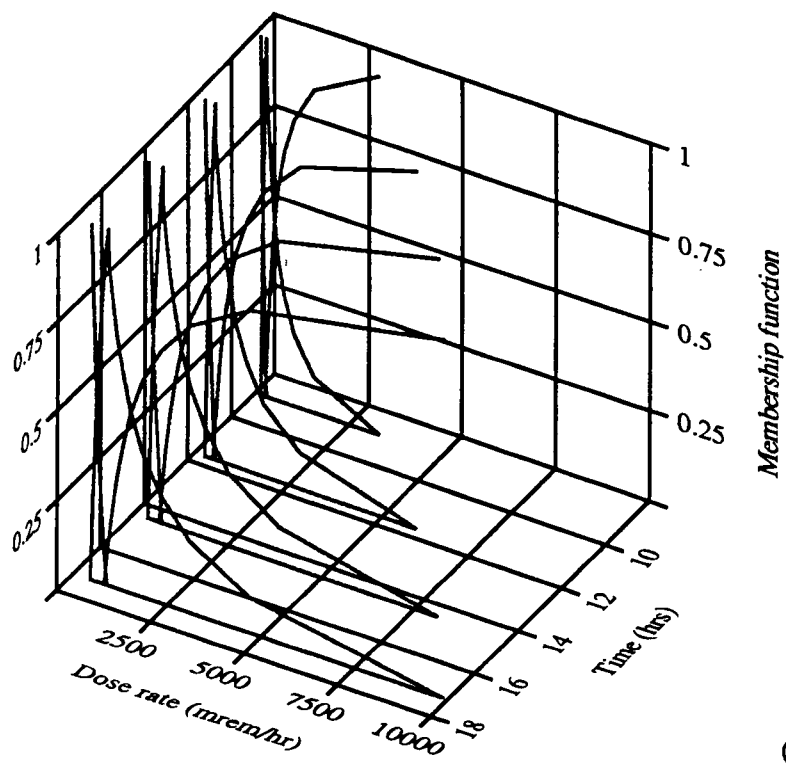


(b)

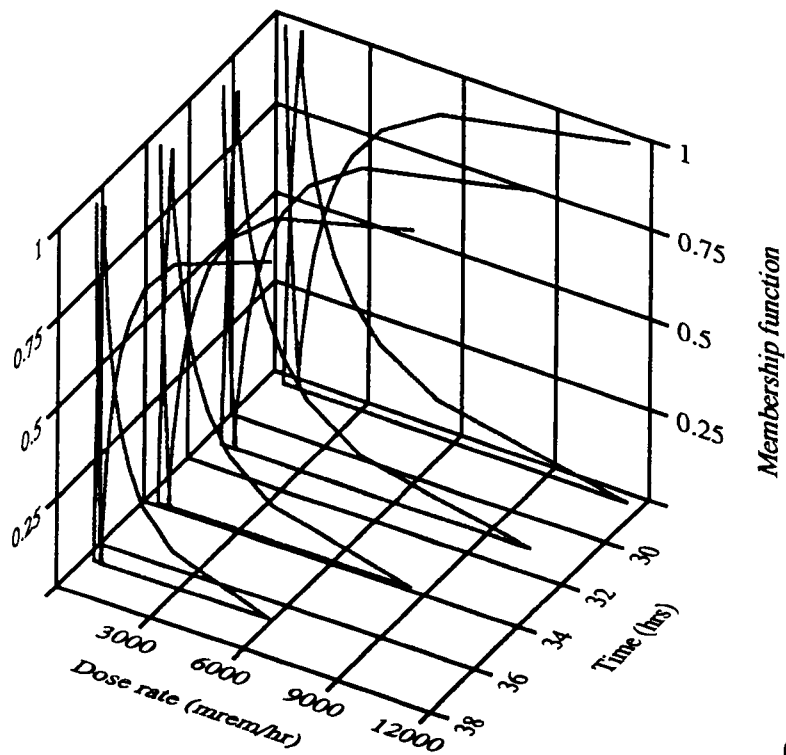


(c)

Figure 6.10 Membership functions of dose rates as leakage decreases (continued).



(a)



(b)

Figure 6.11 Three dimensional view of the dose rate membership.

For this case, however, the "reasonable" portion of the membership function can be distinguished and plotted to examine the change in degree of truth as a function of time. This is done for the purpose of finding the combined membership function of low dose rate and reasonable costs. The lines in figure 6.12 represent the "*low and reasonable dose rate*" for the first part of the leak and figure 6.13 when the leak decreases.

The data points in figure 6.12 and 6.13 were obtained by the parameterization process described in section 4.4. In order to represent this change mathematically, each membership function has been fitted by a natural logarithmic function. Table 6.1 shows the results of fitting all the membership functions as a function of time. The first part of these equations have the same form, and the second term represents the movement of the membership function as a result of the increase and decrease of leakage, as shown in figure 6.14.

As a consequence of this one can also find the equation which would fit the second term of the equation with a second degree polynomial. This approach leads to a final representation of the membership function of the "*low and reasonable dose rate*" as a function of dose rate  $x$ , and time  $t$ , equation 6.1:

$$\mu_{\text{low dose rate}}(x,t) = -1.446 \ln x - 0.01643 t^2 + 0.8206 t + 0.5178 \quad (6.1)$$

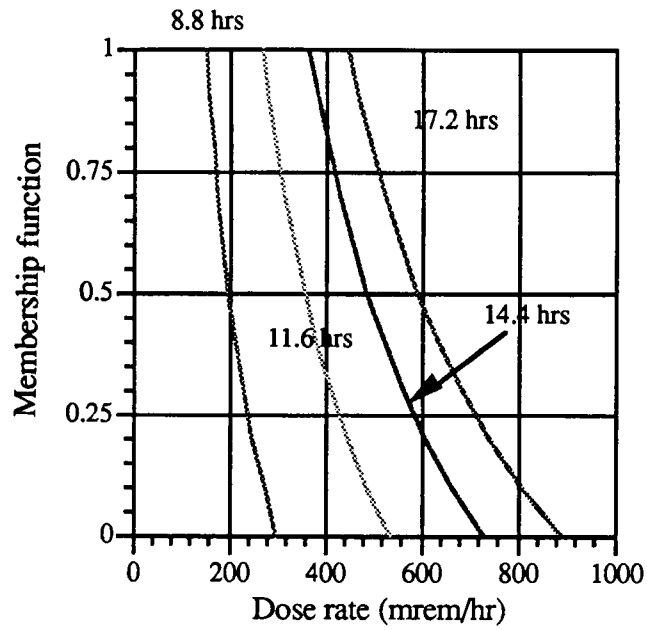


Figure 6.12. Membership functions of low and reasonable dose rate as leak increases.

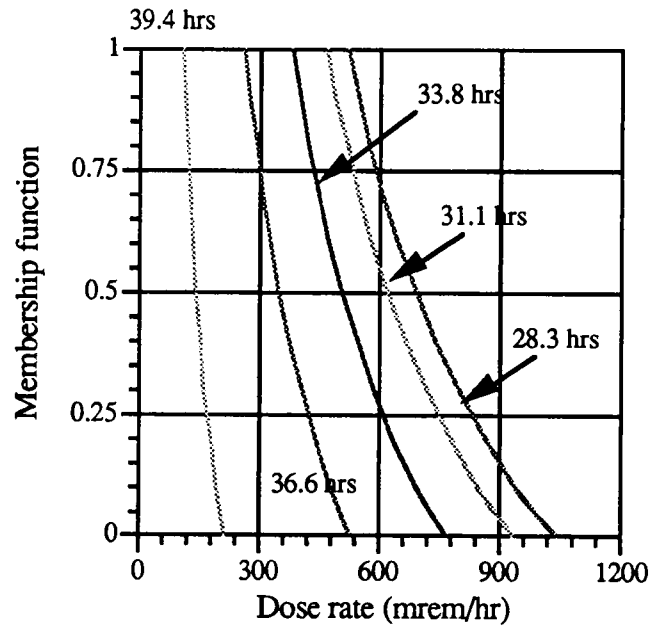


Figure 6.13. Membership function of low and reasonable dose rate as leak decreases.

Table 6.1 Membership function curve fitting results for a single compartment.

| Time (hrs) | Membership curve fitting $\mu$<br>of dose rate $x$ , in mrem/hr |
|------------|-----------------------------------------------------------------|
| 3.3        | - 1.446 $\ln x$ + 1.171                                         |
| 6.1        | - 1.446 $\ln x$ + 5.023                                         |
| 8.8        | - 1.446 $\ln x$ + 8.187                                         |
| 11.6       | - 1.446 $\ln x$ + 9.026                                         |
| 14.4       | - 1.446 $\ln x$ + 9.483                                         |
| 17.2       | - 1.446 $\ln x$ + 9.765                                         |
| 20.0       | - 1.446 $\ln x$ + 9.939                                         |
| 22.7       | - 1.446 $\ln x$ + 10.03                                         |
| 25.5       | - 1.446 $\ln x$ + 10.05                                         |
| 28.3       | - 1.446 $\ln x$ + 9.99                                          |
| 31.1       | - 1.446 $\ln x$ + 9.837                                         |
| 33.8       | - 1.446 $\ln x$ + 9.549                                         |
| 36.6       | - 1.446 $\ln x$ + 9.01                                          |
| 39.4       | - 1.446 $\ln x$ + 7.710                                         |

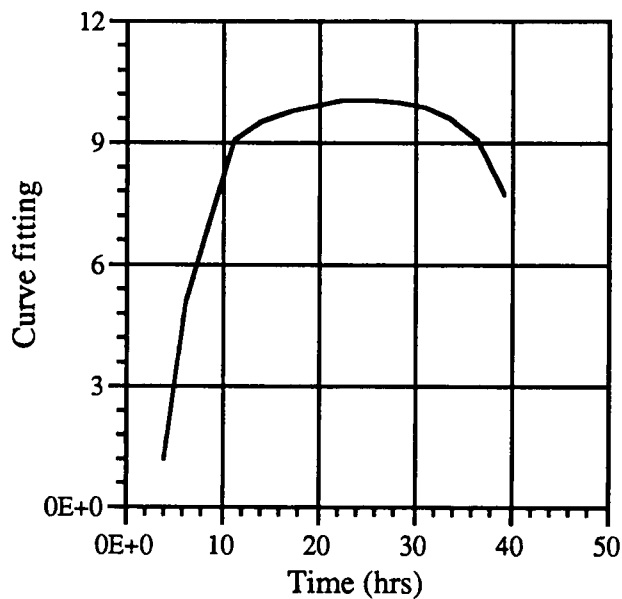


Figure 6.14 Membership function time dependence as leak increases and decreases.

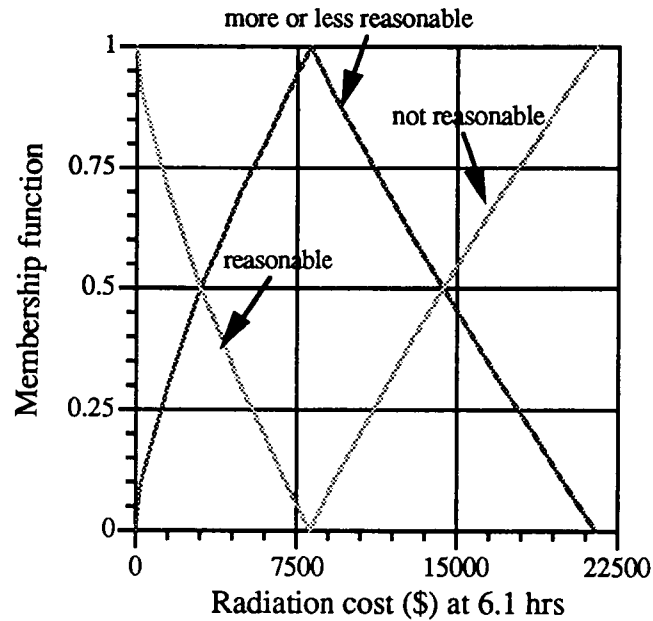
Although the same procedure can be performed to obtain the general equation of the membership function of cost and detriment, the primary objective of this research is to define and quantify reasonable cost and low dose rate. Furthermore, since the membership functions are derived by a parameterization procedure during the entire pipe leakage, one can also find the membership function for the three fuzzified variables, just as it was accomplished for the dose rate.

### 6.3 FUZZY RADIOLOGICAL RESULTS FOR THE SECOND CUBICLE

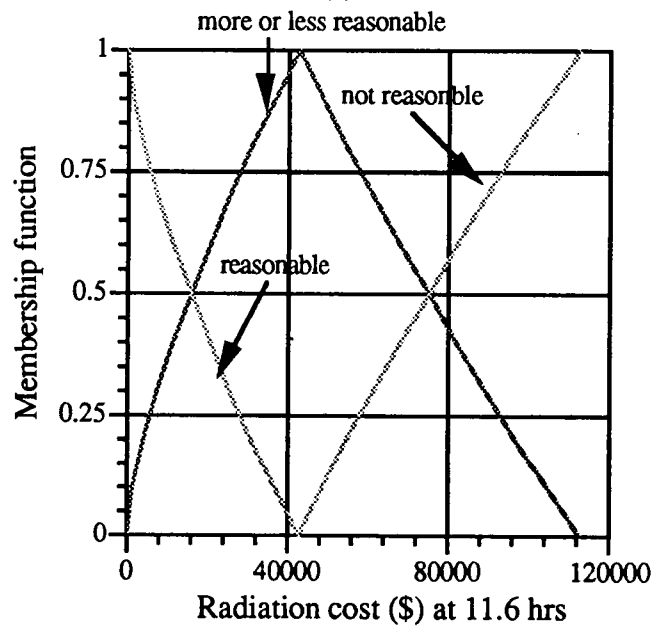
The following section (figures 6.15 through 6.22) presents the same results for the second compartment. The results have also been fitted by a logarithmic function and a polynomial function for the second term of the general equation. The first part of the equation has the same form as the first compartment. The second term of both equations



6.1 and 6.2 represents the increase and decrease of leakage which is reflected on the dose rate and cost membership functions.

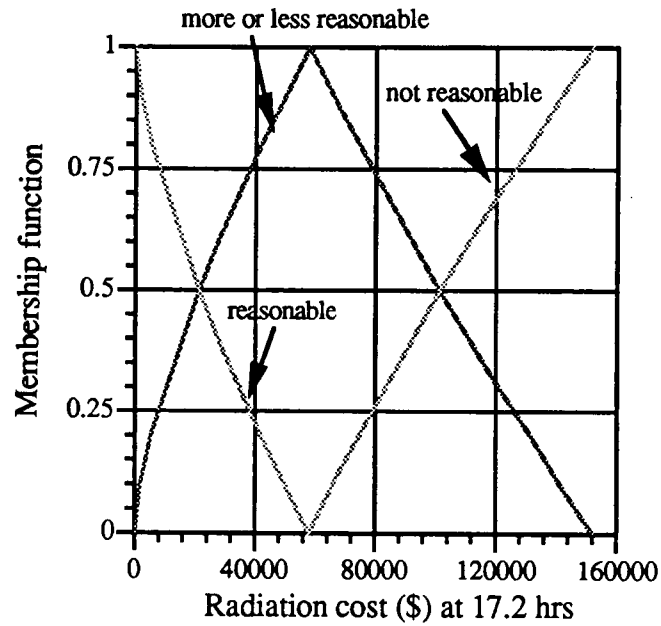


(a)



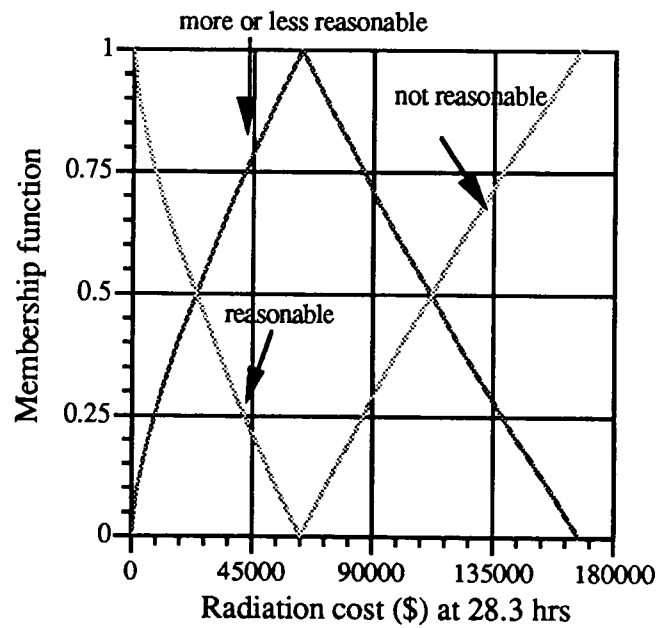
(b)

Figure 6.15 Cost membership function as leakage increases for the second compartment.



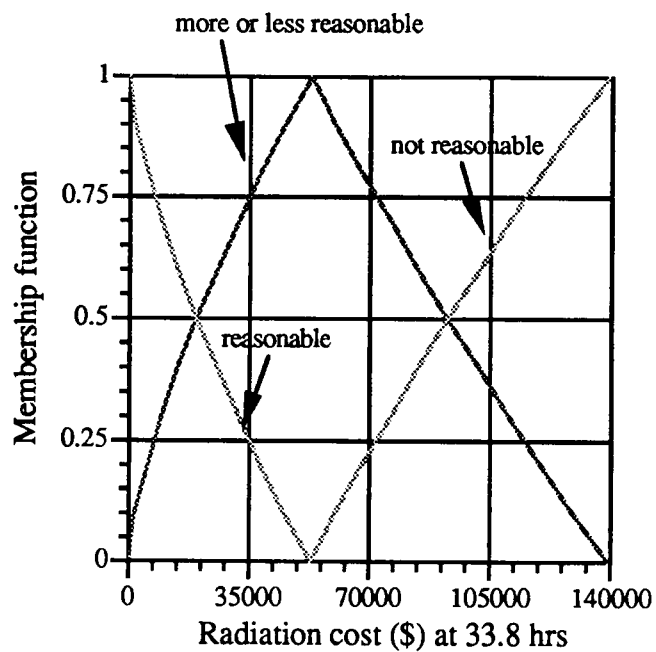
(c)

Figure 6.15 Cost membership function as leakage increases (continued).

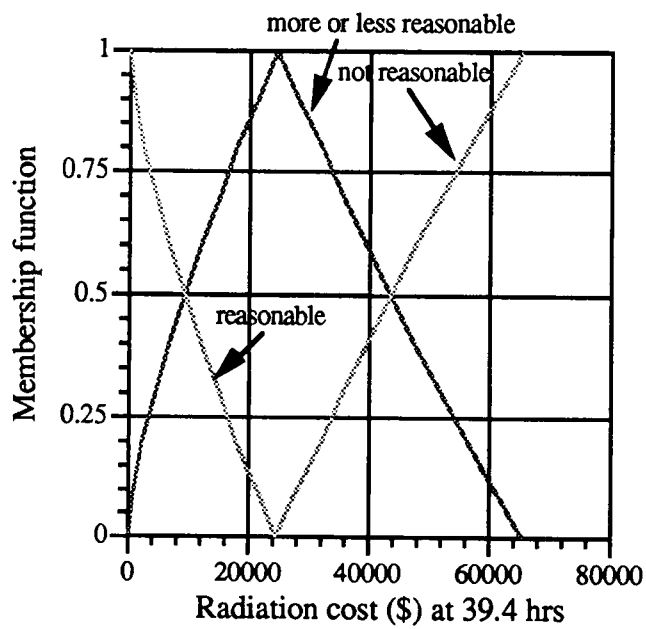


(a)

Figure 6.16 Cost membership function as leakage decreases.



(b)



(c)

Figure 6.16 Cost membership function as leakage decreases (continued).

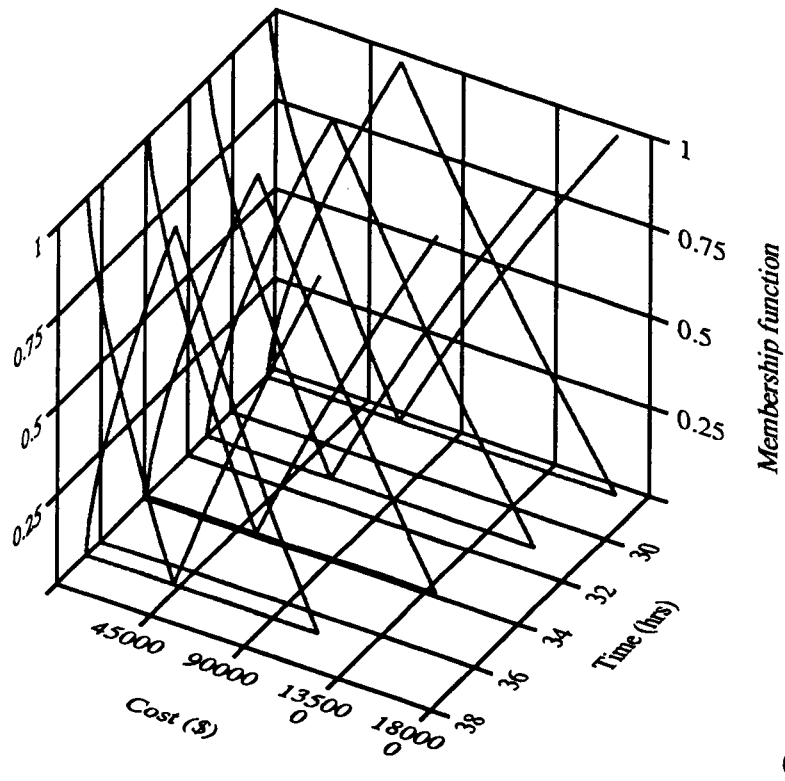
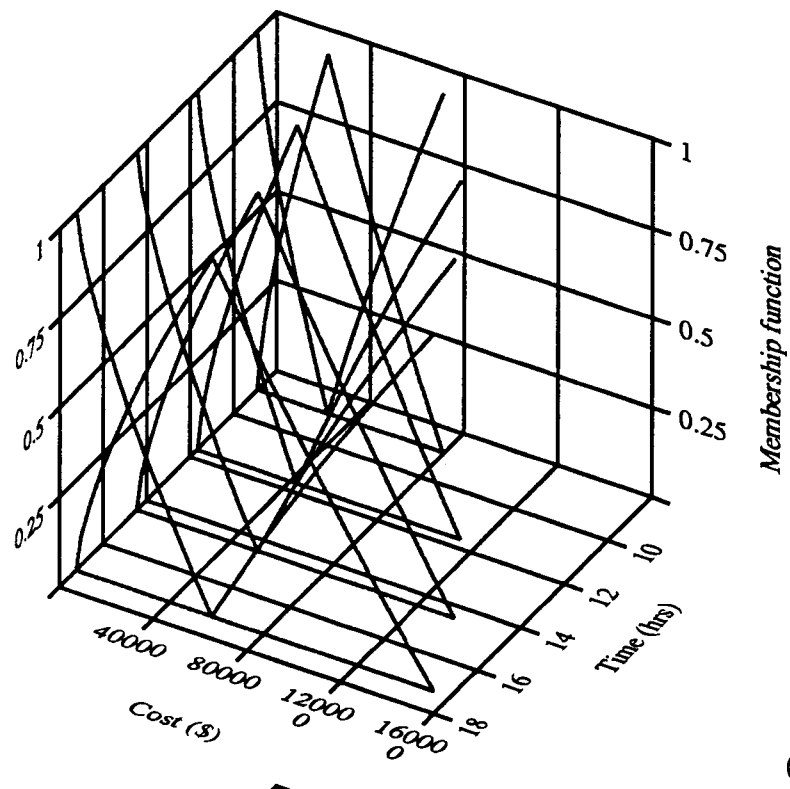
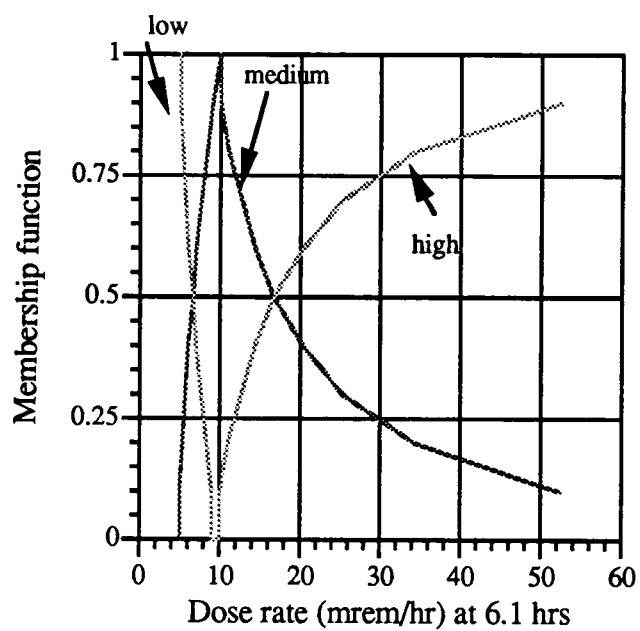
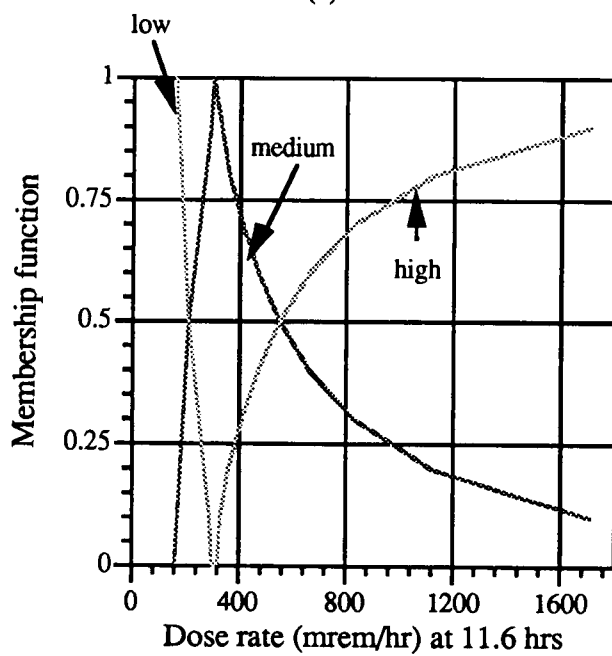


Figure 6.17 Three dimensional view of the cost membership functions as leakage decreases.

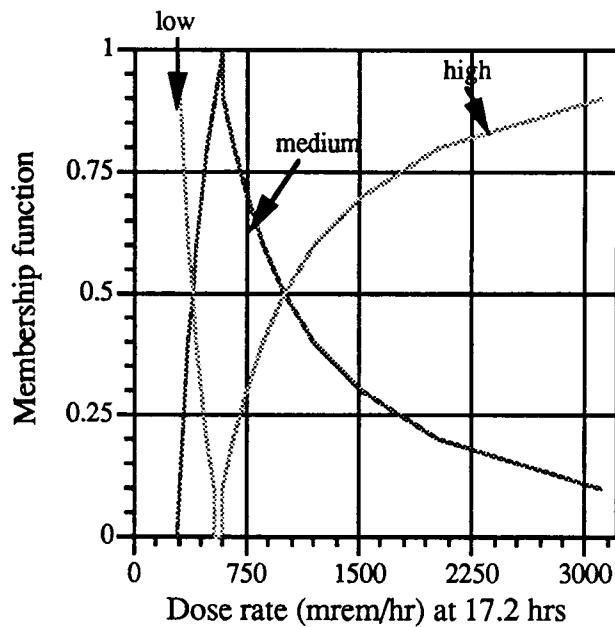


(a)



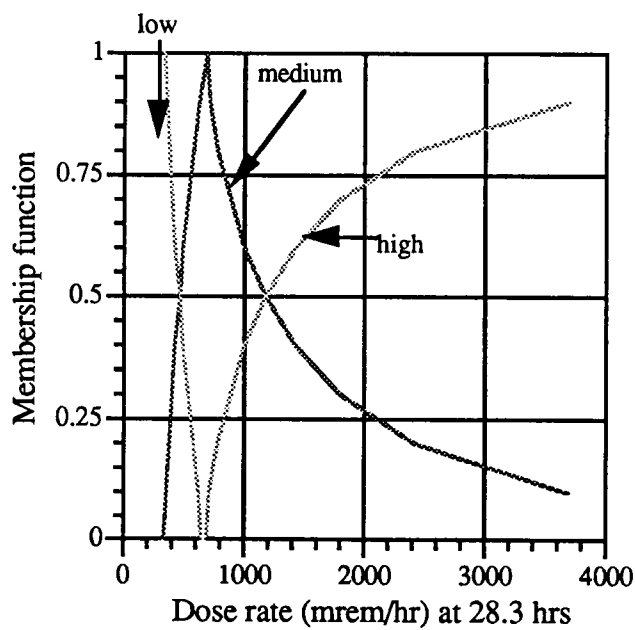
(b)

Figure 6.18 Membership function of dose rate as leakage increases.



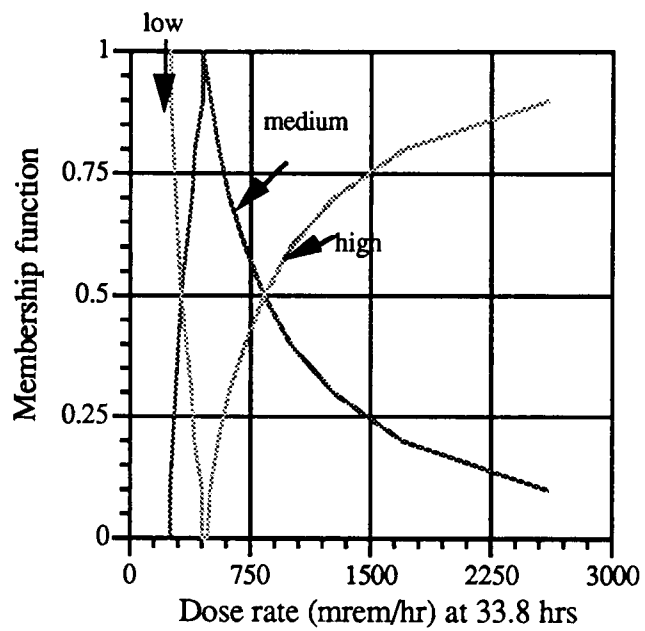
(c)

Figure 6.18 Membership function of dose rate as leakage increases (continued).

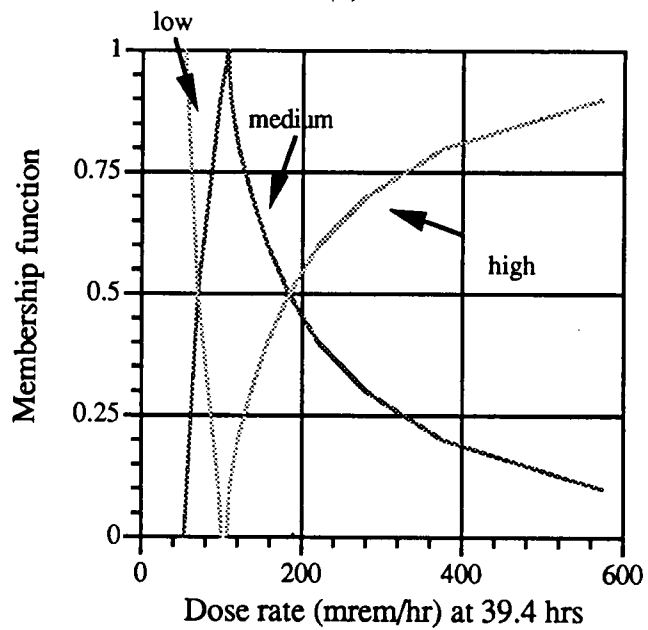


(a)

Figure 6.19 Membership function of dose rate as leakage decreases.

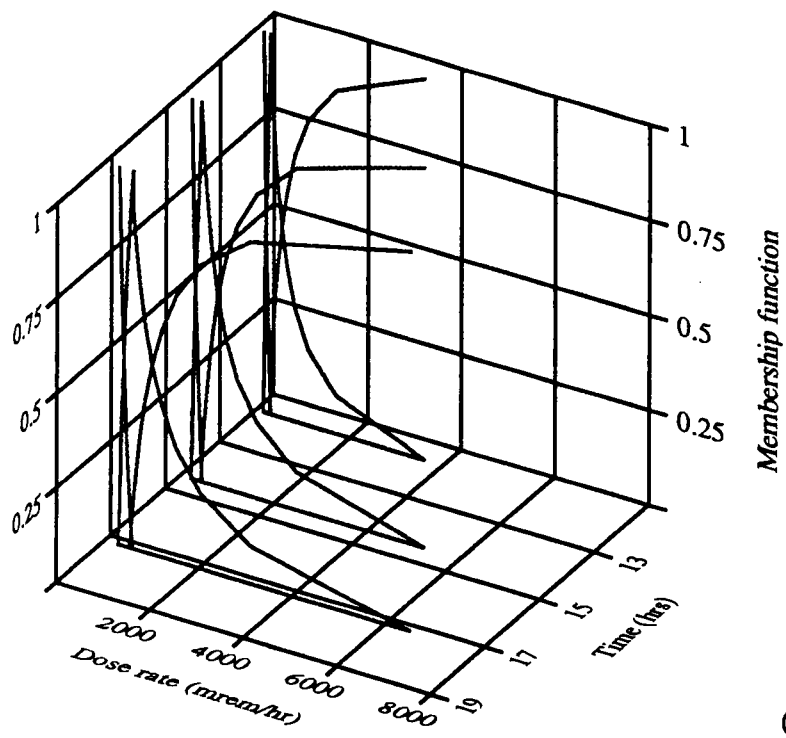


(b)

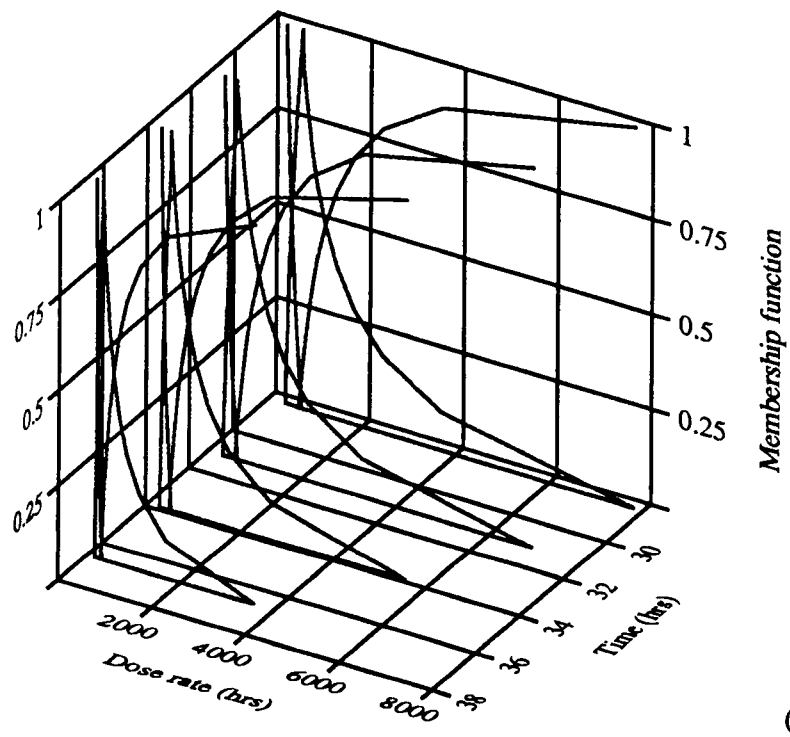


(c)

Figure 6.19 Membership function of dose rate as leakage decreases.



(a)



(b)

Figure 6.20 Three dimensional view of the membership function of dose rate.



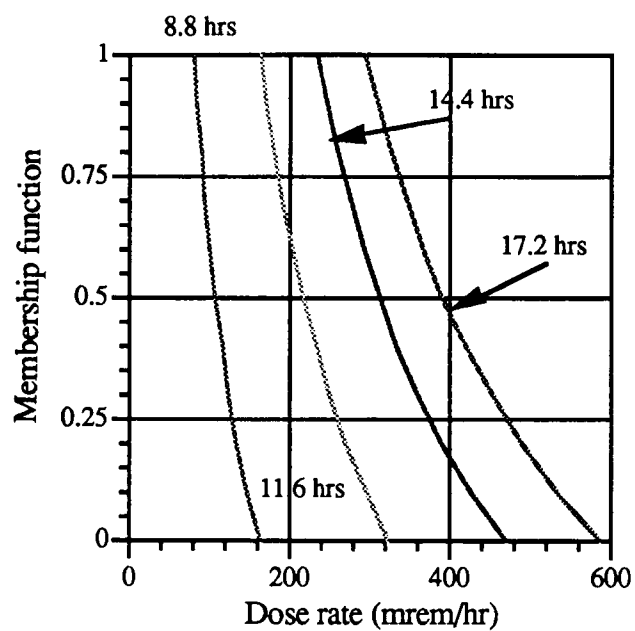


Figure 6.21 Membership function of "low and reasonable" dose rate as leakage increases.

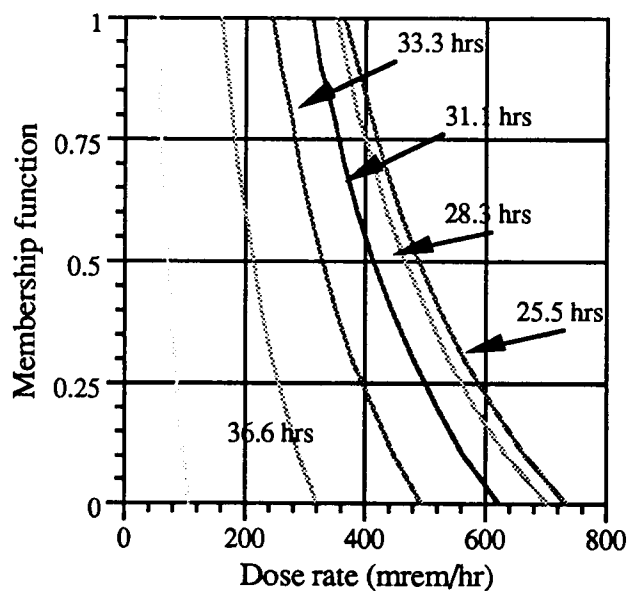


Figure 6.22 Membership function of "low and reasonable" dose rate as leakage decreases.

Table 6.2 Membership function curve fitting results for a second compartment.

| Time (hrs) | Membership curve fitting $\mu$<br>of dose rate x, in mrem/hr |
|------------|--------------------------------------------------------------|
| 3.3        | - 1.446 ln x - 1.964                                         |
| 6.1        | - 1.446 ln x + 3.270                                         |
| 8.8        | - 1.446 ln x + 8.314                                         |
| 11.6       | - 1.446 ln x + 8.314                                         |
| 14.4       | - 1.446 ln x + 8.844                                         |
| 17.2       | - 1.446 ln x + 9.169                                         |
| 20.0       | - 1.446 ln x + 9.366                                         |
| 22.7       | - 1.446 ln x + 9.470                                         |
| 25.5       | - 1.446 ln x + 9.490                                         |
| 28.3       | - 1.446 ln x + 9.420                                         |
| 31.1       | - 1.446 ln x + 9.251                                         |
| 33.8       | - 1.446 ln x + 8.920                                         |
| 36.6       | - 1.446 ln x + 8.293                                         |
| 39.4       | - 1.446 ln x + 6.732                                         |

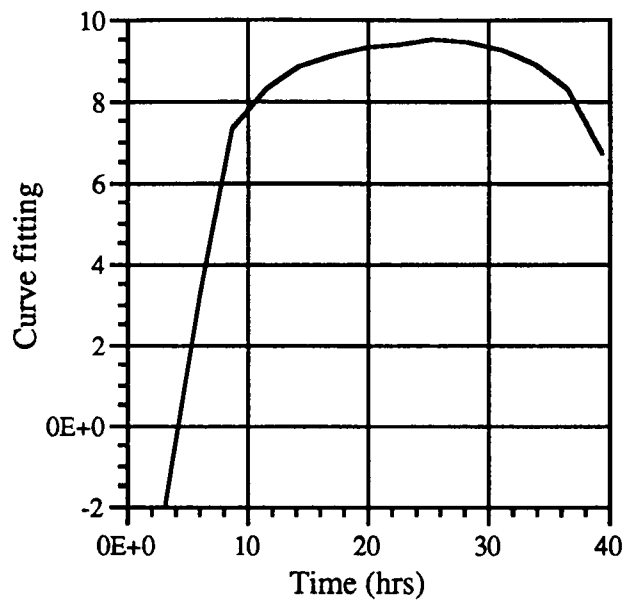


Figure 6.23 Membership function time dependence as leak increases and decreases.

The general equation of the membership function found using the same methodology as in the single compartment, as a function of dose rate  $x$ , and time  $t$ :

$$\mu_{\text{low dose rate}} = -1.44 \ln x - 0.0205 t^2 + 1.03 t - 2.54 \quad (6.2)$$

#### 6.4 FUZZY OPTIMIZATION RESULTS FOR THE SECOND CUBICLE

As far as the fuzzy optimization, the following results and observations were obtained. From the point of view of fuzzy optimization, the intersection of the fuzzy variable cost (constraint) and detriment (goal) represents the best cost option from two fuzzy variables. The fuzzy linguistic values of cost and detriment used for this analysis (table 4.2) was derived by use of the parameterization procedure.

For the first compartment the detriment function increases according to equations 3.21. The results of figure 4.6 show that the derived membership function of detriment adjust to this increases with time. One thing to note about the derived membership functions of detriment is that the universe of discourse covers less area than the universe of discourse of cost. In other words the derived detriment membership functions become less distinguishable in the acceptable and more or less acceptable regions. Therefore, the derived function of acceptable detriment has a short span in the universe of discourse. The not acceptable detriment region becomes an asymptote as collective dose increases.

In order to understand the fuzzy radiological optimization results, one must examine first the change of the membership function of cost and detriment. The fuzzification of the ICRP air flow by use of the parameterization procedure resulted in the derivation of the three meanings of cost: "reasonable" cost, "more or less reasonable" cost and "not reasonable" cost. Figures 6.6 and 6.7 illustrate the resultant membership functions of cost for the first compartment as leakage increases and decreases. The increase and decrease of the membership functions of cost shown in figure 6.8 are due to the dependence of radiation protection cost on the air flow. On the other hand, detriment is an constantly increasing function. Even though, the occupancy decreases, the integrated dose always increases. The membership function of detriment reflects this effect as time increases. This means, in effect, that the corresponding fuzzy values of acceptable detriment and more or less acceptable detriment region are reduced as detriment increases.

The highest value of the radiation protection cost corresponds to the "not reasonable" cost region of the membership function which takes place when the leak is at the highest point. This resultant membership function of cost reflects an elastic action of

increase and decrease. On the other hand, since the collective dose always increases, the detriment also increases. As a result of this effect, the detriment universe of discourse always increases. In fuzzy optimization terms, this increase results in no intersections when the detriment cost is higher than the radiation protection cost.

The optimum solution of the goal detriment and cost constraint is the highest value of the intersections of the corresponding membership function. Figure 6.24 presents the resultant intersection points of reasonable cost and acceptable detriment. According with figure 4.7, the derived membership functions of detriment are contained within the reasonable region of cost when the leakage increases at 11.6 hrs. As a consequence of this, there are several fuzzy optimal points of "reasonable" cost and "more or less acceptable" detriment as shown in figure 6.25. Figure 6.26 presents the "reasonable" radiation protection cost and "not acceptable" detriment results. As detriment cost increases, it enters the radiation protection cost region defined as "more or less reasonable" cost. Therefore, the fuzzy optimization results in intersections of "more or less reasonable" cost and "more or less acceptable" detriment as presented in figure 6.27. The corresponding fuzzy optimization points of "more or less reasonable" cost and "acceptable" detriment are shown in figure 6.28. Obviously, we would be interested in the "reasonable" cost results which are also acceptable from the radiological point of view (acceptable detriment).

Figures 6.29 through 6.33 present the same fuzzy optimization results for the second cubicle. Since the radiation protection cost decreases, the fuzzy optimization cost intersections are consistently reduced, so is the corresponding cost. The results for the third cubicle are similar to the second cubicle and are not presented.

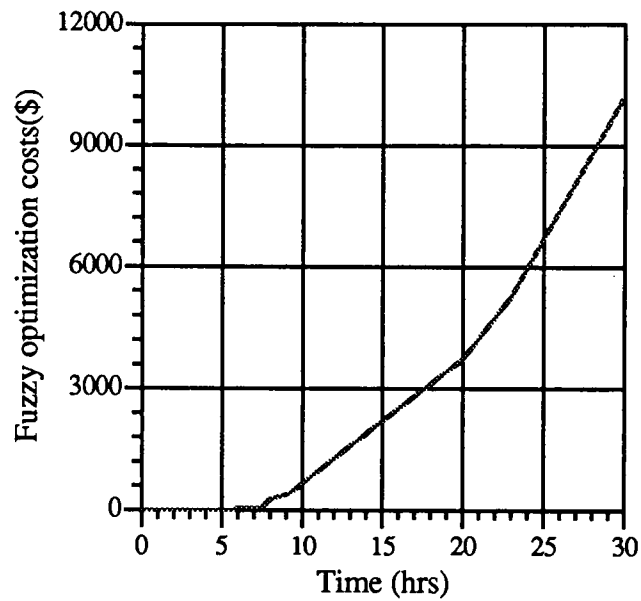


Figure 6.24 "Reasonable" radiation protection cost and "acceptable" detriment cost for the first cubicle.

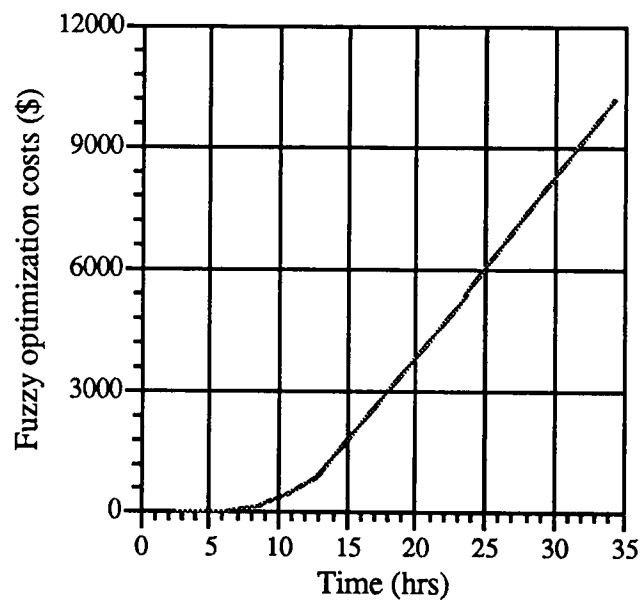


Figure 6.25 "Reasonable" radiation protection cost and "more or less acceptable" detriment cost for the first cubicle.

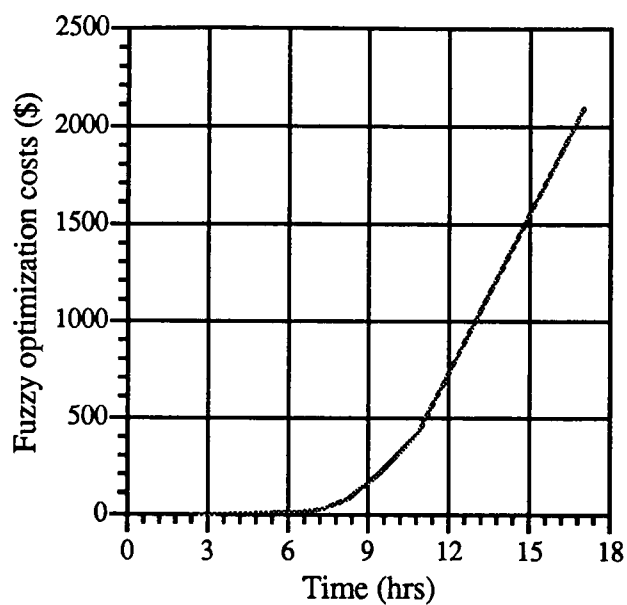


Figure 6.26 "Reasonable" radiation protection cost and "not acceptable" detriment cost for the first cubicle.

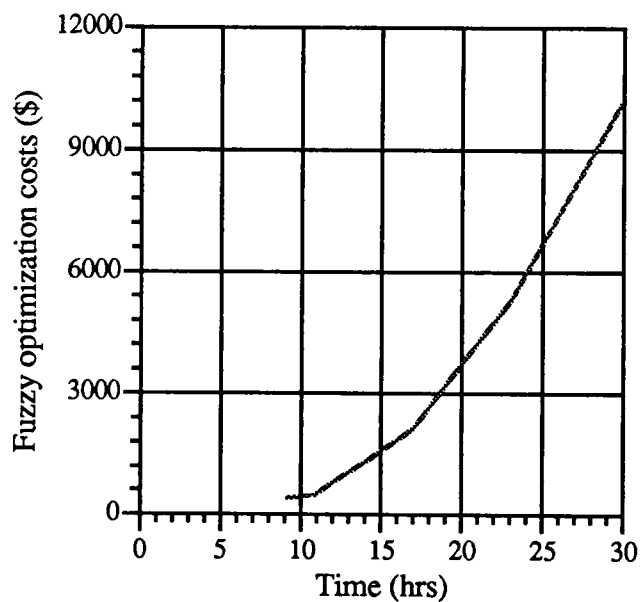


Figure 6.27 "More or less reasonable" cost and "more or less acceptable" detriment cost for the first cubicle.

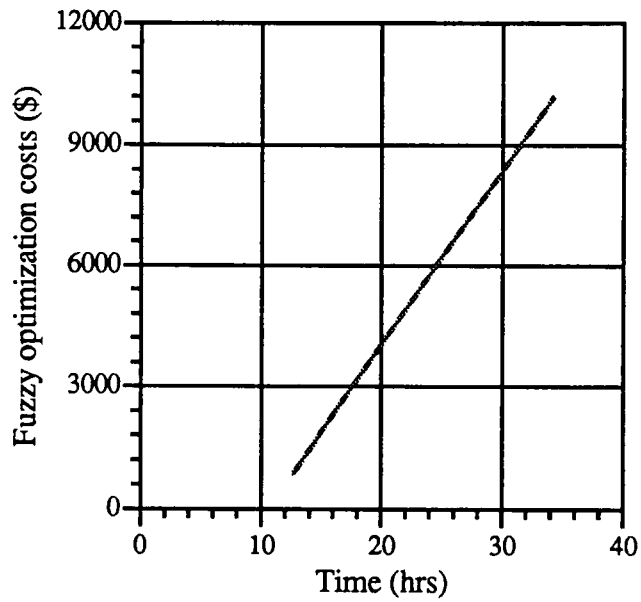


Figure 6.28 "More or less reasonable" protection cost and "acceptable" detriment cost for the first cubicle.

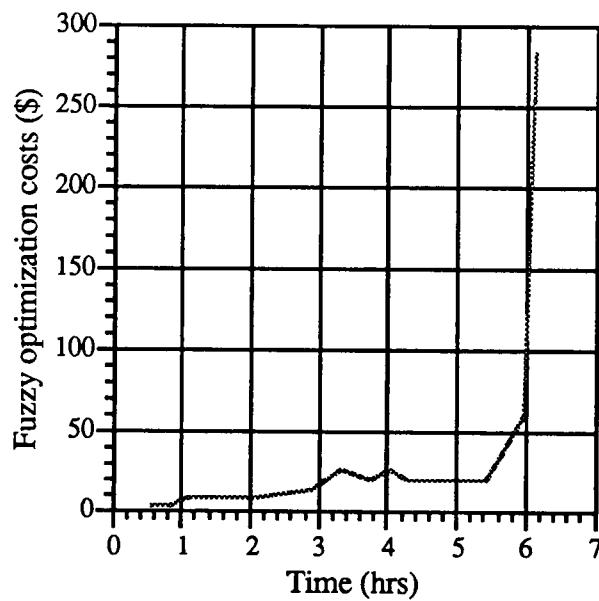


Figure 6.29 "Reasonable" radiation protection cost and "acceptable" detriment cost for the second cubicle.



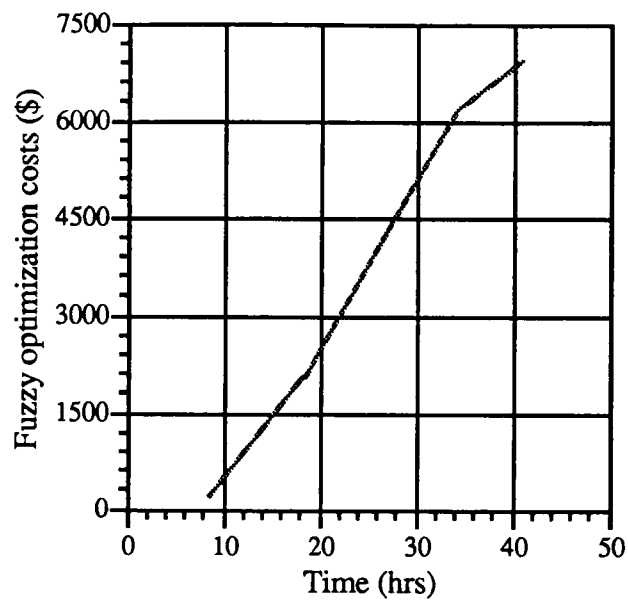


Figure 6.30 "Reasonable" radiation protection cost and "more or less acceptable" detriment cost for the second cubicle.

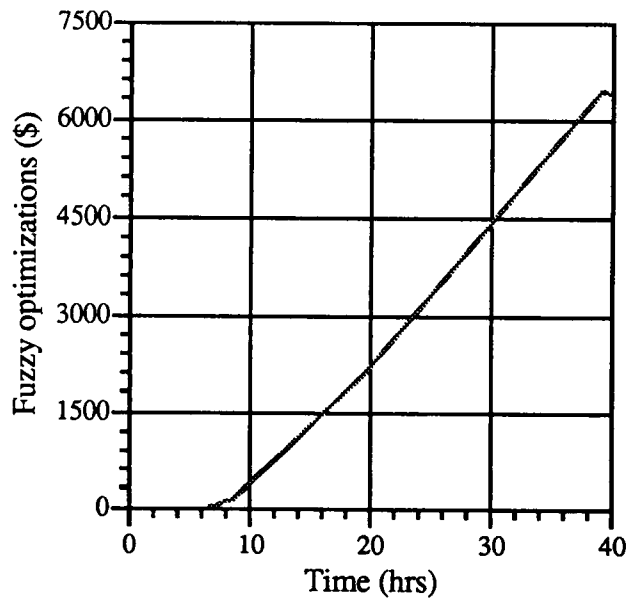


Figure 6.31 "Reasonable" radiation protection cost and "not acceptable" detriment cost for the second cubicle.

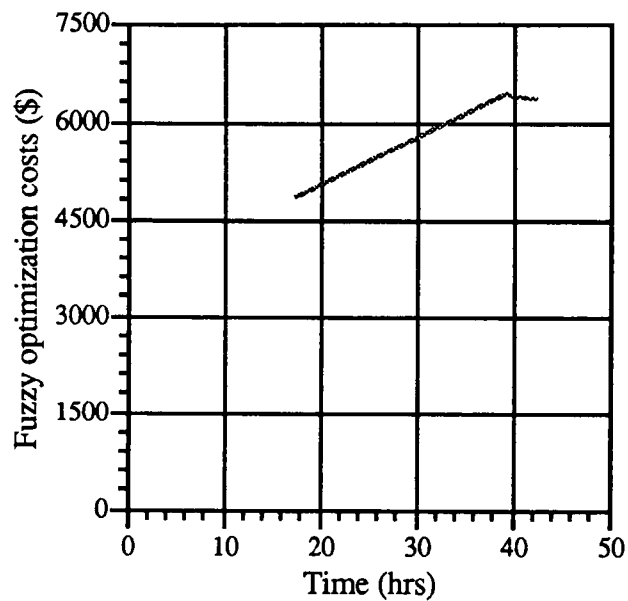


Figure 6.32 "More or less reasonable" radiation cost and "more or less acceptable" detriment for the second cubicle.

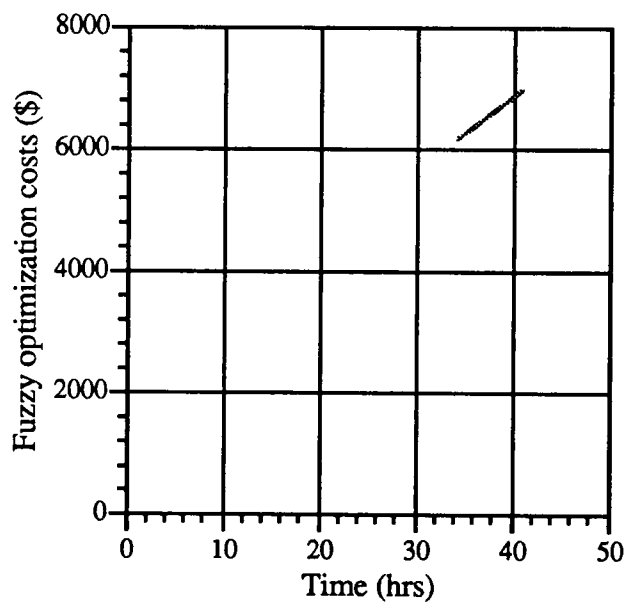


Figure 6.33 "More or less reasonable" radiation protection cost and "acceptable" detriment cost for the second cubicle.

## CHAPTER 7

### CONCLUSIONS

#### 7.1 IMPLICATIONS OF THIS RESEARCH

This section reviews the impact of the results and initial objectives of this research in relation to the "as low as reasonably achievable" principle. The objective of this research was to find a new method that uses fuzzy mathematics in order to quantify uncertain linguistic terminology used in ALARA when performing a radiological assessment. Based on the results presented in the previous sections, ALARA can be measured through fuzzy logic. The approach used to combine cost benefit analysis and fuzzy set theory (fuzzification of air flow and parameterization) demonstrates that a distinction can be made between various levels of "low and reasonable dose rate." A critical step in the development of the membership functions of low and reasonable dose is the use of a fuzzify frame of reference in the definition of linguistic terminology in connection with cost benefit analysis by fuzzification of the ICRP air flow.

The three concepts of the reasonableness of cost become distinct in three membership functions. Their corresponding universe of discourse is extended to reflect the radiation protection cost model, equations (3.2), (3.3) and (3.4). Here the total cost of radiation protection is assumed to be a function of air flow which is fuzzified to distinguish between three concepts of costs. From a fuzzy logic point of view, the "as low as reasonable" principle in radiation protection implementation can be measured through membership functions.

Linguistic terminology has been used in the past to evaluate and describe radiation exposure effects. In the early forties the need of limitations in the exposure of radiation was recognized to a certain extent. At that time exposures were simply called "tolerable doses," which referred to doses below a threshold for non-stochastic effects that would not produce or induce any harmful results. Doses were labeled as "tolerable doses" when the effect of exposure to radiation was not well known [9]. The reason for this approach was that no known threshold had yet been established to set limits which associates a risk level comparable to other tasks. Consequently the ALARA principle recommended that doses should be reduced to low (below the limit) as long as economically feasible. This recommendation implies that all doses below the limit are acceptable. In this case, the concept of low is associated with safe radiation exposures. This reasoning suggests that all doses below the limit are safe. Consequently, one may even interpret that all low doses induced no harmful effects. It must be mentioned that the reason for the "tolerable dose" limit, established forty years ago, was the result of the uncertainty concerning the effects of radiation. Perhaps the reason for this principle is that we tend to make assumptions when we encounter uncertainty, complexity, and imprecision. The ALARA philosophy has apparently used the same approach because there is no other alternative.

Therefore, the interpretation of ALARA philosophy applied to doses below the limit is vague and imprecise. We view essentially "low dose" in one dimension, for we cannot make a distinction between various levels of low dose; low doses cover all doses below the limit, however small. Fuzzy logic is a window through which we can see a three dimensional image of a fuzzy concept "low" which can be interpreted only by subjective human reasoning.

## 7.2 LIMITATIONS OF THIS RESEARCH

There are several limitations of the expert system RAD. From the computational point of view section 5.2.2 outlines the assumptions made as far as the expert system's development and implementation are concerned. A disadvantages of the computer language OPS5 is that, if used to develop big codes which interface with several subroutines, it then becomes slow. Speed is very important in dynamically changing problems.

Another assumption made, which was already mentioned, is that only one isotope was used for this analysis. The main objective of the model was to demonstrate the fuzzy algorithm. This assumption was made in order to keep numerical computations simple. Another point worth mentioning is that filtration between cubicles was not considered. Filtration between cubicles reduces the dose rate. RAD does not use monitor data; instead it simulates leakage and calculates the resulting dose rates and all necessary data for the analysis. This problem can be made more realistic by attempting to analyze real time data from a mixture of sources which would come from sensors or monitor systems.

Another area of concern is the development of the RAD knowledge-base. The rule base in RAD represents knowledge about the operation of the air flow system, and therefore, there may be some imprecision associated with knowledge representation, for the rules (rules of thumb) represent desired modes of operation, and some rules may not always apply. RAD contains an inherent imprecision because the premise built into the knowledge base uses imprecise terms. The fuzzy variables (dose rate, leakage and dose) can introduce uncertainty and imprecision if their meaning is not accurately represented in their corresponding membership functions. If the rules were inconsistently formulated, the fuzzy algorithm will lead to imprecise results or will leave gaps in the prescribed air flow.

When this occurs, the prescribed air flow rate oscillates because rules fire when they should not. Since the dose rate is dependent on the air flow rate it also oscillates. Another source of imprecision may come from the data to be analyzed (from external subroutines). The rules are applied as long as a set of conditions is satisfied. Any inconsistency in the data may cause rules not to be applied thus leaving gaps in the results.

There may be problems due to redundant rules, conflicting rules, or rules which do not accurately describe the behavior of the system, even to the point of having an incomplete knowledge base (something that would become evident during testing). Even though RAD has been tested under the environment for which it was designed, there was extensive tuning performed. Tuning refers to the adjustments made to the fuzzy variables, dose rate, leakage and air flow rate in order to obtain consistent results.

### **7.3 CONTRIBUTION OF THIS RESEARCH**

The major contribution of this dissertation has been the introduction and development of a fuzzy algorithm to numerically represent fuzzy ALARA variables encountered in radiological assessment. Another major contribution of this research is the use of the cost benefit analysis presented in the International Commission on Radiation Protection, Publication No. 37, to quantify the meaning of reasonable cost through a fuzzification process.

The new fuzzy approach to cost benefit analysis serves as a link between the reasonableness of radiation protection parameters and derived low dose rates. This new methodology was carried out by use of a fuzzy algorithm which makes use of radiological variables relevant in radiological assessments. The results of this dissertation show that

fuzzy logic can be applied in the definition and qualification of radiological variables which make use of linguistic terms that change with time. The results presented in Chapter 6 also show that this new methodology can be used as an aid in the decision process when evaluating radiological levels of contamination at nuclear power plants. Moreover the most important contribution from this research is the evident need to redefine the "as low as reasonably achievable" principle (low doses and reasonable cost). Reasonable costs are relative and have changed and will continue to change; whereas the unknown effects of low doses may not. In conclusion, the ALARA philosophy should be redefined, for its linguistic definitions have vague and imprecise objectives which cannot easily be interpreted or implemented.

#### **7.4 RECOMMENDATIONS FOR FURTHER RESEARCH**

First of all, one of the recommendations should be the further reduction of occupational radiation exposure. From a health physics point of view, one must consider all precautions which have been already mentioned in chapter 1. There are several areas that need further development.

Due to the fact that one of the difficulties in the development of RAD was determining the precise fuzzy definition of low dose rate, the first recommendation would be to test the fuzzy algorithm under different environments for the purpose of achieving consistency in the parameterization procedure. Based on the observation of these results, the next logical step as far as fuzzy theory is concerned, would be to implement and connect the fuzzy algorithm with the derived membership function. The new fuzzy methodology, of deriving membership functions from traditionally well-known mathematical equations, connects vague concepts with mathematical formulas which can be manipulated in fuzzy

mathematics. This new approach can extend the already derived reference concept of "low and reasonable" to more semantic manipulations in fuzzy mathematics. For instance, it has been accepted that if one knows the membership function of "low dose rate," then one can find the membership function of "very" low dose rate by squaring the membership function of low dose.

$$\mu_{\text{very low dose}} = \mu_{\text{low dose rate}}^2 \quad (7.1)$$

In this fashion one can use the already derived membership functions and extend meanings (for instance very reasonable and very low cost). Another example of a fuzzy computation that may be employed to extend meanings would be the complement of a membership function which derives a negation of a concept.

$$\mu_{\text{no reasonable cost}} = 1 - \mu_{\text{reasonable cost}} \quad (7.2)$$

The remaining task would be to find the applicability of the derived membership functions within fuzzy mathematics framework for the purpose of performing fuzzy computational manipulations with semantics. In general the objective is to apply the fuzzy algorithm and the fuzzy parameterization procedure in different problems. A further objective would be to test the methodology presented here in order to establish a link between non-fuzzy and fuzzy mathematics as established in the *extension principle*.



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## LIST OF REFERENCES

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## **APPENDIX**

## OPS5 RADIOLOGICAL SCREENING PROGRAM

PROGRAM NAME: FUZZY.OPS

; PURPOSE : This code analyzes the environment conditions in a single  
cubicle model

; LANGUAGE : VAX OPS5

; DATE : AUGUST 14, 1991

\*\*\*\*\*

The following list contains the names of the external

; subroutines and funtions which fuzzy-ops interfaces

; with:

|                |                                                         |
|----------------|---------------------------------------------------------|
| ; comp1-for    | For the estimation of the isotopic concentrations       |
|                | in the first compartment of the model                   |
| ; comp2-for    | Second compartment                                      |
| ; comp3-for    | third compartment                                       |
| ; comp4-for    | Divided compartment                                     |
| ; fo1-for      | Subroutine for fuzzy optimization, in the first cubicle |
| ; fo2-for      | Second cubicle                                          |
| ; fo3-for      | Third cubicle                                           |
| ; fo4-for      | Divide cubicle                                          |
| ; fuzzydr1-for | Subroutine for the estimation of the membership         |
|                | functions of dose rate in the first cubicle             |
| ; fuzzydr2-for | Membership functions for second cubicle                 |
| ; fuzzydr3-for | Membership functions for third cubicle                  |
| ; fuzzyd1-for  | Membership functions for dose (integrated dose)         |
|                | for cubicle one.                                        |
| ; fuzzyd2-for  | Membership functions for second cubicle                 |
| ; fuzzyd3-for  | Membership functions for third cubicle                  |
| ; fuzzyl-for   | Membership functions for leakage rate                   |
| ; fuzzyf-for   | Subroutine to defuzzyfied centroid, flow rate           |
| ; cost-for     | All cost calculation                                    |
| ; leak-for     | Leak simulation model                                   |
| ; occup-for    | Occupancy requirements                                  |
| ; min-for      | Subroutine to obtain the minimum value according        |
|                | to the Max-Dot methodology.                             |
| ; icrp1-for    | International Commission on Radiation Protection        |
|                | methodology for optimum air flow rate, first cubicle    |
| ; icrp2-for    | Second cubicle                                          |
| ; icrp3-for    | Third cubicle                                           |
| ; icrp4-for    | Divided cubicle                                         |

\*\*\*\*\*

|     |     |
|-----|-----|
| *** | *** |
| *** | *** |
| *** | *** |
| *** | *** |
| *** | *** |
| *** | *** |

FUZZY ANALYZES CODE

\*\*\*\*\*

```

;-----;
;      EXTERNAL ROUTINES      ;
;-----;
(external fuzzyd1_for) (external fuzzydr1_for)
(external fuzzyd2_for) (external fuzzydr2_for)
(external fuzzyd3_for) (external fuzzydr3_for)
(external fuzzyd4_for) (external fuzzydr4_for)
(external fuzzyl_for)
(external fuzzyf_for)   (external cost_for)
(external min_for)      (external leak_for)   (external occup_for)
(external icrp1_for)    (external comp1_for)  (external fo1_for)
(external icrp2_for)    (external icrp3_for)  (external icrp4_for)
(external comp2_for)    (external comp3_for)  (external comp4_for)
(external fo2_for)      (external fo3_for)    (external fo4_for)
;-----;
;      LITERALIZATIONS      ;
;-----;
;
;
(literalize FUZZY_LEAK  DM1 L1 DM2 L2) (literalize FUZZY_DOSE DM1 L1 DM2 L2)
(literalize FUZZY_DOSE_R DM1 L1 DM2 L2) (literalize FUZZY_DET  DM1 L1 DM2 L2)
(literalize FUZZY_FLOW  DM1 L1 DM2 L2)
;
;-----;
(literalize comp_one dose_rate) (literalize comp_two dose_rate)
(literalize comp_three dose_rate)(literalize comp_four dose_rate)
(literalize comp_five dose_rate)
;
;-----;
(literalize data cubicle DOSE COLLECTIVE)
(literalize STATE_FLOW  FLOW_RATE) (literalize REQUEST VALUE NEW_DOSE)
(literalize STATE      TIME)        (literalize TASK NAME)
(literalize CYCLE      ONE TWO)      (literalize VALUES  LEAK)
(literalize ICRP       COST)          (literalize flow centroid)
(literalize points one two three four five six seven)
(literalize goal action)(vector-attribute dose_rate)
;-----;
;      START-UP      ;
;-----;
(startup (make start) (strategy mea) (disable halt) (watch 0) (run))
;-----;
;      RULES TO GATHER INFORMATION      ;
;-----;
(p initiate { <start> (start) }
--> (remove <start>)
(write |-----|
(crlf) |
(crlf) |      +-----+

```



```

(crlf) |----- DATA TO INITIATE THE ANALYSIS -----|
(crlf) |
(crlf) |      +-----+
(crlf) |** The following analysis is performed from a forward      **|
(crlf) |** chaining mode to test 120 production rules that        **|
(crlf) |** interface w/ external routines to create wms.          **|
(crlf) |** What type of cubicle model do you like?                **|
(crlf) |*****|
(crlf) | to use:                                                  **|
(crlf) | single (1)                                              **|
(crlf) | double_cubicle (2)                                     **|
(crlf) | three_cubicles (3)                                     **|
(crlf) | divided_cubicles (4)                                   **|
(crlf) |*****|
(crlf) |**
(crlf) |** * enter exit to terminate here *
(crlf) |**
(crlf) |*****|
(bind <cubicle> (accept))

```

```

;-----
(openfile dataout1 |data1.out| out)
(openfile dataout2 |data2.out| out)
(openfile dataout3 |data3.out| out)
(openfile leakout1 |leak1.out| out)
(openfile leakout2 |leak2.out| out)
(openfile leakout3 |leak3.out| out)
;-----
  (make comp_one ^dose_rate 0.1 )
  (make comp_two ^dose_rate 0.1 )
  (make comp_three ^dose_rate 0.1 )
  (make comp_four ^dose_rate 0.1 )
  (make state ^time 0.00001)
  (make values ^leak 1.1)
  (make icrp ^cost 0.1)
;  (make flow ^centroid 0.1)
  (make data ^cubicle <cubicle>
    ^dose 0.00001
    ^collective 0.001))
;-----;
(p stop_the_program (data ^cubicle << e ex exi exit >> )
--> (halt))
;-----;
;the units of the <dose1> dose-rate are "mrem/hr", integrated dose <dose2>;
;are "mrem", collective dose in "man-mrem", detriment in $,a=$ 5000/manrem;
;-----;
(p fuzzy_optimization
{ <fuzzy> (task ^name fuzzy) }
-->

```

```

(write |-----|
(crlf) |
(crlf) |      +-----+
(crlf) |----- FUZZY OPTIMIZATION PART -----|
(crlf) |
(crlf) |      +-----+
(crlf) |** The following analysis is performed from a forward      **|
(crlf) |** chaining mode to test 120 production rules.            **|
(crlf) |*****|
(crlf) | enter 11 to perform fuzzy optimization for                **|
(crlf) | the single compartment                                    **|
(crlf) | double compartment (12)                                   **|
(crlf) | third compartment (13)                                   **|
(crlf) | divided compartment (14)                                 **|
(crlf) |                                                           **|
(crlf) | reable det = reasonable detriment                         **|
(crlf) | m or l reable= more or less reasonable                  **|
(crlf) |                                                           **|
(crlf) |*****|
(crlf) |**                                                         **|
(crlf) |** * enter exit to terminate here *                       **|
(crlf) |**                                                         **|
(crlf) |*****|)
(bind <cubicle> (accept))
  (make data ^cubicle <cubicle>))
;*****
;*** rules for single cubicle--compartment 1                      **
;*****
(p get_membership_funt_comp_1
{<state> (state ^time <time>)} {<values> (values ^leak <leak>)}
{<contam>(data ^cubicle 1 ^dose <dose2> ^collective <coll>)}
{<dose> (comp_one ^dose_rate <dose1>)}
--> (bind <time_one> (compute 500.0 + <time>))
(modify <state> ^time <time_one>)(bind <int> (compute 0.000138 * <dose1> ))
(bind <occup> (occup_for <time_one>))(bind <new_coll> (compute <occup> * <int>))
(modify <contam> ^dose (compute <dose2> + <int> )
      ^collective (compute <coll> + <new_coll> ) )
(bind <new_leak> (leak_for <time_one>))(modify <values> ^leak <new_leak>)
  (bind <detri> (compute 100.0 * <coll> ))

; (write (crlf) |coll| <coll> |dose-r| <dose1> |dose| <dose2>)

(call fuzzyl_for <leak> )(call fuzzydr1_for <dose1>)(call fuzzyd1_for <coll>))

(p dose_calc_and_pres_flow_for_comp_1
{ <state> (state ^time <time> ) } {<flow> ( flow ^centroid <centroid> ) }
{<values> (values ^leak <leak>)} {<icrp> (icrp ^cost <cost> ) }
{<contam> ( data ^cubicle 1 ^collective <coll> ) }
{<dose> (comp_one ^dose_rate <dose1>)}
--> (call comp1_for <leak> <centroid>)
(bind <new_cost> (cost_for <time> <centroid>))

```

```

(modify <icrp> ^cost (compute <cost> + <new_cost>))
(bind <new_icrp> (icrp1_for <leak>))(bind <time1> (compute <time> // 3600))
;-----
(write (crlf) |t| <time1> |P.fl <centroid> |L| <leak>
      |icrp| <new_icrp> |dof <dose1>|)
(bind <upper> (compute 1.5 * <new_icrp> ))
;-----
; (default dataout write)
; (write dataout (crlf) (tabto 1 ) <time>
;                      (tabto 11) <leak>
;                      (tabto 26) <coll>
;                      (tabto 42) <upper>))
; (default nil write)
;-----
(bind <com> , )
(default dataout1 write)
(write dataout1 (crlf) <com> <time1> <com> <leak> <com> <time1> <com>
<new_icrp> <com> <time1> <com> <coll> <com> )
(default nil write)
;-----
(default leakout1 write)
(write leakout1 (crlf) <com> <time1> <com> <dose1>
<com> <time1> <com> <centroid>))
(default nil write)
;-----
(remove <dose>)(remove <flow>))
;*****
;*** rules for compartment 2 ***
;*****
(p get_membership_funt_comp_2
 { <state> (state ^time <time>)} { <values> (values ^leak <leak>)}
 { <contam> (data ^cubicle 2 ^dose <dose2> ^collective <coll>)}
 { <dose> (comp_two ^dose_rate <dose1>)}
 --> (bind <time_one> (compute 500.0 + <time>))
(modify <state> ^time <time_one>)(bind <int> (compute 0.000138 * <dose1> ))
(bind <occup> (occup_for <time_one>))(bind <new_coll> (compute <occup> * <int>))
(modify <contam> ^dose (compute <dose2> + <int> )
      ^collective (compute <coll> + <new_coll> ) )
(bind <new_leak> (leak_for <time_one>))(modify <values> ^leak <new_leak>)
(bind <detri> (compute 100.0 * <coll> ))

; (write (crlf) |coll| <coll> |dose-r| <dose1> |dose1 <dose2>|)

(call fuzzyl_for <leak> )(call fuzzydr2_for <dose1>)(call fuzzyd2_for <coll>))
(p dose_calc_and_pres_flow_for_comp-2
 { <state> (state ^time <time> ) } { <flow> ( flow ^centroid <centroid> ) }
 { <values> (values ^leak <leak>)} { <icrp> (icrp ^cost <cost> ) }
 { <contam> ( data ^cubicle 2 ^collective <coll>)}
 { <dose> (comp_two ^dose_rate <dose1>)}
 --> (call comp2_for <leak> <centroid>)
(bind <new_cost> (cost_for <time> <centroid>))

```

```

(modify <icrp> ^cost (compute <cost> + <new_cost>))
(bind <new_icrp> (icrp2_for <leak>))
(bind <time1> (compute <time> // 3600))
(write (crlf)|t| <time1> |P.f| <centroid> |L| <leak>
      licrp| <new_icrp> |dol <dose1> )
(bind <upper> (compute 1.5 * <new_icrp> ))
;-----
(bind <com> , )
(default dataout2 write)
(write dataout2 (crlf) <com> <time1> <com> <coll> <com> <time1> <com>
  <new_icrp> )
(default nil write)
;-----
(default leakout2 write)
(write leakout2 (crlf) <com> <time1> <com> <dose1>
  <com> <time1> <com> <centroid>)
(default nil write)
;-----

;-----
;(default dataout write)
; (write dataout (crlf) (tabto 1 ) <time>
;               (tabto 11) <leak>
;               (tabto 26) <coll>
;               (tabto 42) <upper>)
;(default nil write)
;-----
(remove <dose> )(remove <flow>))
;*****
;*** rules for compartment 3 ***
;*****
(p get_membership_funt_comp_3
 {<state> (state ^time <time>)} {<values> (values ^leak <leak>)}
 {<contam> (data ^cubicle 3 ^dose <dose2> ^collective <coll>)}
 {<dose> (comp_three ^dose_rate <dose1>)}
 --> (bind <time_one> (compute 500.0 + <time>))
 (modify <state> ^time <time_one>)(bind <int> (compute 0.000138 * <dose1> ))
 (bind <occup> (occup_for <time_one>))(bind <new_coll> (compute <occup> * <int>))
 (modify <contam> ^dose (compute <dose2> + <int> )
      ^collective (compute <coll> + <new_coll> ) )
 (bind <new_leak> (leak_for <time_one>))(modify <values> ^leak <new_leak>)
 (bind <detri> (compute 100.0 * <coll> ))

; (write (crlf) |coll| <coll> |dose-r| <dose1> |dose| <dose2>)

(call fuzzyl_for <leak> )(call fuzzydr3_for <dose1>)(call fuzzyd3_for <coll> ))
(p dose_calc_and_pres_flow_for_comp-3
 { <state> (state ^time <time> ) } {<flow> ( flow ^centroid <centroid> ) }
 {<values> (values ^leak <leak>)} {<icrp> (icrp ^cost <cost> ) }
 {<contam> ( data ^cubicle 3 ^collective <coll> ) }
 {<dose> (comp_three ^dose_rate <dose1>)}

```

```

--> (call comp3_for <leak> <centroid>)
(bind <new_cost> (cost_for <time> <centroid>))(remove <dose>)
(modify <icrp> ^cost (compute <cost> + <new_cost>))
(bind <new_icrp> (icrp3_for <leak>))(bind <time1> (compute <time> // 3600))
(write (crlf)|t| <time1> |P.f| <centroid> |L| <leak>
      licrp| <new_icrp> |do=| <dose1>)
(bind <upper> (compute 1.5 * <new_icrp> ))
;-----
(bind <com> , )
(default dataout3 write)
(write dataout3 (crlf) <com> <time1> <com> <coll> <com> <time1> <com>
<new_icrp>)
(default nil write)
;-----
(default leakout3 write)
(write leakout3 (crlf) <com> <time1> <com> <dose1>
<com> <time1> <com> <centroid>)
(default nil write)
;-----

;-----
;(default dataout write)
; (write dataout (crlf) (tabto 1 ) <time>
;               (tabto 11) <leak>
;               (tabto 26) <coll>
;               (tabto 42) <upper>)
; (default nil write)
;-----
(remove <flow>)
*****
*** rules for compartment 4 ***
*****
(p get_membership_funt_comp_4
 {<state> (state ^time <time>)} {<values> (values ^leak <leak>)}
 {<contam>(data ^cubicle 4 ^dose <dose2> ^collective <coll>)}
 {<dose> (comp_four ^dose_rate <dose1>)}
--> (bind <time_one> (compute 500.0 + <time>))
(modify <state> ^time <time_one>) (bind <int> (compute 0.000138 * <dose1>))
(bind <occup> (occup_for <time_one>))(bind <new_coll> (compute <occup> * <int>))
(modify <contam> ^dose (compute <dose2> + <int> )
      ^collective (compute <coll> + <new_coll> ) )
(bind <new_leak> (leak_for <time_one>))(modify <values> ^leak <new_leak>)
  (bind <detri> (compute 100.0 * <coll> ))

; (write (crlf) |coll| <coll> |dose-r| <dose1> |dose| <dose2>)

(call fuzzyl_for <leak> )(call fuzzydr4_for <dose1>)(call fuzzyd4_for <coll>))
(p dose_calc_and_pres_flow_for_comp-4
 { <state> (state ^time <time> ) } { <flow> ( flow ^centroid <centroid> ) }
 { <values> (values ^leak <leak> ) } { <icrp> (icrp ^cost <cost> ) }
 { <contam> ( data ^cubicle 4 ^collective <coll> ) }

```

```

{<dose> (comp_four ^dose_rate <dose1>))
--> (call comp4_for <leak> <centroid>)
(bind <new_cost> (cost_for <time> <centroid>))
(modify <icrp> ^cost (compute <cost> + <new_cost>))
(bind <new_icrp> (icrp4_for <leak>))(bind <time1> (compute <time> // 3600))
;-----
(write (crLf)|t| <time1> |P.f| <centroid> |L| <leak>
      |icrp| <new_icrp> |do=| <dose1>)
(bind <upper> (compute 1.5 * <new_icrp> ))
;-----
;(default dataout write)
; (write dataout (crLf) (tabto 1 ) <time>
;                      (tabto 11) <leak>
;                      (tabto 26) <coll>
;                      (tabto 42) <upper>)
; (default nil write)
;-----
(remove <dose>) (remove <flow>))
;-----
;
; FUZZY OPTIMIZATION
;
;-----
(p open_file_for_fuzzy_optimization_1
 {<contam>(data ^cubicle 11 ^dose <dose2> ^collective <coll>)})
-->(openfile file |data.out| in)
  (default file accept)
  (make points ^one (accept)
               ^two (accept)
               ^three (accept)
               ^four (accept))
(write (crLf) |**file 'data.out' has been opened**|)
(make goal ^action fuzzy1)
(p continue_fuzzy_optimization_1
 ( goal ^action fuzzy1 )
 { <data> (points ^one { <time> <> stop }
                   ^two { <leak> <> stop }
                   ^three { <coll> <> stop }
                   ^four { <upper> <> stop } ) })
-->
(modify <data> ^one (accept)
      ^two (accept)
      ^three (accept)
      ^four (accept) )
(bind <time1> (compute <time> // 3600))
(write (crLf) |time step...| <time1> |L| <leak>
      | Col <coll> |up| <upper> )
(bind <opt> (fo1_for <time> <leak> <coll> <upper>)))
(p open_file_for_fuzzy_optimization_2
 {<contam>(data ^cubicle 12 ^dose <dose2> ^collective <coll>)})
-->(openfile file |data.out| in)

```

```

(default file accept)
(make points ^one (accept)
      ^two (accept)
      ^three (accept)
      ^four (accept))
(write (crlf) |**file 'data.out' has been opened**|)
(make goal ^action fuzzy2))
(p continue_fuzzy_optimization_2
  ( goal ^action fuzzy2 )
  { <data> (points ^one { <time> <> stop }
              ^two { <leak> <> stop }
              ^three { <coll> <> stop }
              ^four { <upper> <> stop } ))
-->
(modify <data> ^one (accept)
      ^two (accept)
      ^three (accept)
      ^four (accept) )
(bind <time1> (compute <time> // 3600))
(write (crlf) |time step...| <time1> |L| <leak>
| Col <coll> |upl| <upper> )
(bind <opt> (fo2_for <time> <leak> <coll> <upper>)))
(p open_file_for_fuzzy_optimization_3
  {<contam>(data ^cubicle 13 ^dose <dose2> ^collective <coll>)})
-->(openfile file |data.out| in)
  (default file accept)
  (make points ^one (accept)
        ^two (accept)
        ^three (accept)
        ^four (accept))
(write (crlf) |**file 'data.out' has been opened**|)
(make goal ^action fuzzy3))
(p continue_fuzzy_optimization_3
  ( goal ^action fuzzy3 )
  { <data> (points ^one { <time> <> stop }
              ^two { <leak> <> stop }
              ^three { <coll> <> stop }
              ^four { <upper> <> stop } ))
-->
(modify <data> ^one (accept)
      ^two (accept)
      ^three (accept)
      ^four (accept) )
(bind <time1> (compute <time> // 3600))
(write (crlf) |time step...| <time1> |L| <leak>
| Col <coll> |upl| <upper> )
(bind <opt> (fo3_for <time> <leak> <coll> <upper>)))
(p open_file_for_fuzzy_optimization_4
  {<contam>(data ^cubicle 14 ^dose <dose2> ^collective <coll>)})
-->(openfile file |data.out| in)
  (default file accept)

```

```

(make points ^one (accept)
      ^two (accept)
      ^three (accept)
      ^four (accept))
(write (crlf) |**file 'data.out' has been opened**|)
(make goal ^action fuzzy4))
(p continue_fuzzy_optimization_4
  (goal ^action fuzzy4 )
  { <data> (points ^one { <time> <> stop }
      ^two { <leak> <> stop}
      ^three { <coll> <> stop}
      ^four { <upper> <> stop} )})
-->
(modify <data> ^one (accept)
      ^two (accept)
      ^three (accept)
      ^four (accept))
(bind <time1> (compute <time> // 3600))
(write (crlf) |time step...| <time1> ||| <leak>
| Col <coll> |up| <upper> )
(bind <opt> (fo4_for <time> <leak> <coll> <upper>)))
;-----;
;*****
;*****
;
;**      FUZZY RULES      **
;
;*****
;*****
;
(p rule_1
{ <x1> (fuzzy_leak ^dm1 <dm1_l> ^l1 1 ^dm2 <dm2_l> ^l2 2 )}
{ <X2> (fuzzy_dose_r ^dm1 <dm1_d> ^l1 1 ^dm2 <dm2_d> ^l2 2 )}
{ <x3> (fuzzy_dose ^dm1 <dm1_i> ^l1 1 ^dm2 <dm2_i> ^l2 2 )}
--> (bind <minmfs1> (min_for <dm1_l> <dm1_d> <dm1_i>))
      (bind <minmfs2> (min_for <dm2_l> <dm2_d> <dm2_i>))
      (bind <label1> 1) (bind <label2> 2)
      (call fuzzyf_for <label1> <minmfs1> <label2> <minmfs2> )
      (remove <x1> <x2> <x3>)(write (crlf) |**!|))
(p rule_2
{ <x1> (fuzzy_leak ^dm1 <dm1_l> ^l1 1 ^dm2 <dm2_l> ^l2 2 )}
{ <X2> (fuzzy_dose_r ^dm1 <dm1_d> ^l1 1 ^dm2 <dm2_d> ^l2 2 )}
{ <x3> (fuzzy_dose ^dm1 <dm1_i> ^l1 2 ^dm2 <dm2_i> ^l2 3)}
--> (bind <minmfs1> (min_for <dm1_l> <dm1_d> <dm1_i>))
      (bind <minmfs2> (min_for <dm2_l> <dm2_d> <dm2_i>))
      (bind <label1> 1) (bind <label2> 2)
      (call fuzzyf_for <label1> <minmfs1> <label2> <minmfs2> )
      (remove <x1> <x2> <x3>)(write (crlf) |**2**|))
(p rule_3
{ <x1> (fuzzy_leak ^dm1 <dm1_l> ^l1 1 ^dm2 <dm2_l> ^l2 2 )}
{ <X2> (fuzzy_dose_r ^dm1 <dm1_d> ^l1 1 ^dm2 <dm2_d> ^l2 2 )}
{ <x3> (fuzzy_dose ^dm1 <dm1_i> ^l1 3 ^dm2 <dm2_i> ^l2 3)}
--> (bind <minmfs1> (min_for <dm1_l> <dm1_d> <dm1_i>))
      (bind <minmfs2> (min_for <dm2_l> <dm2_d> <dm2_i>))

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(bind <label1> 1) (bind <label2> 2)
(call fuzzyf_for <label1> <minmfs1> <label2> <minmfs2> )
(remove <x1> <x2> <x3>)(write (crlf) |**3**|))
(p rule_4
{ <x1> (fuzzy_leak ^dm1 <dm1_l> ^l1 1 ^dm2 <dm2_l> ^l2 2 )}
{ <X2> (fuzzy_dose_r ^dm1 <dm1_d> ^l1 2 ^dm2 <dm2_d> ^l2 3)}
{ <x3> (fuzzy_dose ^dm1 <dm1_i> ^l1 1 ^dm2 <dm2_i> ^l2 2 )}
--> (bind <minmfs1> (min_for <dm1_l> <dm1_d> <dm1_i>))
(bind <minmfs2> (min_for <dm2_l> <dm2_d> <dm2_i>))
(bind <label1> 1) (bind <label2> 2)
(call fuzzyf_for <label1> <minmfs1> <label2> <minmfs2> )
(remove <x1> <x2> <x3>)(write (crlf) |**4**|))
(p rule_5
{ <x1> (fuzzy_leak ^dm1 <dm1_l> ^l1 1 ^dm2 <dm2_l> ^l2 2 )}
{ <X2> (fuzzy_dose_r ^dm1 <dm1_d> ^l1 2 ^dm2 <dm2_d> ^l2 3)}
{ <x3> (fuzzy_dose ^dm1 <dm1_i> ^l1 2 ^dm2 <dm2_i> ^l2 3)}
--> (bind <minmfs1> (min_for <dm1_l> <dm1_d> <dm1_i>))
(bind <minmfs2> (min_for <dm2_l> <dm2_d> <dm2_i>))
(bind <label1> 1) (bind <label2> 2)
(call fuzzyf_for <label1> <minmfs1> <label2> <minmfs2> )
(remove <x1> <x2> <x3>)(write (crlf) |**5**|))
(p rule_6
{ <x1> (fuzzy_leak ^dm1 <dm1_l> ^l1 1 ^dm2 <dm2_l> ^l2 2 )}
{ <X2> (fuzzy_dose_r ^dm1 <dm1_d> ^l1 2 ^dm2 <dm2_d> ^l2 3)}
{ <x3> (fuzzy_dose ^dm1 <dm1_i> ^l1 3 ^dm2 <dm2_i> ^l2 3)}
--> (bind <minmfs1> (min_for <dm1_l> <dm1_d> <dm1_i>))
(bind <minmfs2> (min_for <dm2_l> <dm2_d> <dm2_i>))
(bind <label1> 1) (bind <label2> 2)
(call fuzzyf_for <label1> <minmfs1> <label2> <minmfs2> )
(remove <x1> <x2> <x3>)(write (crlf) |**6**|))
(p rule_7
{ <x1> (fuzzy_leak ^dm1 <dm1_l> ^l1 1 ^dm2 <dm2_l> ^l2 2 )}
{ <X2> (fuzzy_dose_r ^dm1 <dm1_d> ^l1 3 ^dm2 <dm2_d> ^l2 3)}
{ <x3> (fuzzy_dose ^dm1 <dm1_i> ^l1 1 ^dm2 <dm2_i> ^l2 2 )}
--> (bind <minmfs1> (min_for <dm1_l> <dm1_d> <dm1_i>))
(bind <minmfs2> (min_for <dm2_l> <dm2_d> <dm2_i>))
(bind <label1> 1) (bind <label2> 2)
(call fuzzyf_for <label1> <minmfs1> <label2> <minmfs2> )
(remove <x1> <x2> <x3>)(write (crlf) |**7**|))
(p rule_8
{ <x1> (fuzzy_leak ^dm1 <dm1_l> ^l1 1 ^dm2 <dm2_l> ^l2 2 )}
{ <X2> (fuzzy_dose_r ^dm1 <dm1_d> ^l1 3 ^dm2 <dm2_d> ^l2 3)}
{ <x3> (fuzzy_dose ^dm1 <dm1_i> ^l1 2 ^dm2 <dm2_i> ^l2 3)}
--> (bind <minmfs1> (min_for <dm1_l> <dm1_d> <dm1_i>))
(bind <minmfs2> (min_for <dm2_l> <dm2_d> <dm2_i>))
(bind <label1> 1) (bind <label2> 2)
(call fuzzyf_for <label1> <minmfs1> <label2> <minmfs2> )
(remove <x1> <x2> <x3>)(write (crlf) |**8**|))
(p rule_9
{ <x1> (fuzzy_leak ^dm1 <dm1_l> ^l1 1 ^dm2 <dm2_l> ^l2 2 )}
{ <X2> (fuzzy_dose_r ^dm1 <dm1_d> ^l1 3 ^dm2 <dm2_d> ^l2 3)}

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{ <x3> (fuzzy_dose ^dm1 <dm1_i> ^l1 3 ^dm2 <dm2_i> ^l2 3)}
--> (bind <minmfs1> (min_for <dm1_l> <dm1_d> <dm1_i>))
      (bind <minmfs2> (min_for <dm2_l> <dm2_d> <dm2_i>))
      (bind <label1> 1) (bind <label2> 2)
      (call fuzzyf_for <label1> <minmfs1> <label2> <minmfs2> )
      (remove <x1> <x2> <x3>)(write (crlf) |**9 |))
(p rule_10
{ <x1> (fuzzy_leak ^dm1 <dm1_l> ^l1 2 ^dm2 <dm2_l> ^l2 3)}
{ <X2> (fuzzy_dose_r ^dm1 <dm1_d> ^l1 1 ^dm2 <dm2_d> ^l2 2 )}
{ <x3> (fuzzy_dose ^dm1 <dm1_i> ^l1 1 ^dm2 <dm2_i> ^l2 2 )}
--> (bind <minmfs1> (min_for <dm1_l> <dm1_d> <dm1_i>))
      (bind <minmfs2> (min_for <dm2_l> <dm2_d> <dm2_i>))
      (bind <label1> 2) (bind <label2> 3)
      (call fuzzyf_for <label1> <minmfs1> <label2> <minmfs2> )
      (remove <x1> <x2> <x3>)(write (crlf) |**10**|))
(p rule_11
{ <x1> (fuzzy_leak ^dm1 <dm1_l> ^l1 2 ^dm2 <dm2_l> ^l2 3)}
{ <X2> (fuzzy_dose_r ^dm1 <dm1_d> ^l1 1 ^dm2 <dm2_d> ^l2 2 )}
{ <x3> (fuzzy_dose ^dm1 <dm1_i> ^l1 2 ^dm2 <dm2_i> ^l2 3 )}
--> (bind <minmfs1> (min_for <dm1_l> <dm1_d> <dm1_i>))
      (bind <minmfs2> (min_for <dm2_l> <dm2_d> <dm2_i>))
      (bind <label1> 2) (bind <label2> 3)
      (call fuzzyf_for <label1> <minmfs1> <label2> <minmfs2> )
      (remove <x1> <x2> <x3>)(write (crlf) |**11**|))
(p rule_12
{ <x1> (fuzzy_leak ^dm1 <dm1_l> ^l1 2 ^dm2 <dm2_l> ^l2 3)}
{ <X2> (fuzzy_dose_r ^dm1 <dm1_d> ^l1 1 ^dm2 <dm2_d> ^l2 2 )}
{ <x3> (fuzzy_dose ^dm1 <dm1_i> ^l1 3 ^dm2 <dm2_i> ^l2 3 )}
--> (bind <minmfs1> (min_for <dm1_l> <dm1_d> <dm1_i>))
      (bind <minmfs2> (min_for <dm2_l> <dm2_d> <dm2_i>))
      (bind <label1> 2) (bind <label2> 3)
      (call fuzzyf_for <label1> <minmfs1> <label2> <minmfs2> )
      (remove <x1> <x2> <x3>)(write (crlf) |**12**|))
;(p rule_13
;{ <x1> (fuzzy_leak ^dm1 <dm1_l> ^l1 2 ^dm2 <dm2_l> ^l2 3)}
;{ <X2> (fuzzy_dose_r ^dm1 <dm1_d> ^l1 2 ^dm2 <dm2_d> ^l2 3 )}
;{ <x3> (fuzzy_dose ^dm1 <dm1_i> ^l1 1 ^dm2 <dm2_i> ^l2 2 )}
;--> (bind <minmfs1> (min_for <dm1_l> <dm1_d> <dm1_i>))
;      (bind <minmfs2> (min_for <dm2_l> <dm2_d> <dm2_i>))
;      (bind <label1> 2) (bind <label2> 3)
;      (call fuzzyf_for <label1> <minmfs1> <label2> <minmfs2> )
;      (remove <x1> <x2> <x3>)(write (crlf) |**13**|))
;(p rule_14
;{ <x1> (fuzzy_leak ^dm1 <dm1_l> ^l1 2 ^dm2 <dm2_l> ^l2 3)}
;{ <X2> (fuzzy_dose_r ^dm1 <dm1_d> ^l1 2 ^dm2 <dm2_d> ^l2 3 )}
;{ <x3> (fuzzy_dose ^dm1 <dm1_i> ^l1 2 ^dm2 <dm2_i> ^l2 3 )}
;--> (bind <minmfs1> (min_for <dm1_l> <dm1_d> <dm1_i>))
;      (bind <minmfs2> (min_for <dm2_l> <dm2_d> <dm2_i>))
;      (bind <label1> 2) (bind <label2> 3)
;      (call fuzzyf_for <label1> <minmfs1> <label2> <minmfs2> )
;      (remove <x1> <x2> <x3>)(write (crlf) |**14**|))

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(p rule_15
{ <x1> (fuzzy_leak ^dm1 <dm1_l> ^l1 2 ^dm2 <dm2_l> ^l2 3))
{ <X2> (fuzzy_dose_r ^dm1 <dm1_d> ^l1 2 ^dm2 <dm2_d> ^l2 3 )}
{ <x3> (fuzzy_dose ^dm1 <dm1_i> ^l1 3 ^dm2 <dm2_i> ^l2 3 )}
--> (bind <minmfs1> (min_for <dm1_l> <dm1_d> <dm1_i>))
      (bind <minmfs2> (min_for <dm2_l> <dm2_d> <dm2_i>))
      (bind <label1> 2) (bind <label2> 3)
      (call fuzzyf_for <label1> <minmfs1> <label2> <minmfs2> )
      (remove <x1> <x2> <x3>)(write (crlf) |**15**|))
(p rule_16
{ <x1> (fuzzy_leak ^dm1 <dm1_l> ^l1 2 ^dm2 <dm2_l> ^l2 3))
{ <X2> (fuzzy_dose_r ^dm1 <dm1_d> ^l1 3 ^dm2 <dm2_d> ^l2 3 )}
{ <x3> (fuzzy_dose ^dm1 <dm1_i> ^l1 1 ^dm2 <dm2_i> ^l2 2 )}
--> (bind <minmfs1> (min_for <dm1_l> <dm1_d> <dm1_i>))
      (bind <minmfs2> (min_for <dm2_l> <dm2_d> <dm2_i>))
      (bind <label1> 2) (bind <label2> 3)
      (call fuzzyf_for <label1> <minmfs1> <label2> <minmfs2> )
      (remove <x1> <x2> <x3>)(write (crlf) |**16**|))
(p rule_17
{ <x1> (fuzzy_leak ^dm1 <dm1_l> ^l1 2 ^dm2 <dm2_l> ^l2 3))
{ <X2> (fuzzy_dose_r ^dm1 <dm1_d> ^l1 3 ^dm2 <dm2_d> ^l2 3 )}
{ <x3> (fuzzy_dose ^dm1 <dm1_i> ^l1 2 ^dm2 <dm2_i> ^l2 3 )}
--> (bind <minmfs1> (min_for <dm1_l> <dm1_d> <dm1_i>))
      (bind <minmfs2> (min_for <dm2_l> <dm2_d> <dm2_i>))
      (bind <label1> 2) (bind <label2> 3)
      (call fuzzyf_for <label1> <minmfs1> <label2> <minmfs2> )
      (remove <x1> <x2> <x3>)(write (crlf) |**17**|))
(p rule_18
{ <x1> (fuzzy_leak ^dm1 <dm1_l> ^l1 2 ^dm2 <dm2_l> ^l2 3))
{ <X2> (fuzzy_dose_r ^dm1 <dm1_d> ^l1 3 ^dm2 <dm2_d> ^l2 3 )}
{ <x3> (fuzzy_dose ^dm1 <dm1_i> ^l1 3 ^dm2 <dm2_i> ^l2 3 )}
--> (bind <minmfs1> (min_for <dm1_l> <dm1_d> <dm1_i>))
      (bind <minmfs2> (min_for <dm2_l> <dm2_d> <dm2_i>))
      (bind <label1> 2) (bind <label2> 3)
      (call fuzzyf_for <label1> <minmfs1> <label2> <minmfs2> )
      (remove <x1> <x2> <x3>)(write (crlf) |**18**|))
(p rule_19
{ <x1> (fuzzy_leak ^dm1 <dm1_l> ^l1 3 ^dm2 <dm2_l> ^l2 4))
{ <X2> (fuzzy_dose_r ^dm1 <dm1_d> ^l1 1 ^dm2 <dm2_d> ^l2 2 )}
{ <x3> (fuzzy_dose ^dm1 <dm1_i> ^l1 1 ^dm2 <dm2_i> ^l2 2 )}
--> (bind <minmfs1> (min_for <dm1_l> <dm1_d> <dm1_i>))
      (bind <minmfs2> (min_for <dm2_l> <dm2_d> <dm2_i>))
      (bind <label1> 3) (bind <label2> 4)
      (call fuzzyf_for <label1> <minmfs1> <label2> <minmfs2> )
      (remove <x1> <x2> <x3>)(write (crlf) |**19**|))
;(p rule_20
;{ <x1> (fuzzy_leak ^dm1 <dm1_l> ^l1 3 ^dm2 <dm2_l> ^l2 4))
;{ <X2> (fuzzy_dose_r ^dm1 <dm1_d> ^l1 1 ^dm2 <dm2_d> ^l2 2 )}
;{ <x3> (fuzzy_dose ^dm1 <dm1_i> ^l1 2 ^dm2 <dm2_i> ^l2 3 )}
;--> (bind <minmfs1> (min_for <dm1_l> <dm1_d> <dm1_i>))
;      (bind <minmfs2> (min_for <dm2_l> <dm2_d> <dm2_i>))
;

```

```

; (bind <label1> 3) (bind <label2> 4)
; (call fuzzyf_for <label1> <minmfs1> <label2> <minmfs2> )
; (remove <x1> <x2> <x3>)(write (crlf) |**20**|))
(p rule_21
{ <x1> (fuzzy_leak ^dm1 <dm1_l> ^l1 3 ^dm2 <dm2_l> ^l2 4)}
{ <X2> (fuzzy_dose_r ^dm1 <dm1_d> ^l1 1 ^dm2 <dm2_d> ^l2 2 )}
{ <x3> (fuzzy_dose ^dm1 <dm1_i> ^l1 3 ^dm2 <dm2_i> ^l2 3 )}
--> (bind <minmfs1> (min_for <dm1_l> <dm1_d> <dm1_i>))
      (bind <minmfs2> (min_for <dm2_l> <dm2_d> <dm2_i>))
      (bind <label1> 3) (bind <label2> 4)
      (call fuzzyf_for <label1> <minmfs1> <label2> <minmfs2> )
      (remove <x1> <x2> <x3>)(write (crlf) |**21**|))
; (p rule_22
; { <x1> (fuzzy_leak ^dm1 <dm1_l> ^l1 3 ^dm2 <dm2_l> ^l2 4)}
; { <X2> (fuzzy_dose_r ^dm1 <dm1_d> ^l1 2 ^dm2 <dm2_d> ^l2 3 )}
; { <x3> (fuzzy_dose ^dm1 <dm1_i> ^l1 1 ^dm2 <dm2_i> ^l2 2 )}
; --> (bind <minmfs1> (min_for <dm1_l> <dm1_d> <dm1_i>))
;      (bind <minmfs2> (min_for <dm2_l> <dm2_d> <dm2_i>))
;      (bind <label1> 3) (bind <label2> 4)
;      (call fuzzyf_for <label1> <minmfs1> <label2> <minmfs2> )
;      (remove <x1> <x2> <x3>)(write (crlf) |**22**|))
; (p rule_23
; { <x1> (fuzzy_leak ^dm1 <dm1_l> ^l1 3 ^dm2 <dm2_l> ^l2 4)}
; { <X2> (fuzzy_dose_r ^dm1 <dm1_d> ^l1 2 ^dm2 <dm2_d> ^l2 3 )}
; { <x3> (fuzzy_dose ^dm1 <dm1_i> ^l1 2 ^dm2 <dm2_i> ^l2 3 )}
; --> (bind <minmfs1> (min_for <dm1_l> <dm1_d> <dm1_i>))
;      (bind <minmfs2> (min_for <dm2_l> <dm2_d> <dm2_i>))
;      (bind <label1> 3) (bind <label2> 4)
;      (call fuzzyf_for <label1> <minmfs1> <label2> <minmfs2> )
;      (remove <x1> <x2> <x3>)(write (crlf) |**23**|))
; (p rule_24
; { <x1> (fuzzy_leak ^dm1 <dm1_l> ^l1 3 ^dm2 <dm2_l> ^l2 4)}
; { <X2> (fuzzy_dose_r ^dm1 <dm1_d> ^l1 2 ^dm2 <dm2_d> ^l2 3 )}
; { <x3> (fuzzy_dose ^dm1 <dm1_i> ^l1 3 ^dm2 <dm2_i> ^l2 3 )}
; --> (bind <minmfs1> (min_for <dm1_l> <dm1_d> <dm1_i>))
;      (bind <minmfs2> (min_for <dm2_l> <dm2_d> <dm2_i>))
;      (bind <label1> 3) (bind <label2> 4)
;      (call fuzzyf_for <label1> <minmfs1> <label2> <minmfs2> )
;      (remove <x1> <x2> <x3>)(write (crlf) |**24**|))
; (p rule_25
; { <x1> (fuzzy_leak ^dm1 <dm1_l> ^l1 3 ^dm2 <dm2_l> ^l2 4)}
; { <X2> (fuzzy_dose_r ^dm1 <dm1_d> ^l1 3 ^dm2 <dm2_d> ^l2 3 )}
; { <x3> (fuzzy_dose ^dm1 <dm1_i> ^l1 1 ^dm2 <dm2_i> ^l2 2 )}
; --> (bind <minmfs1> (min_for <dm1_l> <dm1_d> <dm1_i>))
;      (bind <minmfs2> (min_for <dm2_l> <dm2_d> <dm2_i>))
;      (bind <label1> 3) (bind <label2> 4)
;      (call fuzzyf_for <label1> <minmfs1> <label2> <minmfs2> )
;      (remove <x1> <x2> <x3>)(write (crlf) |**25**|))
; (p rule_26
; { <x1> (fuzzy_leak ^dm1 <dm1_l> ^l1 3 ^dm2 <dm2_l> ^l2 4)}
; { <X2> (fuzzy_dose_r ^dm1 <dm1_d> ^l1 3 ^dm2 <dm2_d> ^l2 3 )}

```

```

{ <x3> (fuzzy_dose ^dm1 <dm1_i> ^l1 2 ^dm2 <dm2_i> ^l2 3 )}
--> (bind <minmfs1> (min_for <dm1_l> <dm1_d> <dm1_i>))
      (bind <minmfs2> (min_for <dm2_l> <dm2_d> <dm2_i>))
      (bind <label1> 3) (bind <label2> 4)
      (call fuzzyf_for <label1> <minmfs1> <label2> <minmfs2> )
      (remove <x1> <x2> <x3>)(write (crlf) |**26**|))
(p rule_27
{ <x1> (fuzzy_leak ^dm1 <dm1_l> ^l1 3 ^dm2 <dm2_l> ^l2 4)}
{ <X2> (fuzzy_dose_r ^dm1 <dm1_d> ^l1 3 ^dm2 <dm2_d> ^l2 3 )}
{ <x3> (fuzzy_dose ^dm1 <dm1_i> ^l1 3 ^dm2 <dm2_i> ^l2 3 )}
--> (bind <minmfs1> (min_for <dm1_l> <dm1_d> <dm1_i>))
      (bind <minmfs2> (min_for <dm2_l> <dm2_d> <dm2_i>))
      (bind <label1> 3) (bind <label2> 4)
      (call fuzzyf_for <label1> <minmfs1> <label2> <minmfs2> )
      (remove <x1> <x2> <x3>)(write (crlf) |**27**|))
(p rule_28
{ <x1> (fuzzy_leak ^dm1 <dm1_l> ^l1 4 ^dm2 <dm2_l> ^l2 5)}
{ <X2> (fuzzy_dose_r ^dm1 <dm1_d> ^l1 1 ^dm2 <dm2_d> ^l2 2 )}
{ <x3> (fuzzy_dose ^dm1 <dm1_i> ^l1 1 ^dm2 <dm2_i> ^l2 2 )}
--> (bind <minmfs1> (min_for <dm1_l> <dm1_d> <dm1_i>))
      (bind <minmfs2> (min_for <dm2_l> <dm2_d> <dm2_i>))
      (bind <label1> 4) (bind <label2> 5)
      (call fuzzyf_for <label1> <minmfs1> <label2> <minmfs2> )
      (remove <x1> <x2> <x3>)(write (crlf) |**28**|))
(p rule_29
{ <x1> (fuzzy_leak ^dm1 <dm1_l> ^l1 4 ^dm2 <dm2_l> ^l2 5)}
{ <X2> (fuzzy_dose_r ^dm1 <dm1_d> ^l1 1 ^dm2 <dm2_d> ^l2 2 )}
{ <x3> (fuzzy_dose ^dm1 <dm1_i> ^l1 2 ^dm2 <dm2_i> ^l2 3 )}
--> (bind <minmfs1> (min_for <dm1_l> <dm1_d> <dm1_i>))
      (bind <minmfs2> (min_for <dm2_l> <dm2_d> <dm2_i>))
      (bind <label1> 4) (bind <label2> 5)
      (call fuzzyf_for <label1> <minmfs1> <label2> <minmfs2> )
      (remove <x1> <x2> <x3>)(write (crlf) |**29**|))
(p rule_30
{ <x1> (fuzzy_leak ^dm1 <dm1_l> ^l1 4 ^dm2 <dm2_l> ^l2 5)}
{ <X2> (fuzzy_dose_r ^dm1 <dm1_d> ^l1 1 ^dm2 <dm2_d> ^l2 2 )}
{ <x3> (fuzzy_dose ^dm1 <dm1_i> ^l1 3 ^dm2 <dm2_i> ^l2 3 )}
--> (bind <minmfs1> (min_for <dm1_l> <dm1_d> <dm1_i>))
      (bind <minmfs2> (min_for <dm2_l> <dm2_d> <dm2_i>))
      (bind <label1> 4) (bind <label2> 5)
      (call fuzzyf_for <label1> <minmfs1> <label2> <minmfs2> )
      (remove <x1> <x2> <x3>)(write (crlf) |**30**|))
(p rule_31
{ <x1> (fuzzy_leak ^dm1 <dm1_l> ^l1 4 ^dm2 <dm2_l> ^l2 5)}
{ <X2> (fuzzy_dose_r ^dm1 <dm1_d> ^l1 2 ^dm2 <dm2_d> ^l2 3 )}
{ <x3> (fuzzy_dose ^dm1 <dm1_i> ^l1 1 ^dm2 <dm2_i> ^l2 2 )}
--> (bind <minmfs1> (min_for <dm1_l> <dm1_d> <dm1_i>))
      (bind <minmfs2> (min_for <dm2_l> <dm2_d> <dm2_i>))
      (bind <label1> 4) (bind <label2> 5)
      (call fuzzyf_for <label1> <minmfs1> <label2> <minmfs2> )
      (remove <x1> <x2> <x3>)(write (crlf) |**31**|))

```



```

(bind <label1> 5) (bind <label2> 5)
(call fuzzyf_for <label1> <minmfs1> <label2> <minmfs2> )
(remove <x1> <x2> <x3>)(write (crlf) |**37**|))
(p rule_38
{ <x1> (fuzzy_leak ^dm1 <dm1_l> ^l1 5 ^dm2 <dm2_l> ^l2 5)}
{ <X2> (fuzzy_dose_r ^dm1 <dm1_d> ^l1 1 ^dm2 <dm2_d> ^l2 2 )}
{ <x3> (fuzzy_dose ^dm1 <dm1_i> ^l1 2 ^dm2 <dm2_i> ^l2 3 )}
--> (bind <minmfs1> (min_for <dm1_l> <dm1_d> <dm1_i>))
(bind <minmfs2> (min_for <dm2_l> <dm2_d> <dm2_i>))
(bind <label1> 5) (bind <label2> 5)
(call fuzzyf_for <label1> <minmfs1> <label2> <minmfs2> )
(remove <x1> <x2> <x3>)(write (crlf) |**38**|))
(p rule_39
{ <x1> (fuzzy_leak ^dm1 <dm1_l> ^l1 5 ^dm2 <dm2_l> ^l2 5)}
{ <X2> (fuzzy_dose_r ^dm1 <dm1_d> ^l1 1 ^dm2 <dm2_d> ^l2 2 )}
{ <x3> (fuzzy_dose ^dm1 <dm1_i> ^l1 3 ^dm2 <dm2_i> ^l2 3 )}
--> (bind <minmfs1> (min_for <dm1_l> <dm1_d> <dm1_i>))
(bind <minmfs2> (min_for <dm2_l> <dm2_d> <dm2_i>))
(bind <label1> 5) (bind <label2> 5)
(call fuzzyf_for <label1> <minmfs1> <label2> <minmfs2> )
(remove <x1> <x2> <x3>)(write (crlf) |**39**|))
(p rule_40
{ <x1> (fuzzy_leak ^dm1 <dm1_l> ^l1 5 ^dm2 <dm2_l> ^l2 5)}
{ <X2> (fuzzy_dose_r ^dm1 <dm1_d> ^l1 2 ^dm2 <dm2_d> ^l2 3 )}
{ <x3> (fuzzy_dose ^dm1 <dm1_i> ^l1 1 ^dm2 <dm2_i> ^l2 2 )}
--> (bind <minmfs1> (min_for <dm1_l> <dm1_d> <dm1_i>))
(bind <minmfs2> (min_for <dm2_l> <dm2_d> <dm2_i>))
(bind <label1> 5) (bind <label2> 5)
(call fuzzyf_for <label1> <minmfs1> <label2> <minmfs2> )
(remove <x1> <x2> <x3>)(write (crlf) |**40**|))
(p rule_41
{ <x1> (fuzzy_leak ^dm1 <dm1_l> ^l1 5 ^dm2 <dm2_l> ^l2 5)}
{ <X2> (fuzzy_dose_r ^dm1 <dm1_d> ^l1 2 ^dm2 <dm2_d> ^l2 3 )}
{ <x3> (fuzzy_dose ^dm1 <dm1_i> ^l1 2 ^dm2 <dm2_i> ^l2 3 )}
--> (bind <minmfs1> (min_for <dm1_l> <dm1_d> <dm1_i>))
(bind <minmfs2> (min_for <dm2_l> <dm2_d> <dm2_i>))
(bind <label1> 5) (bind <label2> 5)
(call fuzzyf_for <label1> <minmfs1> <label2> <minmfs2> )
(remove <x1> <x2> <x3>)(write (crlf) |**41**|))
(p rule_42
{ <x1> (fuzzy_leak ^dm1 <dm1_l> ^l1 5 ^dm2 <dm2_l> ^l2 5)}
{ <X2> (fuzzy_dose_r ^dm1 <dm1_d> ^l1 2 ^dm2 <dm2_d> ^l2 3 )}
{ <x3> (fuzzy_dose ^dm1 <dm1_i> ^l1 3 ^dm2 <dm2_i> ^l2 3 )}
--> (bind <minmfs1> (min_for <dm1_l> <dm1_d> <dm1_i>))
(bind <minmfs2> (min_for <dm2_l> <dm2_d> <dm2_i>))
(bind <label1> 5) (bind <label2> 5)
(call fuzzyf_for <label1> <minmfs1> <label2> <minmfs2> )
(remove <x1> <x2> <x3>)(write (crlf) |**42**|))
(p rule_43
{ <x1> (fuzzy_leak ^dm1 <dm1_l> ^l1 5 ^dm2 <dm2_l> ^l2 5)}
{ <X2> (fuzzy_dose_r ^dm1 <dm1_d> ^l1 3 ^dm2 <dm2_d> ^l2 3 )}

```

```

{ <x3> (fuzzy_dose ^dm1 <dm1_i> ^l1 1 ^dm2 <dm2_i> ^l2 2 )}
--> (bind <minmfs1> (min_for <dm1_l> <dm1_d> <dm1_i>))
      (bind <minmfs2> (min_for <dm2_l> <dm2_d> <dm2_i>))
      (bind <label1> 5) (bind <label2> 5)
      (call fuzzyf_for <label1> <minmfs1> <label2> <minmfs2> )
      (remove <x1> <x2> <x3>)(write (crlf) |**43**|))

(p rule_44
{ <x1> (fuzzy_leak ^dm1 <dm1_l> ^l1 5 ^dm2 <dm2_l> ^l2 5)}
{ <X2> (fuzzy_dose_r ^dm1 <dm1_d> ^l1 3 ^dm2 <dm2_d> ^l2 3 )}
{ <x3> (fuzzy_dose ^dm1 <dm1_i> ^l1 2 ^dm2 <dm2_i> ^l2 3 )}
--> (bind <minmfs1> (min_for <dm1_l> <dm1_d> <dm1_i>))
      (bind <minmfs2> (min_for <dm2_l> <dm2_d> <dm2_i>))
      (bind <label1> 5) (bind <label2> 5)
      (call fuzzyf_for <label1> <minmfs1> <label2> <minmfs2> )
      (remove <x1> <x2> <x3>)(write (crlf) |**44**|))

(p rule_45
{ <x1> (fuzzy_leak ^dm1 <dm1_l> ^l1 5 ^dm2 <dm2_l> ^l2 5)}
{ <X2> (fuzzy_dose_r ^dm1 <dm1_d> ^l1 3 ^dm2 <dm2_d> ^l2 3 )}
{ <x3> (fuzzy_dose ^dm1 <dm1_i> ^l1 3 ^dm2 <dm2_i> ^l2 3 )}
--> (bind <minmfs1> (min_for <dm1_l> <dm1_d> <dm1_i>))
      (bind <minmfs2> (min_for <dm2_l> <dm2_d> <dm2_i>))
      (bind <label1> 5) (bind <label2> 5)
      (call fuzzyf_for <label1> <minmfs1> <label2> <minmfs2> )
      (remove <x1> <x2> <x3>)(write (crlf) |***45**|))
,*****
,*****
,***** end of fuzzy rules *****
,*****
,*****
,*****
(p rule_to_holt_the_cycle
(fuzzy_leak ^dm1 1 ^l1 1 ^dm2 0.0 ^l2 2)
(fuzzy_dose_r ^dm1 1 ^l1 1 ^dm2 0.0 ^l2 2)
(fuzzy_dose ^dm1 1 ^l1 3 ^dm2 1 ^l2 3)
(data ^cubicle <comp>
      ^dose { > 206328.1 }
      ^collective { > 100000 })
(values ^leak { = 0.0 })
(multi_one ^dose_rate { =0.0 })
(icrp ^cost { > 20 })
(flow ^centroid { < 1.0 } )
(state ^time { >= 170000 })
-->

(write (crlf) |_____|
      (crlf) | ----end of a cycle |)
(closefile dataout)
(make task ^name fuzzy))
(p stop_program-1
(fuzzy_leak ^dm1 1.0 ^l1 1 ^dm2 0.0 ^l2 2)
(fuzzy_dose_r ^dm1 1.0 ^l1 1 ^dm2 0.0 ^l2 2)
(fuzzy_dose ^dm1 <d1> ^l1 2 ^dm2 <d2> ^l2 3)

```



```

-->
(write (crlf) | _____ |)
(write (crlf) | ----end of a cycle rule 1----- |)
(closefile dataout)
(write (crlf) |**file 'data.out' has been closed**|)
(make task ^name fuzzy))
(p stop_program-2
{ <x1> (fuzzy_leak ^dm1 1.0 ^l1 1 ^dm2 0.0 ^l2 2 )}
{ <X2> (fuzzy_dose_r ^dm1 1.0 ^l1 1 ^dm2 0.0 ^l2 2 )}
{ <x3> (fuzzy_dose ^dm1 <1> ^l1 <2> ^dm2 <3> ^l2 <4>)})
-->
(write (crlf) | _____ |)
(write (crlf) | ----end of a cycle rule 2      | (crlf) )
(closefile dataout)
(write (crlf) |**file 'data.out' has been closed**|)
(make task ^name fuzzy))
;-----
;(default dataout write)
; (write dataout (crlf) (tabto 1 ) <time>
;                (tabto 10) <leak>
;                (tabto 23) <coll>
;                (tabto 38) <upper>
;                (tabto 45) <cost>
;                (tabto 55) <centroid>
;                (tabto 65) <dose1>)
; (default nil write)
;-----
$

```

```
*****
*****
```

# SUBROUTINE COMP1\_FOR()

```
*-----*
* SINGLE COMPARTMENT MODEL *
* This program calculates the dose rate *
* as a function of time *
*-----*
```

IMPLICIT REAL (A-Z)

```
C definition of VAX OPS5 support routine
INCLUDE 'OPS$LIBRARY:OPSDEF.FOR'
INTEGER dose_atom,dr_atom
INTEGER I,atom_one,atom_two,k1,c,V,time
REAL DOSE1,CO,a,d,b,total,intdose,t,w,f,b1
REAL flow,leak
```

```
character*8 class
character*9 atr1
```

```
data class / 'COMP_ONE' /
data atr1 / 'DOSE_RATE' /
```

```
IF (OPS$PARAMETERCOUNT() .LE. 2) THEN
```

```
atom_one = OPS$PARAMETER(%VAL(1))
atom_two = OPS$PARAMETER(%VAL(2))
```

```
END IF
```

```
IF (OPS$INTEGER(%VAL(atom_one))) THEN
leak= OPS$CVAN (%VAL(atom_one))
ELSE IF (OPS$FLOATING(%VAL(atom_one))) THEN
leak= OPS$CVAF (%VAL(atom_one))
END IF
```

```
IF (OPS$INTEGER(%VAL(atom_two))) THEN
flow= OPS$CVAN (%VAL(atom_two))
ELSE IF (OPS$FLOATING(%VAL(atom_two))) THEN
flow= OPS$CVAF (%VAL(atom_two))
END IF
```

```
print*, leak,flow
```

```
k1=472.1
c= 20.00
v1= 3.0E+10
a= flow/v1
d= 0.1337*0.1*leak*c/flow
```

```

DO I=1,500.0,10
  b=-a*k1*I
  CO= d*(1-exp(b))
  DOSE1= CO * 8.33E+06
END DO

```

```

print*, 'dose-rate after loop',dose1

```

```

c-----
c  the dose rate is in mrem/hr and the integrated dose           c
c  in mrem, partition factor is 10% (0.1), decay constant for   c
c  I-131 is 6.0e-05 min, typical air flow is 5000 cub-ft=      c
c  1.41e+08 cc, c the concentration of the I-131 in the water  c
c  is 20 micro-curie/cc,con multi by 1.0E+06 gives mrem/hr the c
c  concentration is in micro-curie/cc.                          c
c-----

```

```

dr_atom= OPS$CVFA (%VAL(DOSE1))

```

```

CALL OPS$CLEAR
CALL OPS$RESET()

```

```

CALL OPS$VALUE (%VAL (OPS$INTERN( %REF (CLASS),
1              %VAL( LEN( CLASS )))))

```

```

C ATTRIBUTE dose rate

```

```

CALL OPS$TAB( %VAL( OPS$INTERN( %REF( atr1 ),
1              %VAL( LEN( atr1 ) ) ) ) )

```

```

CALL OPS$VALUE(%VAL (dr_atom), %VAL( LEN( atr1 )))

```

```

c  CALL OPS$WRITE ()

```

```

CALL OPS$ASSERT ()

```

```

RETURN

```

```

END

```

```

$

```

```

SUBROUTINE COMP2_FOR()
*-----*
* SINGLE COMPARTMENT MODEL *
* This program calculates the dose rate *
* as a function of time *
*-----*
IMPLICIT REAL (A-Z)
C definition of VAX OPS5 support routine
INCLUDE 'OPS$LIBRARY:OPSDEF.FOR'
INTEGER dose_atom,dr_atom
INTEGER I,atom_one,atom_two,k1,c,V,time
REAL DOSE1,CO,a,d,b,total,intdose,t,w,f,b1
REAL*4 flow,leak

character*8 class
character*9 atr1

data class / 'COMP_TWO' /
data atr1 / 'DOSE_RATE' /

IF (OPSP$PARAMETERCOUNT() .LE. 2) THEN

    atom_one = OPSP$PARAMETER(%VAL(1))
    atom_two = OPSP$PARAMETER(%VAL(2))

END IF

IF (OPSP$INTEGER(%VAL(atom_one))) THEN
leak= OPSP$CVAN (%VAL(atom_one))
ELSE IF (OPSP$FLOATING(%VAL(atom_one))) THEN
leak= OPSP$CVAF (%VAL(atom_one))
END IF

IF (OPSP$INTEGER(%VAL(atom_two))) THEN
flow= OPSP$CVAN (%VAL(atom_two))
ELSE IF (OPSP$FLOATING(%VAL(atom_two))) THEN
flow= OPSP$CVAF (%VAL(atom_two))
END IF

k1= 472.0
k2= 0.1337*0.1*20.0

v1= 3.0E+10
v2= 1.33E+09
k3= v1/(v1-v2)

d1= leak*k2/flow
d2= leak*k2*k3/flow

```

DO I=1,500.0,10

a= -(flow/v1)\*k1\*I

b= -(flow/v2)\*k1\*I

CO=d1\*(1-exp(b))+d2\*(exp(b)-exp(a))

DOSE2= CO\*8.33e+06

END DO

c-----  
c the dose rate is in mrem/hr c  
c in mrem, partition factor is 10% (0.1), decay constant for c  
c I-131 is 6.0e-05 min, typical air flow is 5000 cub-ft= c  
c 1.41e+08 cc, c the concentration of the I-131 in the water c  
c is 20 micro-curie/cc, con multi by 1.0E+06 gives mrem/hr the c  
c concentration is in micro-curie/cc. c

c-----

dr\_atom= OPS\$CVFA (%VAL(DOSE2))

CALL OPS\$RESET()

CALL OPS\$VALUE (%VAL (OPS\$INTERN( %REF (CLASS),  
1 %VAL( LEN( CLASS )))))

C ATTRIBUTE dose rate

CALL OPS\$TAB( %VAL( OPS\$INTERN( %REF( atr1 ),  
1 %VAL( LEN( atr1 ) ) ) ) )

CALL OPS\$VALUE(%VAL (dr\_atom), %VAL( LEN( atr1 ) ) )

c CALL OPS\$WRITE ()

CALL OPS\$ASSERT ()

RETURN

END

```

SUBROUTINE COMP3_FOR ()
*-----*
* THIRD COMPARTMENT MODEL
* This program calculates the dose rate
* as a function of time
*-----*
IMPLICIT REAL (A-Z)
INCLUDE 'OPSLIBRARY:OPSDEF.FOR'
INTEGER dose_atom,dr_atom,k1
INTEGER I,atom_one,atom_two,time
REAL f1,f3,k2,k3,k6,k8,k05,k5
REAL flow,leak,co,a,b,c

character*10 class
character*9 atr1

data class / 'COMP_THREE' /
data atr1 / 'DOSE_RATE' /

IF (OPSPARAMETERCOUNT() .LE. 2) THEN

    atom_one = OPSPARAMETER(%VAL(1))
    atom_two = OPSPARAMETER(%VAL(2))

END IF

IF (OPSPINTEGER(%VAL(atom_one))) THEN
leak= OPSCVAN (%VAL(atom_one))
ELSE IF (OPSFLOATING(%VAL(atom_one))) THEN
leak= OPSCVAF (%VAL(atom_one))
END IF

IF (OPSPINTEGER(%VAL(atom_two))) THEN
flow= OPSCVAN (%VAL(atom_two))
ELSE IF (OPSFLOATING(%VAL(atom_two))) THEN
flow= OPSCVAF (%VAL(atom_two))
END IF

c    print*, 'leak',leak, 'flow',flow

v1= 3.0E+10
v2= 1.33E+09
v3= 6.8520E+08

k1= 472.0
k2= 0.1337*0.1*20

k3= v1**2
k4= v2**2

```

```

k5= (v1-v2)*(v1-v3)
k05= (v1-v2)*(v2-v3)
k6= leak*k2*k4/k05
k8= leak*k2*k3/k5

```

```

DO I=1,500.0,10
a= -(flow*k1/v1)*I
b= -(flow*k1/v2)*I
c= -(flow*k1/v3)*I

```

```

f1= k6*(exp(b)-exp(c))/flow + leak*k2*(1-exp(c))/flow
f3= k8*(exp(c)-exp(a))/flow

```

```

CO= f3+f1

```

```

DOSE3 = CO*8.33e+06
END DO

```

```

c      print*,'k8',k8,'c-a',exp(c)-exp(a),'f3',f3
c      print*,'k6',k6,'b-c',exp(b)-exp(c),'f1',f1
c      print*, f1, f3, ' + ', 'co',co

```

```

c-----
c      the dose rate is in mrem/hr                                     c
c      in mrem, partition factor is 10% (0.1), decay constant for    c
c      I-131 is 6.0e-05 min, typical air flow is 5000 cub-ft=        c
c      1.41e+08 cc, c the concentration of the I-131 in the water    c
c      is 20 micro-curie/cc,con multi by 1.0E+06 gives mrem/hr the   c
c      concentration is in micro-curie/cc.                             c
c-----

```

```

dr_atom= OPSCVFA (%VAL(DOSE3))

```

```

CALL OPSCLEAR
CALL OPS$RESET()

```

```

CALL OPS$VALUE (%VAL (OPSC$INTERN( %REF (CLASS),
1              %VAL( LEN( CLASS ) )))

```

```

C ATTRIBUTE dose rate
CALL OPSC$TAB( %VAL( OPSC$INTERN( %REF( atr1 ),
1              %VAL( LEN( atr1 ) ) ) ) )
CALL OPS$VALUE(%VAL (dr_atom), %VAL( LEN( atr1 ) ) )

```

```

c      CALL OPS$WRITE ()

```

```

CALL OPS$ASSERT ()

```

```

RETURN

```

```

END

```

```

SUBROUTINE COMP4_FOR()
*-----*
* DIVIDED COMPARTMENT MODEL *
* This program calculates the dose rate *
* as a function of time *
*-----*
IMPLICIT REAL (A-Z)
C definition of VAX OPS5 support routine
INCLUDE 'OPS$LIBRARY:OPSDEF.FOR'
INTEGER dose_atom,dr_atom
INTEGER I,atom_one,atom_two,k1,c,V,time
REAL DOSE1,CO,a,d,b,total,intdose,t,w,f,b1
REAL*4 flow,leak

character*9 class
character*9 atr1

data class / 'COMP_FOUR' /
data atr1 / 'DOSE_RATE' /

IF (OPS$PARAMETERCOUNT() .LE. 2) THEN

    atom_one = OPS$PARAMETER(%VAL(1))
    atom_two = OPS$PARAMETER(%VAL(2))

END IF

IF (OPS$INTEGER(%VAL(atom_one))) THEN
leak= OPS$CVAN (%VAL(atom_one))
ELSE IF (OPS$FLOATING(%VAL(atom_one))) THEN
leak= OPS$CVAF (%VAL(atom_one))
END IF

IF (OPS$INTEGER(%VAL(atom_two))) THEN
flow= OPS$CVAN (%VAL(atom_two))
ELSE IF (OPS$FLOATING(%VAL(atom_two))) THEN
flow= OPS$CVAF (%VAL(atom_two))
END IF

k1=472.0
k2= 0.1337*0.1*20.0

v1= 5.0E+10
v2= 4.0E+09

k03= 2*(v1-2*v2)
k3= v1/k03

I=500.0
a= -(flow*2*k1*I)/v1

```



b= -(flow\*k1\*I)/v2

f1= k2\*leak/flow

f2= k2\*leak\*k3/flow

CO=f1\*(1-exp(b))/2+f2\*(exp(b)-exp(a))

DOSE4=CO\*8.33E+06

```
c-----
c  the dose rate is in mrem/hr and the integrated dose           c
c  in mrem, partition factor is 10% (0.1), decay constant for    c
c  I-131 is 6.0e-05 min, typical air flow is 5000 cub-ft=       c
c  1.41e+08 cc, c the concentration of the I-131 in the water   c
c  is 20 micro-curie/cc,con multi by 1.0E+06 gives mrem/hr the  c
c  concentration is in micro-curie/cc.                           c
c-----
```

dr\_atom= OPS\$CVFA (%VAL(DOSE4))

CALL OPS\$RESET()

CALL OPS\$VALUE (%VAL (OPS\$INTERN( %REF (CLASS),  
1 %VAL( LEN( CLASS )))))

C ATTRIBUTE dose rate

CALL OPS\$TAB( %VAL( OPS\$INTERN( %REF( atr1 ),  
1 %VAL( LEN( atr1 ) ) ) ) )

CALL OPS\$VALUE(%VAL (dr\_atom), %VAL( LEN( atr1 ) ) )

c CALL OPS\$WRITE ()

CALL OPS\$ASSERT ()

RETURN

END

# SUBROUTINE FUZZYD1\_FOR()

```

*-----*
*
* FUZZY DOSE
* This program calculates the membership functions
* of collective dose
*-----*
c  IMPLICIT REAL (A-Z)
C  definition of VAX OPS5 support routine
  INCLUDE 'OPS$LIBRARY:OPSDEF.FOR'
  INTEGER atr1_atom,atr2_atom,atr3_atom,atr4_atom
  INTEGER atom_one,labelone,labeltwo
  REAL dose,x,msfone,msftwo
  REAL m1,m2,m3,m4,m5

  character*10 class
  character*3 atr1
  character*2 atr2
  character*3 atr3
  character*2 atr4

  data  class / 'FUZZY_DOSE' /
  data  atr1 / 'DM1' /
  data  atr2 / 'L1' /
  data  atr3 / 'DM2' /
  data  atr4 / 'L2' /

  IF (OPSP$PARAMETERCOUNT() .LE. 1) THEN

    atom_one = OPSP$PARAMETER(%VAL(1))

  END IF

  IF (OPSP$INTEGER(%VAL(atom_one))) THEN
    dose= OPSP$CVAN (%VAL(atom_one))
  ELSE IF (OPSP$FLOATING(%VAL(atom_one))) THEN
    dose= OPSP$CVAF (%VAL(atom_one))
  END IF

c  print*, ' passed dose',dose
*****
*  COLLECTIVE DOSE MEMBERSHIP FUNCTIONS  *
*****

  x=dose/65.0

  IF( x .GE. 0.0 .AND. x .LE. 0.5) THEN
    m1= 1-2*x

```

```

msfone=1.0
labelone= 1
m2= 2*x
msftwo=1.0
labeltwo= 2
END IF

```

```

IF( x .GT. 0.5 .AND. x .LT. 1.0)THEN
m3= 2-2*x
msfone=1.0
labelone= 2
m4= 2*x-1
msftwo=1.0
labeltwo= 3
END IF

```

```

IF( x .GE. 1.0)THEN
msfone=1.0
labelone= 3
msftwo=1.0
labeltwo= 3
END IF

```

```

c  print*, labelone, ' ',msfone, ' ',labeltwo, ' ',msftwo
c  print*, '
c  print*, 'msfone',msfone,'msftwo',msftwo
c  print*, 'labelone',labelone,'labeltwo',labeltwo

```

```

atr1_atom= OPS$CVFA (%VAL(msfone))
atr2_atom= OPS$CVNA (%VAL(labelone))
atr3_atom= OPS$CVFA (%VAL(msftwo))
atr4_atom= OPS$CVNA (%VAL(labeltwo))

```

```

CALL OPS$CLEAR()
CALL OPS$RESET()

```

```

CALL OPS$VALUE (%VAL (OPS$INTERN( %REF (CLASS),
1          %VAL( LEN( CLASS )))))

```

```

C ATTRIBUTE m1
CALL OPS$TAB( %VAL( OPS$INTERN( %REF( atr1 ),
1          %VAL( LEN( atr1 ) ) ) ) )
CALL OPS$VALUE(%VAL (atr1_atom), %VAL( LEN( atr1 )))

```

```

C ATTRIBUTE m2
CALL OPS$TAB( %VAL( OPS$INTERN( %REF( atr2 ),
1          %VAL( LEN( atr2 ) ) ) ) )
CALL OPS$VALUE(%VAL (atr2_atom), %VAL( LEN( atr2 )))

```

```

C ATTRIBUTE label1

```

```
CALL OPS$TAB( %VAL( OPS$INTERN( %REF( atr3 ),
1      %VAL( LEN( atr3 ) ) ) ) )
CALL OPS$VALUE(%VAL (atr3_atom), %VAL( LEN( atr3 )))
```

C ATTRIBUTE label2

```
CALL OPS$TAB( %VAL( OPS$INTERN( %REF( atr4 ),
1      %VAL( LEN( atr4 ) ) ) ) )
CALL OPS$VALUE(%VAL (atr4_atom), %VAL( LEN( atr4 )))
```

c CALL OPS\$WRITE ()

CALL OPS\$ASSERT ()

RETURN

END

```

SUBROUTINE FUZZYDR1_FOR()
*-----*
* FUZZY DOSE RATE MODEL *
* This program calculates the membership functions *
* the dose rate *
*-----*
  INCLUDE 'OPSS$LIBRARY:OPSDEF.FOR'
  INTEGER atr1_atom,atr2_atom,atr3_atom,atr4_atom
  INTEGER atom_one,labelone,labeltwo
  REAL dose,x
  REAL m1,m2,m3,m4,m5,m6,m7,msfone,msftwo,m8,m9,m10

  character*12 class
  character*3 atr1
  character*2 atr2
  character*3 atr3
  character*2 atr4

  data class / 'FUZZY_DOSE_R' /
  data atr1 / 'DM1' /
  data atr2 / 'L1' /
  data atr3 / 'DM2' /
  data atr4 / 'L2' /

  IF (OPSS$PARAMETERCOUNT() .LE. 1) THEN

    atom_one = OPSS$PARAMETER(%VAL(1))

  END IF

  IF (OPSS$INTEGER(%VAL(atom_one))) THEN
    dose= OPSS$CVAN (%VAL(atom_one))
  ELSE IF (OPSS$FLOATING(%VAL(atom_one))) THEN
    dose= OPSS$CVAF (%VAL(atom_one))
  END IF

c  print*,' dose rate passed to fortran', dose

*****
*      DOSE RATE MEMBERSHIP FUNCTIONS      *
*****

  x=dose/1200.0

  IF( x .GE. 0.0 .AND. x .LE. 0.5) THEN
    m1= 1-2*x
    msfone=m1
    labelone= 1
    m2= 2*x
    msftwo=m2

```

```

labeltwo= 2
END IF
IF( x .GT. 0.5 .AND. x .LT. 1.0)THEN
  m3= 2-2*x
  msfone=m3
  labelone= 2
  m4= 2*x-1
  msftwo=m4
  labeltwo= 3
END IF

```

```

IF( x .GE. 1.0)THEN
  msfone=1.0
  labelone= 3
  msftwo=1.0
  labeltwo= 3
END IF

```

```

c  print*, 'msfone',msfone, 'labelone', labelone
c  print*, 'mfstwo', msftwo, 'labeltwo', labeltwo
c  print*, '

```

```

atr1_atom= OPS$CVFA (%VAL(msfone))
atr2_atom= OPS$CVNA (%VAL(labelone))
atr3_atom= OPS$CVFA (%VAL(msftwo))
atr4_atom= OPS$CVNA (%VAL(labeltwo))

```

```

C-----
CALL OPS$CLEAR()
CALL OPS$RESET()

CALL OPS$VALUE (%VAL (OPS$INTERN( %REF (CLASS),
1          %VAL( LEN( CLASS )))))

```

```

C ATTRIBUTE msfone
CALL OPS$TAB( %VAL( OPS$INTERN( %REF( atr1 ),
1          %VAL( LEN( atr1 ) ) ) ) )
CALL OPS$VALUE(%VAL (atr1_atom), %VAL( LEN( atr1 )))

```

```

C ATTRIBUTE label_1
CALL OPS$TAB( %VAL( OPS$INTERN( %REF( atr2 ),
1          %VAL( LEN( atr2 ) ) ) ) )
CALL OPS$VALUE(%VAL (atr2_atom), %VAL( LEN( atr2 )))

```

```

C ATTRIBUTE m2
CALL OPS$TAB( %VAL( OPS$INTERN( %REF( atr3 ),
1          %VAL( LEN( atr3 ) ) ) ) )
CALL OPS$VALUE(%VAL (atr3_atom), %VAL( LEN( atr3 )))

```

```

C ATTRIBUTE label_2

```

```

CALL OPS$TAB( %VAL( OPS$INTERN( %REF( atr4 ),
1          %VAL( LEN( atr4 ) ) ) ) )
CALL OPS$VALUE(%VAL (atr4_atom), %VAL( LEN( atr4 )))

```

```

c  CALL OPS$WRITE ()

```

```

CALL OPS$ASSERT()

```

```

RETURN

```

```

END

```

```

SUBROUTINE FUZZYL_FOR ()

```

```

*-----*
*
* FUZZY LEAK MODEL
* This program calculates the membership functions
* THE LEAK
*-----*

```

```

C  definition of VAX OPS5 support routine
  INCLUDE 'OPS$LIBRARY:OPSDEF.FOR'
  INTEGER atr1_atom,atr2_atom,atr3_atom,atr4_atom
  INTEGER atom_one,labelone,labeltwo
  REAL m1,m2,m3,m4,m5,m6,m7,m8,mfsone,mfstwo
  REAL leak,x

```

```

character*10 class
character*3 atr1
character*2 atr2
character*3 atr3
character*2 atr4

```

```

data  class / 'FUZZY_LEAK' /
data  atr1 / 'DM1' /
data  atr2 / 'L1' /
data  atr3 / 'DM2' /
data  atr4 / 'L2' /

```

```

IF (OPS$PARAMETERCOUNT() .LE. 1) THEN

```

```

    atom_one = OPS$PARAMETER(%VAL(1))

```

```

END IF

```

```

IF (OPS$INTEGER(%VAL(atom_one))) THEN
leak= OPS$CVAN (%VAL(atom_one))
ELSE IF (OPS$FLOATING(%VAL(atom_one))) THEN
leak= OPS$CVAF (%VAL(atom_one))
END IF

```

```

c  print*, ' passed leak in fortran', leak

```

```
*****
*      LEAK MEMBERSHIP FUNCTIONS      *
*****
```

```
x=leak/47.0
```

```
IF(x .GE. 0.0 .AND. x .LE. 0.25) THEN
m1= 1- 4*x
mfsone= m1
labelone= 1
m2 =4*x
mfstwo= m2
labeltwo= 2
END IF
```

```
IF(x .GT. 0.25 .AND. x .LT. 0.5) THEN
m3= 2-4*x
mfsone= m3
labelone= 2
m4 =4*x-1
mfstwo= m4
labeltwo= 3
END IF
```

```
IF(x .GE. 0.5 .AND. x .LE. 0.75) THEN
m5= 3-4*x
mfsone= m5
labelone= 3
m6 =4*x-2
mfstwo= m6
labeltwo= 4
END IF
```

```
IF(x .GT. 0.75 .AND. x .LT. 1.0) THEN
m7=4-4*x
mfsone= m7
labelone= 4
m8= 4*x-3
mfstwo= m8
labeltwo= 5
END IF
```

```
IF(x .GT. 1.0) THEN
mfsone= 1.0
labelone= 5
mfstwo= 1.0
labeltwo= 5
END IF
```

```
c  print*, 'values after all the if'
```



c    print\*,msfone,labelone,msftwo,labeltwo

```
atr1_atom= OP$CVFA (%VAL(mfsone))
atr2_atom= OP$CVNA (%VAL(labelone))
atr3_atom= OP$CVFA (%VAL(mfstwo))
atr4_atom= OP$CVNA (%VAL(labeltwo))
```

```
CALL OP$CLEAR
CALL OP$RESET()
```

```
CALL OP$VALUE (%VAL (OP$INTERN( %REF (CLASS),
1            %VAL( LEN( CLASS )))))
```

C ATTRIBUTE m1

```
CALL OP$TAB( %VAL( OP$INTERN( %REF( atr1 ),
1            %VAL( LEN( atr1 ) ) ) ) )
CALL OP$VALUE(%VAL (atr1_atom), %VAL( LEN( atr1 )))
```

C ATTRIBUTE label1

```
CALL OP$TAB( %VAL( OP$INTERN( %REF( atr2 ),
1            %VAL( LEN( atr2 ) ) ) ) )
CALL OP$VALUE(%VAL (atr2_atom), %VAL( LEN( atr2 )))
```

C ATTRIBUTE m2

```
CALL OP$TAB( %VAL( OP$INTERN( %REF( atr3 ),
1            %VAL( LEN( atr3 ) ) ) ) )
CALL OP$VALUE(%VAL (atr3_atom), %VAL( LEN( atr3 )))
```

C ATTRIBUTE level2

```
CALL OP$TAB( %VAL( OP$INTERN( %REF( atr4 ),
1            %VAL( LEN( atr4 ) ) ) ) )
CALL OP$VALUE(%VAL (atr4_atom), %VAL( LEN( atr4 )))
```

c    CALL OP\$WRITE ()

```
CALL OP$ASSERT ()
```

```
RETURN
```

```
END
```

```

SUBROUTINE FUZZYF_FOR ()
*-----*
* FUZZY FLOW MODEL *
* This program calculates the membership functions*
* the HVAC flow *
*-----*
IMPLICIT REAL (A-Z)
C definition of VAX OPS5 support routine
INCLUDE 'OPS$LIBRARY:OPSDEF.FOR'

INTEGER atr1_atom,L1,L2,L3,L4,L5,L6,L7,L8,L9

INTEGER atom_one,atom_two,atom_three,atom_four,atom_five
INTEGER atom_six,atom_seven,atom_eight,atom_nine,atom_ten
INTEGER atom_eleven,atom_twelve,atom_thirteen,atom_fourteen
INTEGER atom_fiveteen,atom_sixteen,atom_seventeen,atom_eighteen
INTEGER atom_nineteen

REAL A1,A2,A3,A4,A5,A6,A7,A8,A9,C1,C2,C3,C4,C5,C6,C7,C8,C9
REAL m1,m2,m3,m4,m5,m6,m7,m8,m9,newflow,num,den

character*4 class
character*8 atr1

data class / 'FLOW' /
data atr1 / 'CENTROID' /

IF (OPSS$PARAMETERCOUNT() .LE. 4) THEN

    atom_one = OPSS$PARAMETER(%VAL(1))
    atom_two = OPSS$PARAMETER(%VAL(2))
    atom_three = OPSS$PARAMETER(%VAL(3))
    atom_four = OPSS$PARAMETER(%VAL(4))

END IF

IF (OPSS$INTEGER(%VAL(atom_one))) THEN
L1= OPSS$CVAN (%VAL(atom_one))
ELSE IF (OPSS$FLOATING(%VAL(atom_one))) THEN
L1= OPSS$CVAF (%VAL(atom_one))
END IF

IF (OPSS$INTEGER(%VAL(atom_two))) THEN
m1= OPSS$CVAN (%VAL(atom_two))
ELSE IF (OPSS$FLOATING(%VAL(atom_two))) THEN
m1= OPSS$CVAF (%VAL(atom_two))
END IF

IF (OPSS$INTEGER(%VAL(atom_three))) THEN
L2= OPSS$CVAN (%VAL(atom_three))

```

```

ELSE IF (OPSS$FLOATING(%VAL(atom_three))) THEN
L2= OPSS$CVAF (%VAL(atom_three))
END IF

```

```

IF (OPSS$INTEGER(%VAL(atom_four))) THEN
m2= OPSS$CVAN (%VAL(atom_four))
ELSE IF (OPSS$FLOATING(%VAL(atom_four))) THEN
m2= OPSS$CVAF (%VAL(atom_four))
END IF

```

```

A1= FLOW(L1,m1)
C1= CENTER(L1)
A2= FLOW(L2,m2)
C2= CENTER(L2)

```

```

c   print*, 'area-1' ,A1, 'centroid' ,C1
c   print*, 'area-2' ,A2, 'centroid' ,C2
c   print*, 'area-3' ,A3, 'centroid' ,C3

```

```

num=C1*A1+C2*A2
den=A1+A2
newflow = int(num/den)

```

```

c   print*, 'flow-centroid-out', newflow

```

```

atr1_atom= OPSS$CVFA (%VAL(newflow))

```

```

CALL OPSS$RESET()

```

```

CALL OPSS$VALUE (%VAL (OPSS$INTERN( %REF (CLASS),
1                %VAL( LEN( CLASS ) ) ) ) )

```

```

C ATTRIBUTE msfone
  CALL OPSS$TAB( %VAL( OPSS$INTERN( %REF( atr1 ),
1                %VAL( LEN( atr1 ) ) ) ) )
  CALL OPSS$VALUE(%VAL (atr1_atom), %VAL( LEN( atr1 ) ) )

```

```

C   CALL OPSS$WRITE ()

```

```

CALL OPSS$ASSERT ()

```

```

RETURN

```

```

*****
*                               *
*                               *
*****

```

# FLOW FUNCTIONS

```

REAL FUNCTION FLOW(L,m)
IMPLICIT REAL (A-Z)
REAL m,delta

```

```

    INTEGER L,up
c   print*, 'real function in fuzzy flow', L,m
    UP=15000.0
    delta=up/4.0
    x0=200.0
    x1=delta
    x2=delta*2
    x3=delta*3
    x4=delta*4
    x5=delta*5

    IF(L .EQ. 1) THEN
        FLOW=(x1-x0)*m
    ELSE IF(L .EQ. 2) THEN
        FLOW=(x2-x1)*m
    ELSE IF(L .EQ. 3) THEN
        FLOW=(x3-x2)*m
    ELSE IF(L .EQ. 4) THEN
        FLOW=(x4-x3)*m
    ELSE IF(L .EQ. 5) THEN
        FLOW=(x5-x4)*m
    END IF
c   print*, 'end flow in real function fuzzy flow',flow
    RETURN
    END
*****
**      function to get the centroid      **
*****
    REAL FUNCTION CENTER(L)
    IMPLICIT REAL (A-Z)
    INTEGER L,uper
    REAL del
c   print*, 'center in fuzzy flow',l
    uper=15000.0
    del=uper/4.0
    x0=200.0
    IF(L .EQ. 1) THEN
        CENTER=x0
    ELSE IF(L .EQ. 2) THEN
        CENTER=del+x0
    ELSE IF(L .EQ. 3) THEN
        CENTER=del*2+x0
    ELSE IF(L .EQ. 4) THEN
        CENTER=del*3+x0
    ELSE IF(L .EQ. 5) THEN
        CENTER=del*4+x0
    END IF
c   print*, 'center out fuzzy flow',center
    RETURN

    END

```

```

INTEGER FUNCTION FO1_FOR
(ATOMONE,ATOMTWO,ATOMTHREE,ATOMFOUR)
IMPLICIT REAL (A-Z)
INCLUDE 'OPSLIBRARY:OPSDEF.FOR'
REAL a,b,t,cost,cost2,flow,c,dose,q1,delta
REAL q1d,q1n,dn,f1n,int,leak,coll
INTEGER ATOMONE,ATOMTWO,ATOMTHREE,ATOMFOUR,time

IF (OPSP$PARAMETERCOUNT () .EQ. 4) THEN
ATOMONE= OPSP$PARAMETER (%VAL (1))
ATOMTWO= OPSP$PARAMETER (%VAL (2))
ATOMTHREE= OPSP$PARAMETER (%VAL (3))
ATOMFOUR = OPSP$PARAMETER (%VAL (4))
END IF

IF (OPSP$INTEGER(%VAL ( %LOC(ATOMONE)))) THEN
time= OPSP$CVAN (%VAL(%LOC(ATOMONE)))
ELSE IF (OPSP$FLOATING(%VAL(%LOC(ATOMONE)))) THEN
time=OPSP$CVAF(%VAL(%LOC(ATOMONE)))
END IF

IF (OPSP$INTEGER(%VAL ( %LOC(ATOMTWO)))) THEN
leak= OPSP$CVAN (%VAL(%LOC(ATOMTWO)))
ELSE IF (OPSP$FLOATING(%VAL(%LOC(ATOMTWO)))) THEN
leak=OPSP$CVAF(%VAL(%LOC(ATOMTWO)))
END IF

IF (OPSP$INTEGER(%VAL ( %LOC(ATOMTHREE)))) THEN
coll= OPSP$CVAN (%VAL(%LOC(ATOMTHREE)))
ELSE IF (OPSP$FLOATING(%VAL(%LOC(ATOMTHREE)))) THEN
coll=OPSP$CVAF(%VAL(%LOC(ATOMTHREE)))
END IF

IF (OPSP$INTEGER(%VAL ( %LOC(ATOMFOUR)))) THEN
upper= OPSP$CVAN (%VAL(%LOC(ATOMFOUR)))
ELSE IF (OPSP$FLOATING(%VAL(%LOC(ATOMFOUR)))) THEN
upper=OPSP$CVAF(%VAL(%LOC(ATOMFOUR)))
END IF

c print*, 'time', time
c print*, 'leak', leak
c print*, 'coll', coll
c print*, 'fuzzy optimization'

delta=5.0/36.0
alfa=100.0
b0=0.1
C-----cost-----
DO x=0.1,1.0,0.01

```

```

q1=upper*(1-x)/2
q2=upper*x/2
q3=upper*(2-x)/2
q4=upper*(x+1)/2

```

```

c1= 0.368*q1+b0*(q1**2)
c2= 0.368*q2+b0*(q2**2)
c3= 0.368*q3+b0*(q3**2)
c4= 0.368*q4+b0*(q4**2)

```

```

c-----detriment -----

```

```

DO y=0.1,1.0,0.005
  q1d=upper*(1-y)/2
  q2d=upper*y/2
  q3d=upper*(2-y)/2
  q4d=upper*(y+1)/2

```

```

dose1=delta*309.37*leak/q1d
dose2=delta*309.37*leak/q2d
dose3=delta*309.37*leak/q3d
dose4=delta*309.37*leak/q4d

```

```

f1=(coll+NFO1(time)*dose1)*alfa
f2=(coll+NFO1(time)*dose2)*alfa
f3=(coll+NFO1(time)*dose3)*alfa
f4=(coll+NFO1(time)*dose4)*alfa

```

```

dif1=sqrt((x-y)**2+(c1-f1)**2)
dif2=sqrt((x-y)**2+(c1-f2)**2)
dif3=sqrt((x-y)**2+(c1-f3)**2)
dif4=sqrt((x-y)**2+(c1-f4)**2)
dif5=sqrt((x-y)**2+(c2-f1)**2)
dif6=sqrt((x-y)**2+(c2-f2)**2)
dif7=sqrt((x-y)**2+(c2-f3)**2)
dif8=sqrt((x-y)**2+(c2-f4)**2)
dif9=sqrt((x-y)**2+(c3-f1)**2)
dif10=sqrt((x-y)**2+(c3-f2)**2)
dif11=sqrt((x-y)**2+(c3-f3)**2)
dif12=sqrt((x-y)**2+(c3-f4)**2)
dif13=sqrt((x-y)**2+(c4-f1)**2)
dif14=sqrt((x-y)**2+(c4-f2)**2)
dif15=sqrt((x-y)**2+(c4-f3)**2)
dif16=sqrt((x-y)**2+(c4-f4)**2)

```

```

c      print*, 'x', x, 'y', y, dif1, dif2

```

```

c-----

```

```

  IF(dif1 .LE.0.08)then
    labelc=1
    labeld=11
    p=((c1+f1)/2)
    print*, 'reable cost and ', 'reable der', ' at $', p
  end if

```

```

C-----
  IF(dif2 .LE.0.08)then
    labelc=1
    labeld=12
    p=((c1+f2)/2)
    print*, 'reable cost and ', 'm or l reable det', ' at $', p
  end if

C-----
  IF( dif3 .LE.0.08)then
    labelc=1
    labeld=12
    p=((c1+f3)/2)
    print*, 'reable cost and ', 'm or l reable det', ' at $', p
  end if

C-----
  IF( dif4 .LE.0.08)then
    labelc=1
    labeld=13
    p=((c1+f4)/2)
    print*, 'reable cost and ', 'not reable det', ' at $', p
  end if

C-----
  IF( dif5 .LE.0.08)then
    labelc=2
    labeld=11
    p=((c2+f1)/2)
    print*, 'm or l reable cost and ', 'reable det', ' at $', p
  end if

C-----
  IF( dif6 .LE.0.08)then
    labelc=2
    labeld=12
    p=((c2+f2)/2)
    print*, 'm or l reable cost and ', 'm or l reable det', ' at $', p
  end if

C-----
  IF( dif7 .LE.0.08)then
    labelc=2
    labeld=12
    p=((c2+f3)/2)
    print*, 'm or l reable cost and ', 'm or l reable det', ' at $', p
  end if

C-----
  IF( dif8 .LE.0.08)then
    labelc=2
    labeld=13
    p=((c2+f4)/2)
    print*, 'm or l reable cost and ', 'not reable det', ' at $', p
  end if

C-----

```

```

IF( dif9 .LE.0.08)then
labelc=2
labeld=11
p=((c3+f1)/2)
print*,'m or l reable cost and  ','reable det',' at $',p
end if

```

```

c-----
IF( dif10 .LE.0.08)then
labelc=2
labeld=12
p=((c3+f2)/2)
print*,'m or l reable cost and  ','m ro l reable det',' at $',p
end if

```

```

c-----
IF( dif11 .LE.0.08)then
labelc=2
labeld=12
p=((c3+f3)/2)
print*,'m or l reable cost and  ','m or l reable det',' at $',p
end if

```

```

c-----
IF( dif12 .LE.0.08)then
labelc=2
labeld=13
p=((c3+f4)/2)
print*,'m or l reable cost and  ','not reable det',' at $',p
end if

```

```

c-----
IF( dif13 .LE.0.08)then
labelc=3
labeld=11
p=((c4+f1)/2)
print*,'not reable cost and  ','reable det',' at $',p
end if

```

```

c-----
IF( dif14 .LE.0.08)then
labelc=3
labeld=12
p=((c4+f2)/2)
print*,'not reable cost and  ','m or l reable det',' at $',p
end if

```

```

c-----
IF( dif15 .LE.0.08)then
labelc=3
labeld=12
p=((c4+f3)/2)
print*,'not reable cost and  ','m or l reable det',' at $',p
end if

```

```

c-----
IF( dif16 .LE.0.08)then
labelc=3

```



```

labeld=13
p=((c4+f4)/2)
  print*,'not reable cost and  ','not reable det',' at $',p
end if

```

c-----

```

END DO
END DO

```

```

DETRIMENT= point

```

```

CALL OP$VALUE (%VAL(OP$CVFA (%VAL(DETRIMENT))))
END

```

\*\*\*\*\*

\* OCCUPANCY REQUIREMENTS \*

\*\*\*\*\*

```

REAL FUNCTION NFO1(x)
INTEGER x

```

```

IF(x .GE. 0.0 .AND. x .LE. 28800.0) NFO1= 2
IF(x .GT. 28800.0 .AND. x .LT. 57600.0) NFO1= 5
IF(x .GE. 57600.0 .AND. x .LE. 86400.0) NFO1= 7
IF(x .GT. 86400.0 .AND. x .LT. 108000.0) NFO1= 10
IF(x .GE. 108000.0 .AND. x .LE. 136800.0) NFO1= 1
IF(x .GT. 136800.0 .AND. x .LT. 180000.0) NFO1= 8
IF(x .GE. 180000.0) NFO1= 0.0
RETURN
END

```

```

INTEGER FUNCTION ICRP1_FOR (ATOM)
IMPLICIT REAL (A-Z)
INCLUDE 'OPSL$LIBRARY:OPSDEF.FOR'
INTEGER I,k1,con,V,time,Q,delta,c,ATOM
REAL DOSE1,CO,a,d,b,total,cost,w,dif1,dif2
REAL*4 flow,leak,e,total1,coll

```

```

IF (OPSL$INTEGER(%VAL ( %LOC(ATOM)))) THEN
    leak= OPS$CVAN (%VAL(%LOC(ATOM)))
ELSE IF (OPSL$FLOATING(%VAL(%LOC(ATOM)))) THEN
    leak=OPSL$CVAF(%VAL(%LOC(ATOM)))
END IF

```

```

k1=472.1
con= 20.00
V= 1.5e+8
z=0.05
delta=1000.0
w=0.1337*2*8.33/3.6
alfa=1000.0
t=996000
b0=0.1
b=4.09E-05
tao=180000
b=4.09e-4

```

```

c----- c
c the change in the second loop of delta t must be equal to the delta in c
c the cost1 part, the dose rate is in mrem/hr, the collective in c
c men-rem, c
c----- c

```

```

DO Q= 1,50000,50
    dif1=2*b0*Q+z*b*tao/60.0
    dif2=(alfa*w*leak*t)/(Q**2)
c    print*,q,dif1,dif2
c    del=abs(dif2-dif1)
    IF(dif2 .LE. dif1)go to 10
END DO

```

```

c 10 print*, '-----'
c    print*, Q, dif1,dif2

```

```

10    CALL OPS$VALUE (%VAL(OPSL$CVNA (%VAL(Q))))

```

```

END

```

```

$ [K $ type icrp1.for

```

```

INTEGER FUNCTION ICRP2_FOR (ATOM)
IMPLICIT REAL (A-Z)
INCLUDE 'OPSL$LIBRARY:OPSDEF.FOR'

```

```

INTEGER I,k1,con,V,time,Q,delta,c,ATOM
REAL DOSE1,CO,a,d,b,total,cost,w,sum
REAL*4 flow,leak,e,total1,coll

```

```

IF (OPSS$INTEGER(%VAL (%LOC(ATOM)))) THEN
    leak= OPSS$CVAN (%VAL(%LOC(ATOM)))
ELSE IF (OPSS$FLOATING(%VAL(%LOC(ATOM)))) THEN
    leak=OPSS$CVAF(%VAL(%LOC(ATOM)))
END IF

```

```

c-----
c the change in the second loop of delta t must be equal to the delta in
c the cost1 part, the dose rate is in mrem/hr, the collective in
c men-rem,

```

```

*-----*
*          CONSTANTS FOR MODEL          *
*-----*

```

```

k1= 472.0
c1= 20.0
c2= 2.0
v1= 1.5E+08
v2= 2.0E+09
p= 0.1
z=0.05
z1= 4.09E-5
z2=0.1
tao=180000.0
delta=5000.0
w=0.61874
alfa=100.0
k2=v2/(v1-v2)
k3=v1/(v1-v2)

```

```

DO Q= 50,10000,10

```

```

    a1= (Q/v1)*k1
    a2= (Q/v2)*k1
    d10=k1/Q
    d11=d10/v2
    d12=d10/v1
    d13=1/(Q**2)
    dif1=z*z1*tao/60+2*z2*Q
    total = 0.0

```

```

    DO I=0,180000,5000

```

```

        N= occup2(I)
        d=delta*N*w*alfa
        b1=-a1*I
        b2=-a2*I
        f1=d*leak/(Q**2)
        f2=d*leak*k2*(I*d11+d13)

```

```

f3=d*leak*k3*(I*d12+d13)
dif2=f1+f2*exp(b2)+f3*exp(b1)
total=total + dif2
END DO

c    di=abs(total-dif1)
    print*,q,dif1,total
    IF(di .LE. 10)go to 10

END DO

c 10  print*, '-----'
c    print*, Q, dif1,total

10    CALL OPS$VALUE (%VAL(OPS$CVNA (%VAL(Q))))

END
*****
*          OCCUPANCY MODEL          *
*****
REAL FUNCTION occup2(x)
IMPLICIT REAL (A-Z)
INTEGER x
IF(x .GE. 0.0 .AND. x .LE. 28800.0) occup2= 2
IF(x .GT. 28800.0 .AND. x .LT. 57600.0) occup2= 5
IF(x .GE. 57600.0 .AND. x .LE. 86400.0) occup2= 7
IF(x .GT. 86400.0 .AND. x .LT. 108000.0) occup2= 10
IF(x .GE. 108000.0 .AND. x .LE. 136800.0) occup2= 1
IF(x .GT. 136800.0 .AND. x .LT. 180000.0) occup2= 8
IF(x .GE. 180000.0) occup3= 0.0
c    print*, 'occup3', occup3
RETURN
END

```

```

INTEGER FUNCTION ICRP2_FOR (ATOM)
IMPLICIT REAL (A-Z)
INCLUDE 'OP$LIBRARY:OPSDEF.FOR'
INTEGER I,k1,con,V,time,Q,delta,c,ATOM
REAL DOSE1,CO,a,d,b,total,cost,w,sum
REAL*4 flow,leak,e,total1,coll

```

```

IF (OP$INTEGER(%VAL ( %LOC(ATOM)))) THEN
    leak= OP$CVAN (%VAL(%LOC(ATOM)))
ELSE IF (OP$FLOATING(%VAL(%LOC(ATOM)))) THEN
    leak=OP$CVAF(%VAL(%LOC(ATOM)))
END IF

```

```

c-----
c the change in the second loop of delta t must be equal to the delta in
c the cost1 part, the dose rate is in mrem/hr, the collective in
c men-rem,

```

c  
c  
c  
c

```

*-----*
*          CONSTANTS FOR MODEL          *
*-----*

```

```

k1= 472.0
c1= 20.0
c2= 2.0
v1= 1.5E+08
v2= 2.0E+09
p= 0.1
z=0.05
z1= 4.09E-5
z2=0.1
tao=180000.0
delta=5000.0
w=0.61874
alfa=100.0
k2=v2/(v1-v2)
k3=v1/(v1-v2)

```

```

DO Q= 50,10000,10

```

```

    a1= (Q/v1)*k1
    a2= (Q/v2)*k1
    d10=k1/Q
    d11=d10/v2
    d12=d10/v1
    d13=1/(Q**2)
    dif1=z*z1*tao/60+2*z2*Q
    total = 0.0

```

```

    DO I=0,180000,5000

```

```

        N= occup2(I)
        d=delta*N*w*alfa
        b1=-a1*I

```

```

        b2=-a2*I
        f1=d*leak/(Q**2)
        f2=d*leak*k2*(I*d11+d13)
        f3=d*leak*k3*(I*d12+d13)
        dif2=f1+f2*exp(b2)+f3*exp(b1)
        total=total + dif2
    END DO

    di=abs(total-dif1)
c    print*,q,dif1,total
    IF(di .LE. 10)go to 10

END DO

c 10  print*, '-----'
c    print*, Q, dif1,total

10    CALL OPS$VALUE (%VAL(OPS$CVNA (%VAL(Q))))

END
*****
*          occup2ANCY MODEL          *
*****
REAL FUNCTION occup2(x)
IMPLICIT REAL (A-Z)
INTEGER x
IF(x .GE. 0.0 .AND. x .LE. 28800.0) occup2= 2
IF(x .GT. 28800.0 .AND. x .LT. 57600.0) occup2= 5
IF(x .GE. 57600.0 .AND. x .LE. 86400.0) occup2= 7
IF(x .GT. 86400.0 .AND. x .LT. 108000.0) occup2= 10
IF(x .GE. 108000.0 .AND. x .LE. 136800.0) occup2= 1
IF(x .GT. 136800.0 .AND. x .LT. 180000.0) occup2= 8
IF(x .GE. 180000.0) occup3= 0.0
c  print*, 'occup3', occup3
RETURN
END

```

INTEGER FUNCTION ICRP3\_FOR (ATOM)

IMPLICIT REAL (A-Z)

INCLUDE 'OPSL\$LIBRARY:OPSDEF.FOR'

INTEGER I,con,V,time,Q,delta,ATOM

REAL DOSE1,CO,a,d,b,total,cost,w,c

REAL\*4 flow,leak,e,total1,coll

IF (OPSL\$INTEGER(%VAL (%LOC(ATOM)))) THEN

leak= OPSL\$CVAN (%VAL(%LOC(ATOM)))

ELSE IF (OPSL\$FLOATING(%VAL(%LOC(ATOM)))) THEN

leak=OPSL\$CVAF(%VAL(%LOC(ATOM)))

END IF

k1=472.0

v1= 1.5E+08

v2= 2.0E+07

v3= 6.9E+10

z1=0.05

z2=4.09e-5

tao=180000

z3=0.1

w=0.6874

alfa=100.0

delta=5000.0

k10=v1\*v2/((v1-v2)\*(v1-v3))

k11=(v1\*\*2)/((v1-v2)\*(v1-v3))

k12=k11-1-k10

c-----

c the change in the second loop of delta t must be equal to the delta in

c the cost1 part, the dose rate is in mrem/hr, the collective in

c men-rem,

c-----

c

c

c

c

c

DO Q= 50,10000,10

a1=(Q/v1)\*k1

a2=(Q/v2)\*k1

a3=(Q/v3)\*k1

dif1=z1\*z2\*tao/60+2\*z3\*Q

total=0.0

DO I=0,180000,5000

b1=-a1\*I

b2=-a2\*I

b3=-a3\*I

N= occup3(I)

d=delta\*N\*w\*alfa

k13=I\*k1/Q

```

f0=d*leak/(Q**2)
f1=d*leak*k12*(k13/v3+k15)
f2=d*leak*k10*(k13/v2+k15)
f3=d*leak*k11*(k13/v1+v15)
dif2=f1*exp(b3)+f0+f2*exp(b2)+f3*exp(b1)

total=total + dif2

END DO
di=abs(total-dif1)
  IF(di .LE. 10) go to 10
END DO

c 10  print*, '-----'
c    print*, Q, dif1,total

10    CALL OPS$VALUE (%VAL(OPS$CVNA (%VAL(Q))))

END
*****
*          occup3ANCY MODEL          *
*****
REAL FUNCTION occup3(x)
IMPLICIT REAL (A-Z)
INTEGER x
IF(x .GE. 0.0 .AND. x .LE. 28800.0) occup3= 2
IF(x .GT. 28800.0 .AND. x .LT. 57600.0) occup3= 5
IF(x .GE. 57600.0 .AND. x .LE. 86400.0) occup3= 7
IF(x .GT. 86400.0 .AND. x .LT. 108000.0) occup3= 10
IF(x .GE. 108000.0 .AND. x .LE. 136800.0) occup3= 1
IF(x .GT. 136800.0 .AND. x .LT. 180000.0) occup3= 8
IF(x .GE. 180000.0) occup3= 0.0
RETURN
END

```



```

INTEGER FUNCTION COST_FOR (ATOMONE,ATOMTWO)
IMPLICIT REAL (A-Z)
INCLUDE 'OPS$LIBRARY:OPSDEF.FOR'
REAL a,b,t,cost,cost2,flow,c
INTEGER ATOMONE,ATOMTWO,time

IF (OPSP$PARAMETERCOUNT () .EQ. 2) THEN
  ATOMONE= OPSP$PARAMETER (%VAL (1))
  ATOMTWO= OPSP$PARAMETER (%VAL (2))
END IF

IF (OPSP$INTEGER(%VAL ( %LOC(ATOMONE)))) THEN
  time= OPSP$CVAN (%VAL(%LOC(ATOMONE)))
ELSE IF (OPSP$FLOATING(%VAL(%LOC(ATOMONE)))) THEN
  time=OPSP$CVAF(%VAL(%LOC(ATOMONE)))
END IF

IF (OPSP$INTEGER(%VAL ( %LOC(ATOMTWO)))) THEN
  flow= OPSP$CVAN (%VAL(%LOC(ATOMTWO)))
ELSE IF (OPSP$FLOATING(%VAL(%LOC(ATOMTWO)))) THEN
  flow=OPSP$CVAF(%VAL(%LOC(ATOMTWO)))
END IF

a=0.05
t=8.3334
p= 4.09e-04
COST2= a*p*flow*t

CALL OPSP$VALUE (%VAL(OPSP$CVFA (%VAL(COST2))))

END

```

# INTEGER FUNCTION LEAK\_FOR (ATOM)

```

*-----*
* This program calculates the leak      *
* as a funtion of time                  *
*-----*

```

```

C  definition of VAX OPS5 support routine
  INCLUDE 'OPSL$LIBRARY:OPSDEF.FOR'
  INTEGER IO
  REAL tao,a,x,L
  REAL*4 TIME,NEW_LEAK

```

```

  IF (OPSL$INTEGER(%VAL (%LOC(ATOM)))) THEN
time= OPSL$CVAN (%VAL(%LOC(ATOM)))
  ELSE IF (OPSL$FLOATING(%VAL(%LOC(ATOM)))) THEN
time= OPSL$CVAF (%VAL(%LOC(ATOM)))
  END IF

```

```

  x=time/3600.0

```

```

  IF(x .GE. 0.0 .AND. x .LE. 4.0) L= 0.1
  IF(x .GT. 4.0 .AND. x .LT. 33.0) THEN
    L=2.8E-4*(x**4)-2.4e-2*(x**3)+5.9e-1*(x**2)-2.3*x+1.3
  END IF
  IF(x .GE. 33.0 .AND. x .LE. 45.0) THEN
    L= 2.05E-1*(x**2)-1.9e+1*x+440
  END IF
  IF(x .GT. 45.0) L=0.0

```

```

  NEW_LEAK=L

```

```

c  print*, 'values in fortran'
c  print*, 'time',x,'L',L,'new_leak',NEW_LEAK
c  end do

```

```

  CALL OPSL$VALUE (%VAL ( OPSL$CVFA (%VAL(NEW_LEAK))))
  END
$

```

```

INTEGER FUNCTION MIN_FOR (ATOMONE,ATOMTWO,ATOMTHREE)
  IMPLICIT REAL (A-Z)
  INCLUDE 'OPSL$LIBRARY:OPSDEF.FOR'
  REAL VALUE1,VALUE2,VALUE3,VALUE4
  INTEGER ATOMONE,ATOMTWO,ATOMTHREE,ATOMFOUR,time

```

```

  IF (OPSL$PARAMETERCOUNT () .EQ. 3) THEN
    ATOMONE= OPSL$PARAMETER (%VAL (1))

```

```
ATOMTWO= OPS$PARAMETER (%VAL (2))
ATOMTHREE=OPS$PARAMETER (%VAL (3))
END IF
```

```
IF (OPS$INTEGER(%VAL ( %LOC(ATOMONE)))) THEN
    value1= OPS$CVAN (%VAL(%LOC(ATOMONE)))
ELSE IF (OPS$FLOATING(%VAL(%LOC(ATOMONE)))) THEN
    value1=OPS$CVAF(%VAL(%LOC(ATOMONE)))
END IF
```

```
IF (OPS$INTEGER(%VAL ( %LOC(ATOMTWO)))) THEN
    value2= OPS$CVAN (%VAL(%LOC(ATOMTWO)))
ELSE IF (OPS$FLOATING(%VAL(%LOC(ATOMTWO)))) THEN
    value2=OPS$CVAF(%VAL(%LOC(ATOMTWO)))
END IF
```

```
IF (OPS$INTEGER(%VAL ( %LOC(ATOMTHREE)))) THEN
    value3= OPS$CVAN (%VAL(%LOC(ATOMTHREE)))
ELSE IF (OPS$FLOATING(%VAL(%LOC(ATOMTHREE)))) THEN
    value3=OPS$CVAF(%VAL(%LOC(ATOMTHREE)))
END IF
```

```
output= min(value1,value2,value3)
```

```
call ops$clear
call ops$value (%val (ops$cvfa(%val(output))))
```

```
END
```

INTEGER FUNCTION OCCUP\_FOR (ATOM)

```
*-----*
* This program calculates the occupancy      *
* as a funtion of time                      *
*-----*
```

C definition of VAX OPS5 support routine

INCLUDE 'OPS\$LIBRARY:OPSDEF.FOR'

INTEGER I0

REAL tao,a,x,P

REAL\*4 TIME,NEW\_OCCUPANCY

IF (OPS\$INTEGER(%VAL (%LOC(ATOM)))) THEN

x= OPS\$CVAN (%VAL(%LOC(ATOM)))

ELSE IF (OPS\$FLOATING(%VAL(%LOC(ATOM)))) THEN

x= OPS\$CVAF (%VAL(%LOC(ATOM)))

END IF

IF(x .GE. 0.0 .AND. x .LE. 28800.0) P= 2

IF(x .GT. 28800.0 .AND. x .LT. 57600.0) P= 5

IF(x .GE. 57600.0 .AND. x .LE. 86400.0) P= 7

IF(x .GT. 86400.0 .AND. x .LT. 108000.0) P= 10

IF(x .GE. 108000.0 .AND. x .LE. 136800.0) P= 1

IF(x .GT. 136800.0 .AND. x .LT. 180000.0) P= 8

IF(x .GE. 180000.0) P= 0.0

NEW\_OCCUPANCY=P

c print\*, 'values in fortran'

c print\*, 'time',x,'P',P,'new\_occupancy',NEW\_OCCUPANCY

CALL OPS\$VALUE (%VAL ( OPS\$CVFA (%VAL(NEW\_OCCUPANCY))))

END

## VITA

Javier Reyes-Jimenez was born in El Oro, Estado de Mexico, Mexico, on December 2, 1957. He attended elementary school in that city. After graduating from the "Instituto de Ciencia y Tecnologia del Norte del Estado de Mexico", he emigrated to the United States in 1977. In May 1981 he received a B.S. degree in Nuclear Engineering from the University of Illinois at Urbana-Champaign. He continued his study at the same university and received a Master of Science degree in Nuclear Engineering in August of 1983.

After working as a Shielding engineer in the Nuclear Safeguards & Licensing Division at Sargent and Lundy engineer in Chicago. He re-enter graduate school at the University of Tennessee in the fall of 1989. He completed a Doctor of Philosophy Degree in Nuclear Engineering under the Supervision of Dr. L. Tsoukalas.