To the Graduate Council:

I am submitting herewith a thesis written by Brian Ray Bailey entitled "A 1991 Plutonium Wound Incident: A Case Study". I have examined the final copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Masters of Science with a major in Nuclear Engineering.

L. W. Townsend

Dr. L. W. Townsend, Major Professor

We have read this thesis and recommend its acceptance:

Keith Eckerman

Lawrence J Miller

Accepted for the Council:

Lou Winkel

Associate Vice Chancellor and
Dean of the Graduate School

A 1991 Plutonium Wound Incident: A Case Study

A Thesis
Presented for the
Masters of Science
Degree
The University of Tennessee, Knoxville

Brian Ray Bailey
August, 1998

DEDICATION

This thesis is dedicated to my wife Christy, my family and my friends.

Thank you for the love and support through the years.

Above all, thanks goes to my Lord and Savior Jesus Christ.

Without him, I would be lost.

ACKNOWLEDGMENTS

There are so many people who are responsible for the completion of this thesis. I have been fortunate to have had such a patient and knowledgeable faculty to work with in the Nuclear and Radiological Engineering Department. I am particularly grateful to Dr. L. W. Townsend who has led me through this project and has given me the support and guidance to fulfill the requirements.

I have also been blessed with the opportunity to have worked with Dr. K. F. Eckerman from the Life Science Division of Oak Ridge National Laboratory. He has helped me immensely with my research and he has taught me much about internal dosimetry. Although I regard the experience a privilege, I am more honored to call him "friend".

I would also like to thank the Oak Ridge Institute for Science and Education for the Applied Health Physics Fellowship they have bestowed upon me, allowing me the opportunity to pursue my studies at the University of Tennessee. I am truly thankful for the financial support they have given which has allowed me to concentrate on my educational work.

I am also grateful to my friends who have stood by me during these past two years. I will always cherish the relationships which have been formed during my time in Knoxville. I wish you all the very best.

And to Christy, my loving wife and best friend. The one who has listened to my complaints, my troubles and my triumphs. You have inspired me to be my best and have loved me nonetheless through my failures. I thank you for all that you are to me.

Of course, none of this would be possible were it not for the love and mercy of my Lord, Jesus Christ.

The research was performed under appointment to the Applied Health Physics Fellowship Program administered by Oak Ridge Institute for Science and Education under contract number DE-AC05-76OR00033 between the U.S. Department of Energy and Oak Ridge Associated Universities

SPECIAL PROVISION

Complying with the wishes of both the individual and the facility who employed the patient at the time of the incident, the identification of either will not be revealed. The facility will be referred to as Employer while the individual will be addressed either as patient or by job title, Special Operator. Permission to use data obtained from health records of the affected individual has been granted by both the individual and the facility.

ABSTRACT

A 1991 plutonium wound incident case study serves as the basis for establishing the feasibility of developing a mathematical computer model. The code, PCWOUND, will model the urinary excretion of an intake of plutonium and americium from the human body resulting from a contaminated puncture wound. PCWOUND is an adaptation of an existing code, ACTLITE.

Development of the code entailed a study of available treatment options for victims of contamination wounds: surgery and chelation therapy. Although both will be included into the PCWOUND model, the lesser known, more complex chelation therapy is discussed in detail. Side effects, treatment considerations and the kinetics of the chelation agents are some of the topics presented in the discussion.

A case study of the 1991 incident will be performed. The study will include a summarization of the event as well as the treatment schedule and bioassay data collected from the individual. Also, reports from other investigating laboratories are referenced for their evaluations of the incident.

Finally, the bioassay data from the 1991 plutonium wound patient is used to test the feasibility of the PCWOUND computer code. A comparison of the two data sets, the measured data from the incident and the data prediction generated by PCWOUND, is produced in an effort to test the computer model.

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1. INTRODUCTION

Accidents involving radiological contamination are rare. Strict regulations for management of nuclear materials in cooperation with better educated radiological workers has helped facilitate the reduction of radiological contamination cases. Also, as technology advances, so does the understanding of nuclear processes. With this knowledge, more dependable and efficient safeguards can be implemented to help protect the workers.

However, accidents do occur regardless of the level of protection and safety. Such accidents involve inhalation or ingestion of nuclear materials as well as cuts and abrasions involving contamination. Usually minor, these incidents are detected either immediately by the victim or later by bioassay analysis. Regardless of the type of the wound or how it is detected, procedures must be followed to help assess and rectify the situation, insuring that the health of the affected individual is protected.

By analyzing the treatment schedules, procedures and bioassay data from these cases, an evaluation of the case management can assess the success or failure of the treatment program. By doing so, better and more efficient treatment guidelines can be formulated for use with future incidents. This allows a quick, complete remediation of the situation and total confidence in the continued good health of the individual.

In the following pages, such an assessment is made. The data comes from an incident in 1991 where an individual suffered a small puncture wound to the thumb while working in a decontamination cell. The cut was found to contain both plutonium and americium contamination. The patient underwent a combination of two different treatment methods and visited

different laboratories across the nation for an assessment of the wound. Both urinary and fecal excretion data were documented for several weeks after the incident. The urine data are vital in this evaluation of the case.

Moreover, extensive surveys were taken during the treatment period. Both wound and blood were monitored in the first minutes after the event. Later, the patient underwent several unique radiological surveys to determine the extent of translocation of the plutonium and americium.

Analysis of this case has many benefits. For one, the effectiveness of each treatment procedure used during the 1991 Plutonium Wound Incident is beneficial for determination of treatment routines of future contaminated wound events. By reviewing the results of this case, personnel involved in future plutonium and americium wound incidents will have an idea of which methods of treatment are best suited for their situation. Secondly, conclusions drawn from this analysis include suggestions for future research, which will help clarify some of the remaining uncertainties involved with the treatment programs utilized with these cases. Lastly, a computer program is developed to help model wounds involving internal deposition of radionuclides. All of these factors are advantageous for personnel dealing with future incidents .

This thesis presents an analysis of related work in Chapter 2. This involves an examination of present models in an effort to give insight into the evolution of a contaminated wound model that considers the effects of chelation and surgery.

Chapter 3 discusses possible routes of radionuclide intake for workers in nuclear facilities. Also included is a brief overview of the safeguards

employed to prevent such intakes. Accordingly, Chapter 4 introduces the treatment options available for victims of contamination accidents.

Chapter 5 gives an extensive account of one such treatment option, chelation therapy. The chapter begins with a brief introduction , followed by treatment considerations and side effects. Finally, the chapter ends with a discussion of the biokinetics of chelation therapy.

Chapter 6 introduces the 1991 Plutonium Wound Incident, first with a summary of the accident, then a summarization of the treatment schedule and ends with a tabulation of the bioassay data.

This data is analyzed in Chapter 7. The first section addresses the treatment procedures for the 1991 wound patient, followed by a section which examines the wound clearance data. Section 7.3 presents a comparison of the ACTLITE-generated data versus the measured data from 1991. Explanations of the discrepancies between the data sets ends the chapter.

Chapter 8 introduces the adapted ACTLITE code called PCWOUND. Section 8.1 describes the intake component of PCWOUND. The next section, 8.2, examines the differences between the systemic component of the two codes. An explanation of how PCWOUND calculates it's results is found in Section 8.3, while Section 8.4 presents the PCWOUND results.

Chapter 9 includes intake estimates and a dose assessment resulting from the PCWOUND outcomes. Chapter 10 contains conclusions and ideas for future work. The thesis ends with Chapter 11, a short epilogue concerning the 1991 Plutonium Wound patient.

2. PREVIOUS WORK

Previous work concerning contamination wounds is scarce. Because these contamination accidents occur infrequently, allowing few health physicists to experience the dilemma, there exists only a limited amount of previous work available for reference. This is especially true for contaminated wounds which present an extensive variety of complex characteristics. These characteristics consists of such factors as the type of contamination, the means of intake, past medical and intake history and the location of wound. As a result, "one cannot propose a detailed description of the kinetics of the radionuclide" (Piechowski, et al. 1989). In other words, it is nearly impossible to formulate a biological model which will adequately represent every contaminated wound situation.

However, once the material is internally deposited, the characterization of these wound incidents are simplified. All radiological injury cases follow a general model once the circulatory system is contaminated irrespective of the site of the puncture wound. For instance, the same model could sufficiently predict the doses associated with both a puncture wound to the hand as well the same wound to the foot. An example of such a model is described in a paper by Langham, et al. (1980). The paper was based on a study of twelve patients suffering from "chronic disorders such that survival for 10 years was highly improbable" (Langham, et al. 1980). These individuals were administered injections of plutonium in varying amounts. The patients were then closely monitored and underwent various radiological surveys to determine the extent of internal deposition of

the plutonium. Also, their urinary and fecal excretions were surveyed to determine the rate of excretion from the body.

One of the results of the study was a mathematical expression that predicts the urinary excretion of plutonium from the untreated human body. Utilizing the data from Day 0 to Day 138 of the study, it was determined that urinary plutonium excretion following an injected intake could be modeled by the expression:

$$\mathbf{Y}_u = 0.23\ \mathbf{X}^{-0.77}$$

where X is the time of observation in days post injection and Y is the amount of plutonium (expressed as a percentage of injected dose) expected to be present in the urine at time X (Langham, et al., 1980). By utilizing this model, a prediction can be made concerning the amount of plutonium expected to be present in the urinary void of a patient after experiencing an injection of the radionuclide.

The Langham model, like many others, does not take into account the effects of the various treatment procedures administered to the victim. Only one model exists that patterns the excretion rates of radionuclides from patients who receive chelation therapy (Hall, et al., 1978). The authors examined two puncture wound cases and several cases involving inhaled contaminants where the patients were treated with chelating agents.

In these studies, Hall, et al. (1978) analyzed the excretion data from the various patient records and formulated a schematic model of the

principle pathways of transportable plutonium in the human body. It details all possible means of translocation for any mobile plutonium in the bloodstream. The plutonium is thought to "be transported from the site of entry (lung or wound) to the bloodstream as a freely diffusible complex with some of the low molecular weight components of the tissues or body fluids" (Hall, et al. 1978). The schematic of the plutonium behavior shown in Figure 2.1-1 is applicable to plutonium intakes of both inhalation incidents as well as contaminated wounds.

More importantly, Hall and his associates formulated a series of equations to describe the excretion rates of a radionuclide intake after undergoing chelation therapy. The principles are adapted for two different scenarios: one where a single chelation is administered and the other where numerous chelations are administered.

For the first situation, the excretion rate, $E_U(t)$, after a single chelation can be represented by the following expression:

$$\mathbf{E_U(t) = I_a A_0 G(t) + \Delta E(t\text{-}t_c)}$$

where $t \geq t_c$ and $\Delta E(t\text{-}t_c)$ represents "the transient increase in excretion rate due to chelation, t_c is the time of chelation and the first term represents long-term behavior observed after the transient has passed" (Hall, et al., 1978). G(t) symbolizes the relative rate of change in the excretion rate. By applying all the numerical parameters suggested by Hall, et al. (1978), the equation takes the form:

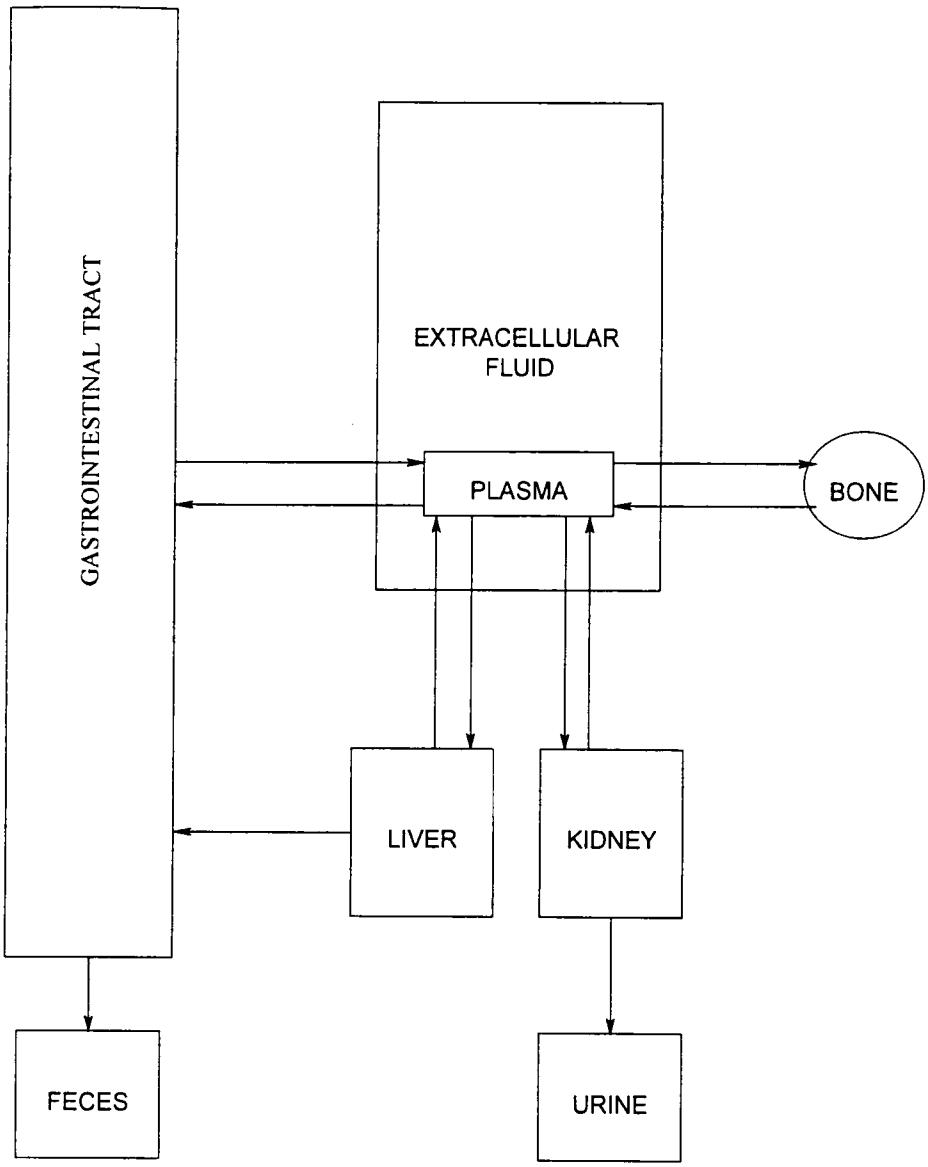


Figure 2.1-1: Principal Metabolic Pathways of Transportable Plutonium in the Body.

$$E_U(t) = I_a A_0 G(t) + I_a G(t_c)[A_6 e^{-\lambda_6 (t-t_c)} + A_7 e^{-\lambda_7 (t-t_c)}]$$

where $A_6 = 0.2$, $A_7 = 0.0044$, $\lambda_6 = 1.3 d^{-1}$ and $\lambda_7 = 0.1 d^{-1}$. I_0 is the initial amount of plutonium injected and G(t) is the relative rate change in excretion.

The equation for multiple chelations is very similar. The general equation for *n* chelations is simply an adaptation of the single chelation model:

$$E_U(t) = I_a(t) A_0 G(t) + \sum \Delta E_j(t-t_j)$$

where the summation runs from j=1 to *n*.

The ideal model of a contaminated puncture wound is based on a state-of-the-art systemic model of plutonium and includes all means of therapy. Thus far, the existing chelation models fail to consider the effects of surgical extraction of radiological material. A complete biological model would be an extension of the chelation models that would take into consideration the type of radionuclide as well the surgical results. By entering this information into a computer code model along with urinalysis results, the initial intake can be appraised. Additionally, a more precise estimate of the dose can be made, resulting in a better idea of the potential radiological risk to the individual.

3. ROUTES OF INTAKE IN THE WORKPLACE

A nuclear facility must take measures to protect its employees from radiological contamination. Within the workplace, there exist several pathways for radiological contamination: inhalation, injection, ingestion and direct contact. The pathway that is affected depends on many factors, one being the form of the nuclear material. The material can take on many forms depending upon its use or the process from which it is produced.

Some nuclear materials are the in form of a fine powder, gas or vapor which can easily be dispersed in air. Once in the air, it can either be inhaled, slightly ingested or seep through the skin pores into the bloodstream. The last pathway is usually negligible because the amount of material ingested is minimal. However, the inhalation pathway is very crucial. Once in the lung, the material is readily absorbed into the bloodstream and dispersed throughout the body. This phenomena is addressed by the International Commission on Radiological Protection (ICRP) in its Publication 66 (1994). In this report, the ICRP presents their mathematical model for the human lung.

The following schematic of Figure 3.1-1 represents the principal components of the ICRP lung model. The ET region represents the extrathoracic region, BB is the bronchial region, bb is the bronchiolar and AI is the alveolar-interstitial area. The $s_i(t)$ is the rate of absorption into the blood from the particular region (i), $g_i(t)$ is the rate of particle transport to the GI tract, $l_i(t)$ is the particle transport to the lymph nodes and $x_{ET}(t)$ is the extrinsic clearance from the ET region. It is also important to note that the model makes three assumptions: the clearance rates due to particle transport

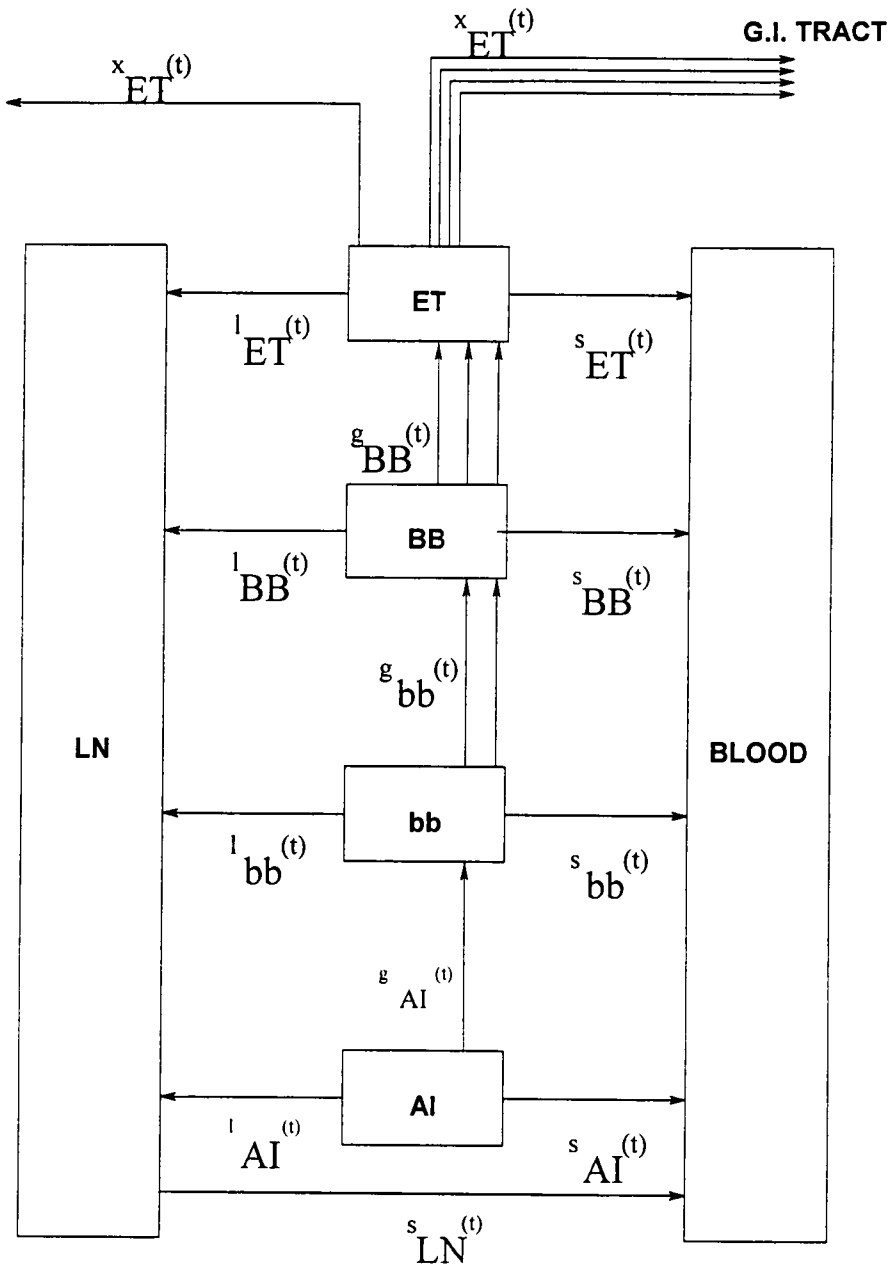


Figure 3.1-1: ICRP Lung Model

are independent of the absorption, particle transport rates are constant for all materials and the rate of absorption of a material into blood (which varies among materials) is the same for all the different regions in the respiratory tract model (ICRP 1994). Using this model and the appropriate parameters, the clearance and absorption rates of inhaled radionuclides can be estimated.

In addition, there exists a model for ingestion of radionuclides. This is not as common a problem among workers at nuclear facilities as inhalation. Areas of radiological contamination are separated from areas of food and drink consumption in order to prevent ingestion of nuclear material with food. Protective clothing aids in keeping contamination from the hands which might otherwise be ingested during eating.

The current ICRP model for ingestion can be found in Publication 30 (1979). The model describes the movement of radionuclides through the digestive tract. Compartments include the stomach, small intestine, upper large intestine and lower large intestine. There are unique transfer coefficients for the pathway between each compartment. These transfer coefficients are derived from their mean residence time. This is the amount of time the radionuclides is present in the region. Mean residence time takes into account both the biological and radiological half-lives of the material (Skrable, et al. 1994). The transfer coefficient is simply the reciprocal of the mean residence time. A diagram of the model and its parameters can be found in Figure 3.1-2. The model assumes no feedback once the material has left a compartment. Absorption is designated to occur only from the small intestine compartment at a rate of λ_{ab}. This rate will vary depending upon the nature of the material ingested.

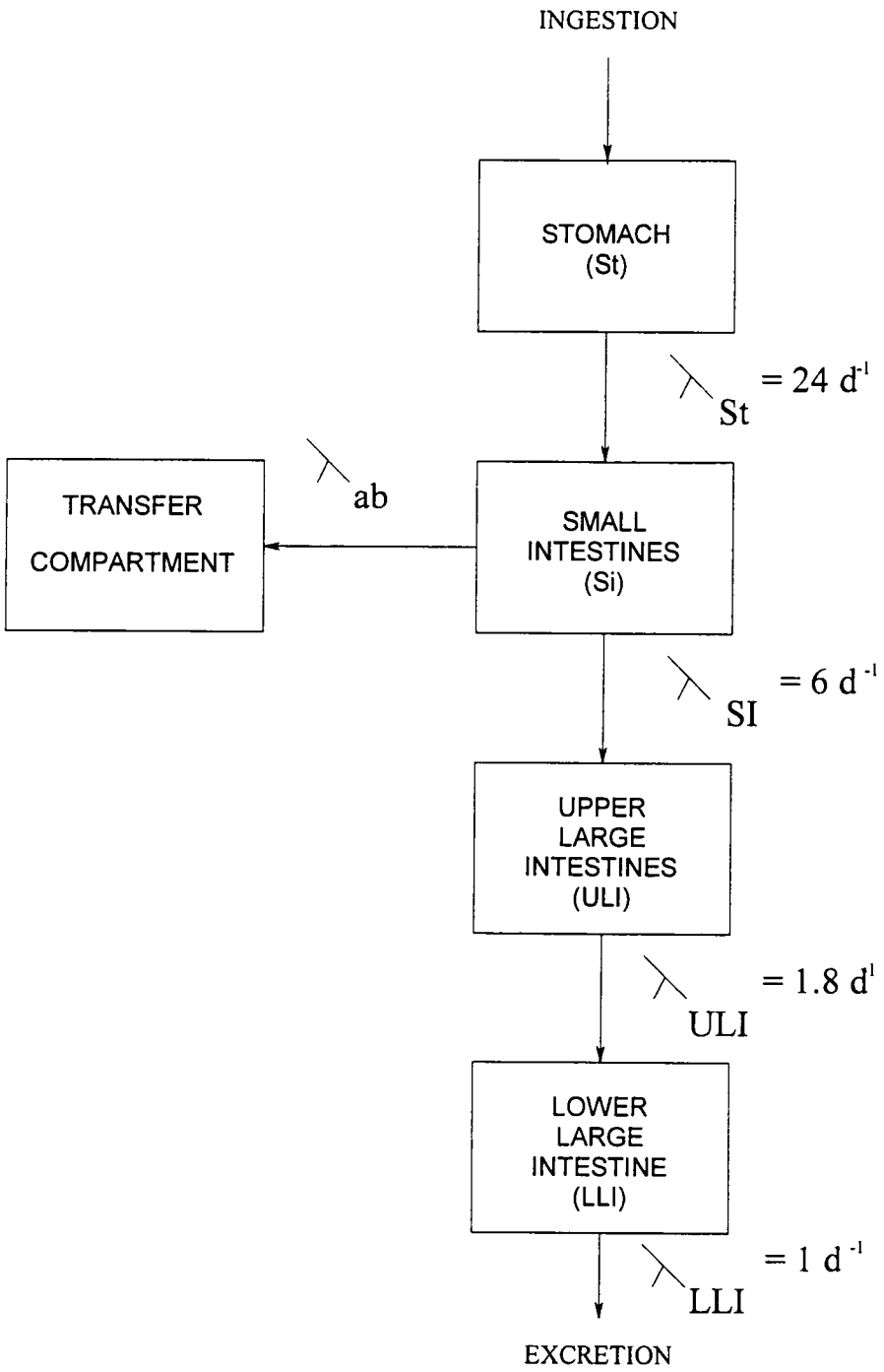


Figure 3.1-2: ICRP Ingestion Model

Lastly, there are models for nuclear contaminated wounds. These models are based upon radionuclide injection studies of urinary excretion as well as urinalysis data from previous wound incidents. From these sources, mathematical equations were formulated to represent the physiology of the circulatory system pertaining to the absorption and distribution of nuclear material. One of the prime examples of this type of model is the previously cited Hall model (1978).

4. TREATMENT OPTIONS FOR INTERNAL CONTAMINATION

Despite possible variations of intake, there exists only three therapeutic procedures available to physicians to alleviate possible large radiation doses and attenuate the intake level: (1) surgical removal of the radiological material from a wound, (2) elimination of radiological material from the lungs (lavage) and (3) elimination of radionuclides from systemic circulation (chelation therapy). Of the three, chelation therapy is the only procedure that treats radiological materials in the bloodstream. "Long term chelation therapy has been extremely effective in limiting the retention of early systemic uptake and corresponding committed dose equivalents" (Carbough, Decker and Swint 1989). The other two, surgery and lavage, prevent materials from entering the bloodstream. They have little or no effect on the contamination once it is incorporated into the circulatory system. Besides, lavage is only applicable to inhalation incidents. As a result, only two treatment options are available for treatment of contaminated wounds.

For the wound itself, surgical excision may be the best method of removing contamination bound at a puncture site. "In practice, a good excision should remove the irradiated tissues, thereby eliminating also the associated risk of a high local dose" (Piechowski, et al. 1989). Furthermore, because the contamination is fixed, "there is, therefore, no case for rushing to an emergency surgical operation" (Piechowski, et al. 1989). Surgical excision provides a fast and efficient way of removing contamination from a

wound. It does not depend on any biological processes, like other treatments, and results are immediately noticeable.

While these procedures are often effective in removing the majority of these targets, there often remains contamination in or around the wound site. "As for the post-surgery residual activity, it is important to be able to distinguish the fraction which remains localized in situ without being metabolized, and that which, on the contrary, slowly passes into the blood" (Piechowski, et al. 1989). In this way, surgery often re-instates the need for chelation treatments. DTPA can bind to the plutonium released from surgical procedures and circulating in the blood, helping to excrete it from the body.

Once the plutonium reaches the bloodstream, it is deposited throughout the body making effective treatment difficult. Plutonium isotopes rank among the more highly toxic radionuclides because they are long-lived alpha-emitters that tend to be tenaciously retained in the organs and tissues of the body (ICRP 1982). Moreover, the chemical properties of plutonium make it very reactive with calcium. As it travels through the bloodstream, plutonium is localized in areas of high calcium concentration. For this very reason, plutonium is known as a "bone seeker" because upon entering the body, plutonium is most predominantly absorbed into skeletal structures. Additionally, radionuclides may decay to other hazardous materials. For example, Americium-241 is formed by the decay of Plutonium-241. Medical complications attributed to the intake of such radionuclides include bone necrosis, fibrosis and sclerosis.

5. CHELATION THERAPY

5. 1 Introduction

There are a variety of chelation agents, but only two are recommended for use in the United States. Trisodium calcium diethlenetriaminepentaacetate (Ca-DTPA) and its partner agent trisodium zinc diethlenetriaminepentaacetate (Zn-DTPA) have been recognized for many years for their ability to remove plutonium prior to its deposition in soft tissue and bone. Both been used in the US as chelating agents for various transuranic elements such as americium, californium, curium and plutonium.

Originally, chelation agents were administered in one of four ways: (1) as a topical ointment, (2) through injection, (3) ingestion or (4) inhalation. These options make chelation therapy a more versatile means of treatment because it does not require the medical expertise necessary for the other two treatment procedures (lavage and surgical excision). There exists, however, definite advantages for aerosol or inhalation therapy over the other methods of administering chelating agents. Aerosol treatments do not require the presence of medical technicians for administration of the treatment. This fact facilitates the need for quick and immediate treatment for contamination victims. "The therapeutic effectiveness of DTPA to eliminate plutonium from the body is greatly reduced with delayed treatment" (Hall, et al. 1978). However, as there is no need of specialized medical personnel to administer the DTPA agents, there need be no wait

before initiating treatment procedures which might hinder the potency of the DTPA therapy.

Secondly, the absence of needles will help alleviate patient anxiety. Stress will already exist at elevated levels as a result of the accident. Brown (1983) noted, "Accidents always result in emotional trauma. When the accident involves radiation there is a possibility of enhanced emotional problems due to the mystique surrounding radiation exposure". However, since most incidents involve personnel at nuclear facilities, these emotional problems should be minimized. Hopefully, during their work experience or training, the "mystery" of radiation will be resolved. Workers should not be ignorant of the nature of radiation and, with this knowledge, the stress associated with the incident should be reduced. Moreover, the absence of hypodermic needles, which can cause stress and trepidation to many people, will help to keep the victim calm and relaxed as much as possible. Unfortunately, inhalation is not the most efficient means of administration.

5. 2 DTPA Treatment Considerations

The efficiency of the DTPA therapy is not 100%. Therefore, to warrant a truly successful and thorough treatment for victims of radiological contamination, DTPA therapy is often combined with other treatment options. For instance, DTPA therapy is often combined with surgical excision of the contaminated area. Thus, contaminated wound victims might undergo surgery to remove the contamination localized at the wound site.

After administering DTPA treatment, "the local activity which persists for moderate or long periods, notably the residual activity after excision, seems above all to be 'inert', not at all or very little metabolisable" (Piechowski, et al. 1989). In other words, any remaining radiological matter may remain at the wound site and probably not circulate through the bloodstream and be deposited in various organs such as the liver or kidneys. Hence, an ideal treatment procedure for a contaminated wound patient would involve both surgical excision and chelation therapy. The DTPA would purge the bloodstream of the contaminant while surgical means would remove the localized activity from the puncture site.

There are, however, some restrictions for DTPA therapy. For one, the form in which the plutonium exists is of particular importance. The efficacy for DTPA therapy is excellent for plutonium formed as soluble salts, such as chlorides and nitrates (Ca-DTPA, 1997). However, the efficacy of Ca-DTPA and Zn-DTPA are "essentially nil" for the high-fired oxides and other highly insoluble compounds (Ca-DTPA, 1997). Definitely, consideration must be given to the properties of the contaminant before DTPA can be consider as an effective means of treatment.

Similarly, the agents can only bind with free monomeric plutonium in the extracellular fluids (Ca-DTPA, 1997). This means that in the case of an intake of plutonium where the radionuclide becomes incorporated into the blood, the DTPA agents will have no effect on intracellular plutonium, plutonium already bound to bone or soft tissues, large deposits of plutonium amassed at the wound site or in the lungs, plutonium on a polymeric form or plutonium bound by other materials, like transferrin, an iron-bearing protein found in human plasma. "In blood,

greater than 90% of the plutonium becomes bound to transferrin," in the absence of the influence of chelation agents (Hall, et al. 1978). In essence, DTPA has to compete with the body's natural processes, which can often hinder the true potency of these treatments.

Although it has no effect on the chemical bond between transferrin and plutonium, DTPA can still help speed the excretion of the bound material. When DTPA is administered as an aerosol, "only about 60% of the plutonium that becomes bound to transferrin in plasma can be removed from the body by the initial DTPA treatment" (Hall, et al. 1978). This is a definite hindrance because the first treatment with DTPA is the most significant. At this time, the levels of unbound plutonium in the bloodstream is at a maximum, which optimizes the efficiency of Ca-DTPA. Yet, if DTPA is not administered immediately, the body's natural excretion capabilities severely limit the effects of the chelating agents. Again, the importance of quick and immediate administration of the DTPA treatments is emphasized.

Once natural excretion processes have bound the nuclear material, these colloidal plutonium-transferrin particles are circulated through the bloodstream until they are absorbed or filtered out. Evidence suggests that these naturally-bound particles are not as stable as the chelates and are susceptible to factors which would separate the bound particles, releasing the radionuclide back into the bloodstream. Consequently, the plutonium could be filtered by the kidneys or liver. "Data for man and other animals show that the removal of plutonium from the blood by the kidneys is a slow process" (Durbin 1972). Durbin's calculations proved that normal, healthy kidneys clear only 3-4% of the plutonium present in blood plasma in

a given 24-hour period (Hall, et al. 1978). As a result, it would take the body's natural clearance abilities many days to rid itself of the plutonium. During this time, the body would be vulnerable to the biological damage associated with the uptake of the radionuclide.

The liver and kidneys are not the only concern from the internal deposition of plutonium. The skeleton is a major site of plutonium deposition, especially the non-calcified, non-cartilaginous bone (Langham, et al. 1980). In other words, the major site of plutonium deposition is areas of trabecular bones, where the bone is honeycombed with small tubular structures filled with bone marrow. Long bones of the body are comprised of both types of bone: the midshafts are made of compact or cortical bone while the ends are trabecular or cancellous bone. The cortical bones are essentially providing the body with stability for walking and moving while simultaneously furnishing protection for the vital organs of the body. Trabecular bone serves as a conduit for bone marrow and the nutrients needed for bone development and restoration. Skeletal structures in which trabecular bone abounds include the skull, vertebrae, rib cage and pelvis, although all bones consists to varying degrees of both types of bone (Toohey1994). The combination of these two bone types forms a skeleton which provides strength and structure while providing efficient means of growth and repair.

Lastly, the benefits of DTPA are highly dependent on time. "The therapeutic effectiveness of DTPA to eliminate plutonium from the body is greatly reduced with delayed treatment" (Hall, et al. 1978). Hence, in order to take full advantage of the benefits of DTPA therapy, Ca-DTPA must be given immediately after the intake of the radiological contamination.

Manufacturers of Ca-DTPA indicate that for optimal effect, that the agent must be administered within 6 hours of exposure (Hall, et al. 1978). This idea correlates with the patterns of plutonium excretion observed in exposure victims not undergoing DTPA therapy. "Since plutonium excretion for humans decreases very rapidly after exposure, the most beneficial treatment period therefore will be immediately following intake when the excretion rate is at its maximum" (Wick 1967). Surely, the best way to take advantage of this optimum treatment time is by ensuring that nuclear facilities maintain an ample amount of DTPA agents in their emergency medical supplies.

Untreated, actinide contamination can cause severe problems for the patient, one problem being osteogenic sarcoma. Osteogenic sarcoma is cancer of the tissues responsible for bone growth or repair. If incorporated into the skeleton, the plutonium will be retained in the bone for an extensive period of time. Once deposited on the bone surface, the site of metabolic activity, the plutonium is encapsulated in the bone as more layers of calcium are added on the outer layer of the skeletal structure. The apparent retention half-life for plutonium in bone is approximately 100 - 200 years (Hall, et al. 1978).

Yet, there is no guarantee that the plutonium will remained fixed at that location. Due to bone growth and the constant fluctuation of the calcium levels in the blood, the skeletal system undergoes constant remodeling. As calcium is absorbed from bone to rejuvenate the body's depleted calcium levels, the bound plutonium may be mobilized back into the bloodstream and subsequently, deposited in the liver and other bone surfaces. As a result, victims of internally deposited plutonium are still

threatened by the hazard of the associated dose for days, months, even years after the incident.

Meanwhile, without the effects of DTPA therapy, progressively larger quantities of the radionuclide deposited in the bone and liver are extracted to maintain equilibrium with extracellular fluids. Due to the plutonium being bound to tissue in the victim's body, the amount of the radionuclide excreted in the urine decreases even though the fraction of plutonium in the plasma which is cleared is constant (Hall, et al. 1978). This indicates that the amount of plutonium present in the blood decreases because more plutonium is being confined in body tissue. "Without therapy, the total amount excreted does not reduce the urinary excretion rate since the body burden is not reduced appreciably by normal elimination processes" (Hall, et al. 1978). Recognition of the fact that the body natural immune abilities are not sufficient for protection from the perils of plutonium emphasizes the importance and potency of DTPA therapy.

5. 3 Chelation Side Effects

There also exists some side effects associated with DTPA therapy. Yet, most of them are correctable by preparation and careful treatment procedures. For instance, patients who have been given numerous Ca-DTPA treatments over a very short period of time can expect to experience nausea, diarrhea, chills , fever, vomiting, pruritus (itching), and muscle cramps during the first day of therapy (Ca-DTPA 1997). These are symptoms which are unavoidable, but may be relieved by additional

medications or increasing recovery time between doses of DTPA. Normally, treatment schedules are designed to provide sufficient recovery time for the patient, thus eliminating the presence of the side effects.

Another disadvantage lies in the difference between Ca-DTPA and Zn-DTPA. Ca-DTPA is approximately 10 times more effective than Zn-DTPA for the initial chelation of transuranic matter (Ca-DTPA 1997). This idea might spur the administration of strictly Ca-DTPA during the treatment regimen. However, this would not prove very beneficial for the patient. Repeated dosages of Ca-DTPA (depending upon the dosage and frequency of administration) will deplete the patient's zinc and manganese reserves thus interfering with biological processes dependent upon these two trace metals. "Zinc deficiency has been described to affect adversely testicular function in both man and animal" (Ca-DTPA 1997). To avoid such problems, a successful treatment regiment includes the intermittent administration of Ca-DTPA and Zn-DTPA or a Ca-DTPA program with concomitant zinc replacement. The former suggestion is facilitated by the fact that after approximately 24 hours, the difference in the efficiencies of the two agents becomes negligible and Zn-DTPA is "for all practical purposes as effective as Ca-DTPA" (Zn-DTPA 1997). This also negates the need for the zinc supplements, reducing the amount of medications and treatment costs.

The superiority of the two possible treatment schedules for DTPA administration is further emphasized in a paper by Kalkwarf (1983) on the 1976 Hanford americium incident. The paper cites a study where a patient underwent six different DTPA treatment schedules within a 3-year

period. Among the group's conclusions was the following statement (Kalkwarf 1983):

> "The data indicate there was no significant depletion of essential metals in the patient's body during this treatment with DTPA salts. This conclusion is based on finding normal concentrations of metals, other than zinc, in his urine samples and comparing the amounts of zinc that were removed by DTPA treatment with those that were introduced by ingestion of zinc sulfate capsules or by the injection of $Na_3ZnDTPA$ were used."

The conclusions continue, adding the resolution: "None of the injection schedules showed any disadvantages in terms of trace-metal losses as long as adequate zinc supplements or $Na_3ZnDTPA$ were used" (Kalkwarf 1983). Clearly, if either of the two programs is followed, the patient will suffer no complications resulting from depletion of trace mineral supplies in the body.

There exists another factor which supports the Ca-DTPA/Zn-DTPA combination: toxicity. Zn-DTPA is less toxic than Ca-DTPA (Ca-DTPA 1997). For that reason, Zn-DTPA is able to be administered to patient who could not be given Ca-DTPA. For instance, Ca-DTPA is not recommended for minors, pregnant women, nephrotics and people with depressed levels of bone marrow (Zn-DTPA 1997). Yet, these people could be given Zn-DTPA without any of the problems or harmful effects that the patient would incur from Ca-DTPA therapy.

This same reasoning suggests that Zn-DTPA is the choice for prolonged DTPA therapy. Although treatment schedules vary, most are based on the concept of an initial treatment with Ca-DTPA followed by succeeding dosages of Zn-DTPA. This cycle may be repeated depending upon the conviction of the attending medical personnel.

Despite the possible side effects, there is no doubt that these chelation agents play a vital role in the successful treatment of contamination victims. A case study of a plutonium contaminated puncture wound that occurred in 1985 at the Hanford Plutonium Finishing Plant discovered that "during the 17 months of chelation therapy, approximately 7 kBq of the Pu-239/240 radioactivity deposited in the wound was excreted in urine" (Carbough, Decker and Swint 1989). Furthermore, one-third of that amount was eliminated from the patient in the first 15 days (Carbough, Decker and Swint 1989). Again the benefits of DTPA therapy were heralded: "In all cases, the excreted Pu-239 for the non-treated period was substantially less than expected" (Carbough, Decker and Swint 1989). The paper continues the idea by citing, "When (DTPA) treatment resumed, the observed excretion exceeded that expected".

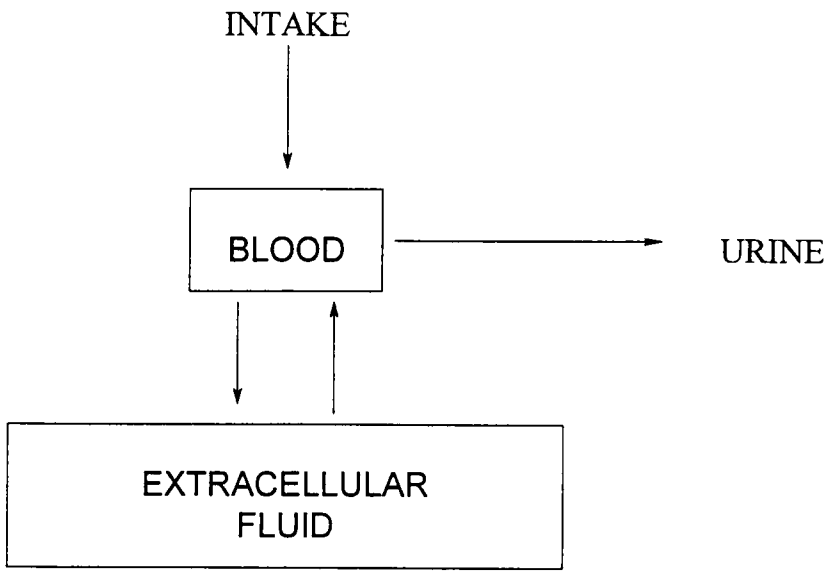
Untreated intakes of plutonium increases the potential incidence of malignant tumors and significantly reduces life expectancy. As a result, concerning this particular plutonium wound victim, DTPA therapy was administered to accelerate the excretion rate of plutonium from the workers body thereby minimizing any harmful effects resulting from the intake. For almost any incident of internal contamination, the benefits of chelation far outweigh the consequences of any possible side effects.

5. 4 Biokinetics of DTPA

According to the Oak Ridge Associated Universities Medical Science Division informational package insert for Ca-DTPA (1997),

> "DTPA belongs to the group of synthetic polyamino acids which form stable complexes (metal chelates) with a large number of metal ions. When releasing a metal such as calcium, it binds to another metal of greater binding power and carries it to the kidneys where it is then excreted in the urine".

In essence, the chelator binds itself with transuranic material found in the victim's bloodstream forming a chelate. In contamination incidents, the principal behind the DTPA agents is that the chelator will bind with the contaminant, like plutonium or americium. This chelate has a stable nature, preventing any chance of the transuranic separating from the DTPA agent before excretion. In the body, the chelate is metabolized like the chelation agent (LaBone 1994). In other words, once bound to the chelator, the properties of the transuranic are masked by the chelator; therefore, the bound transuranic material is excreted at the faster excretion rate characteristic of the chelation agent rather than its own, slower rate. A schematic of the kinetics of DTPA agents can be found in Figure 5.4.1 By doing so, the transuranic matter is excreted more swiftly than normal and biological hazard is reduced.



PARAMETERS FOR DTPA KINETICS

FROM ---> TO	TRANFSER (d-1)
BLOOD --> URINE	1.308
BLOOD --> EXTRACELLULAR	0.2773
EXTRACELLULAR --> BLOOD	0.138

Figure 5.4 -1: The Behavior of DTPA Agents in the Body. The parameters are derived from a work by T. R LaBone : "Evaluation of Intakes of Transuranics Influenced by Chelation Therapy (U), 1994.

There exists a distinct advantage for victims of inhaled contaminants which receive DTPA via aerosol treatments. Hall, et al. (1978) noted, "The most important advantage is that a larger fraction of the transportable plutonium initially deposited in the lung can be removed from the body by aerosol chelation". It is most advantageous for the victim of an inhalation incident that the bond between the plutonium and the chelation agent is formed quickly, preferably in the lung before the plutonium enters the circulatory system. This suggests quick and immediate administration of DTPA agents. "If plutonium is chelated by mass action in the lung prior to reaching the bloodstream, approximately 99% of the Pu-DTPA is excreted in urine with a half-time of ~2 hours" (Hall, et al. 1978). As a result, inhalation accidents could be rectified in a matter of hours if proper chelation therapy is performed immediately. This idea is rational considering the fact that in the lung, the DTPA agents would not have to compete with other binding processes encountered when the chelate is formed in the bloodstream.

For DTPA administered via a nebulizer for treatment of contaminated wound accidents, the chelation agents undergo a more gradual dispersion into the circulatory system. Studies show that inhalation treatment allows the chelation salts to remain in the body longer than injections which deposits the DTPA is deposited within a muscle. "Aerosol inhalation of DTPA is more effective than intramuscular injection, because diffusion to the body from the lung is apparently slower than from the muscle, resulting in a longer lasting plasma burden" (Jolly, et al. 1972). Analysis of urine excretion of test subjects verify this concept. In patients given equal amounts of DTPA, one by injection and the other by inhalation, urinalysis data revealed that at equal times after administration of the agent,

the maximum concentration of DTPA in the inhalation case was 20% less than the concentration from the injection case (Jolly, et al. 1972). This study indicates that the DTPA remained longer in the bloodstream of the person receiving DTPA through inhalation than for the injection patient, presumably as the lung serves as a continuous source of the DTPA agents. Inhalation treatment allows the DTPA to remain in the bloodstream longer, having more opportunity to filter out any unbound or loosely-bound plutonium present in the body.

Still yet, DTPA treatments given orally are far less effective. "DTPA, when orally administered, was only about 10% as effective in increasing urinary output of Pu-239 as when given intravenously" (Norwood 1962). For contaminated wounds, this inefficiency is probably due to the vast extent of translocation the agent must undergo before reaching the affected area. For example, regarding a cut on a finger by a plutonium-contaminated piece of metal, orally administered DTPA would have to travel through the digestive tract before being absorbed into the circulatory system. From there, it would be carried through the body by the blood, eventually reaching the site of the deposited material. Having to experience such complex processes, the DTPA agent would be partially excreted and severely diluted before reaching the site of radionuclide deposition. Because of the inefficiency of this means of administration, DTPA agents are no longer given orally to victims of radionuclide contamination (Goans 1998).

Regardless of the route of administration, the attributes of DTPA therapy are astonishing. Administration of chelation agents such as Ca-DTPA and Zn-DTPA raises the urinary excretion 25 to 100 times (50 on average) over normal urinary excretion rates (Piechowski, et al. 1989). This

increase reduces the time the radionuclide resides in the body and the biological hazard which would result from its presence. Moreover, the effects of a single treatment can last as long as 10 to 20 days before the urinary excretion returns to normal (unchelated) levels (Piechowski, et al. 1989). The extended increase of urinary excretion allows sufficient time for complete and total chelation of all available radionuclear material in the bloodstream.

Experiments involving laboratory mice injected with DTPA exhibit the effectiveness of the agents. One such experiment consisted of plutonium injections for a group of mice, followed three days later with a dose of DTPA. The dose of plutonium was expected to produce bone tumors in a large proportion of the control mice (approximately 65 per cent of those surviving the latent period) It was followed later by an optimal dose of DTPA given from 1-12 days to achieve increasing degrees of plutonium removal. Three days after plutonium administration, the Pu-239 content of the blood was less than 1 per cent of the injected dose (Rosenthal, et al. 1962). The decrease in the levels radionuclear material is clearly attributed to the effects of DTPA agents.

Along with the animal tests, the study of previous incidents where chelation therapy was utilized has greatly contributed to the study of DTPA effects. Hanford case studies of contaminated wound victims undergoing DTPA chelation therapy performed by J. J. Jech, B.V. Anderson and K.R. Heid (1972) concluded, among other things, that the removal effectiveness of these drugs was 50-60%. This conclusion was reached after an in-depth analysis of several plutonium intake cases (both inhalation and injection) and comparisons with untreated cases. As the

information proves, administration of DTPA agents is a reliable means of increasing the excretion of transuranic materials, such as plutonium, from the body.

6. THE 1991 PLUTONIUM WOUND INCIDENT

6. 1 The Incident

Any wound to the body necessitates some degree of concern. However, when the incident involves the possibility of internal radiological contamination, the level of concern is automatically intensified. One such incident occurred on September 5, 1991. A Special Operator at a nuclear facility began the work day in a decontamination cell during a plant-wide decommissioning effort . The operator began working on cleaning a transit sheet dry box. The boxes had been used by the facility during normal operations and had been possibly contaminated with plutonium and americium. Due to the high probability of contamination, the worker wore standard protective clothing. This consisted of a non-porous full body suit, gloves, foot coverings and a respirator. Cleaning procedures involved scrubbing and washing the boxes with detergent and water.

To help ease the burden of laboring in the protective clothing, the Special Operator worked in short time spans in the cell. Upon leaving the cell, the worker underwent a complete radiation survey as facility policy demands. As the protective layers of clothing were removed, inspection personnel noticed a small amount of blood on the operator's left thumb. Further indications of a possible injury included a wet bloodstain on the interior protective glove and a noticeable slit (about ½" long) in the glove. Upon removal of the glove, a wound was evident. A photograph of the wound is found in Figure 6.1-1.

6. 2 Treatment

Immediately, facility management was notified and treatment procedures were initiated. Unfortunately, the facility had no documented procedures for handling contaminated wounds. Relying on their recollection of education and training, a treatment procedure was quickly formulated. A direct survey was taken of the wound site, noting a level of contamination of 200 DPM. This indicated the definite presence of radionuclide contamination within the wound. Following protocol, the wound was vigorously rubbed and washed with sterile saline solution. The follow-up survey found 50 - 100 DPM still present. Hoping to further reduce the contamination within the wound, the area was washed again. This time a lotionized body shampoo was utilized as the wound was once again vigorously rubbed, washed and rinsed. However, another radiation scan still noted the presence of radionuclides. Again, the injury site was washed and rinsed with an alconex detergent.

With the hazard of internal contamination in mind, the decision was made to initiate chelation therapy thirty-four minutes after the wound was discovered. The procedure involved 1 gram of the chelation agent administered through a nebulizer. A nebulizer is an apparatus which will take the liquid DTPA and convert it into a thin mist. The patient breathes through an inhalation mask connected to the nebulizer. The chelation agent was Ca-DTPA.

Figure 6.1-1: Picture of Wounded Thumb

About twenty minutes later, to collaborate with the inhaled chelation regimen, a chelation ointment was applied to the wound. Once again a direct survey of the wound was taken revealing 200 DPM of activity. A blood sample survey presented 800 DPM, confirmed that the contamination had spread to the bloodstream. More ointment was applied fifteen minutes later. Oddly, the next survey measured a direct count of 800-1000 DPM and a blood count of only 100 DPM. Somewhat baffled, attending personnel applied the ointment a third time. Surveys taken at this time, about 10:15 AM, noted that once again about 800 DPM directly and 150-200 DPM from the blood. The fluctuating survey results confused personnel causing uncertainty and doubt in their actions.

The aerosol treatment finished about 10:25 AM. A direct survey of the wound still detected about 800 DPM. However, the blood survey found no contamination above detectable levels. This result was achieved again five minutes later when another blood smear was taken and surveyed. At this time, the wound was treated with an antibiotic ointment to prevent further infection and dressed with gauze and bandaged. The nail bed bled significantly during the evening.

Figure 6.2-1 presents a visual display of the radiological surveys taken during the hours immediately following the incident. Both blood smear and direct wound counts are represented on the graph. As the figure clearly shows, the survey results present a confusing picture. Attending personnel were perplexed by the various results of their radiological surveys of both the wound and the blood.

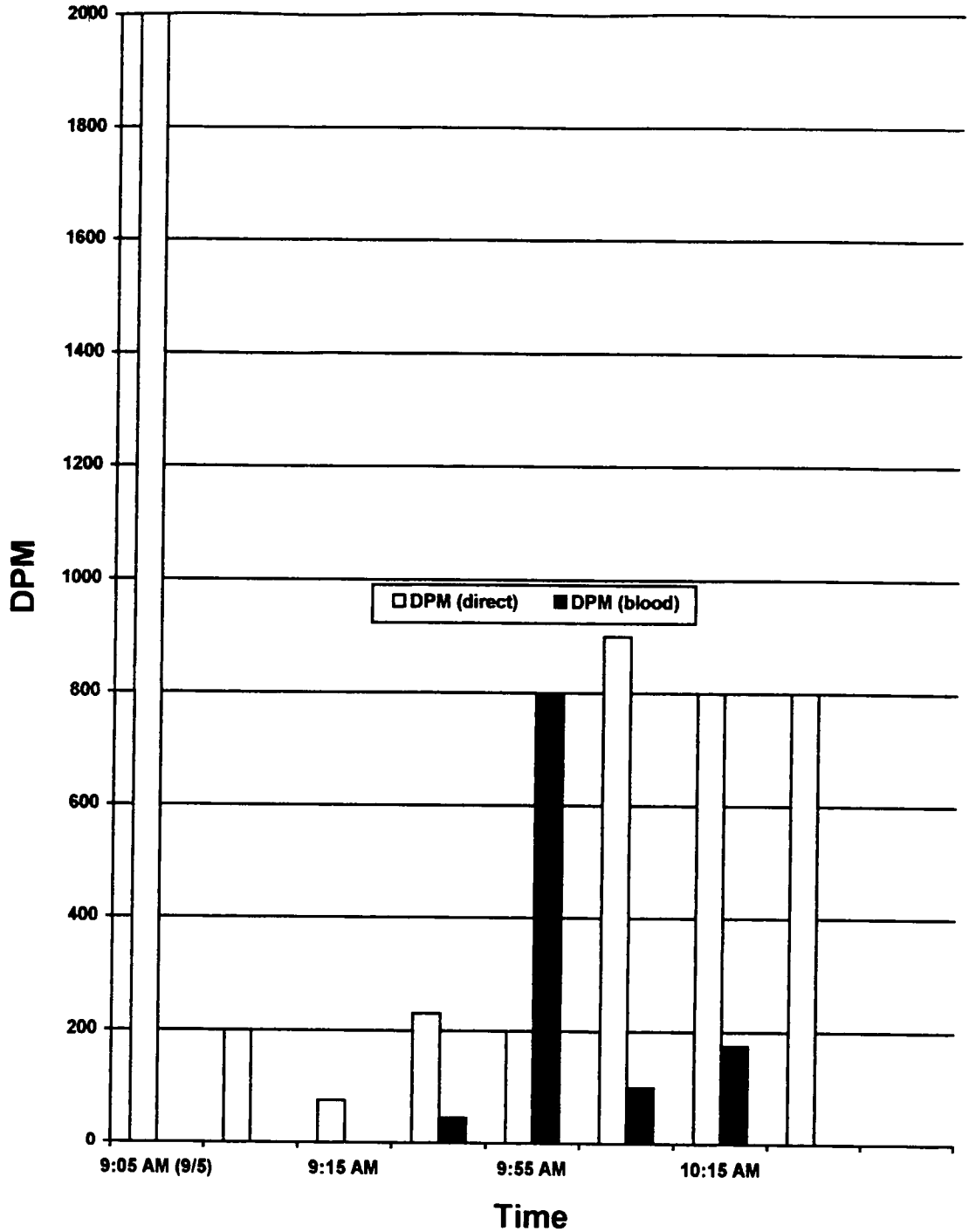


Figure 6.2-1: Early Measurements of Wound and Blood Activity

Meanwhile, the attending physicians began to consult with one another concerning further treatment procedures. One suggestion involved re-opening the wound area and removing the thumb nail. This routine would allow physicians more access to investigate the puncture. At the same time, any metal fragments remaining in the wound could be easily removed. However, because there was no pain or discomfort noted by the patient during the vigorous rubbing and washing procedures, no foreign bodies were thought to be lodged in the wound; hence, no surgical procedures were performed at that time.

The next day, the physicians contacted Radiation Emergency Assistance Center/Training Site (REAC/TS) in Oak Ridge, Tennessee. REAC/TS explained that the chelation ointment was not proven as effective and the medication it contained was extremely potent. Additional application of the topical ointment was not recommended. Furthermore, the physicians changed their minds concerning surgical procedures and decided to remove the nail in the near future.

The patient remained under strict medical supervision to note the status of the wound. On September 10th, five days after the incident, the cuticle area was slightly swollen but no strong signs of infection were present. The attending physician directed the patient to soak the injured thumb in very warm salt water. The next day, the appearance of the wound improved and bleeding appeared to have ceased. However, a spot on the nailbed that appeared to be gradually moving toward the tip of the thumb was discovered. The origin of the spot was unclear and was cause for concern for the health physicists.

A survey of the wound site on September 12th brought additional alarm to the attending personnel. The measurements of radiological contamination were increasing. Operational health physicists from the facility contacted REAC/TS for additional consultation. Suspecting the presence of foreign bodies in the wound, x-rays were taken at a local hospital. However, the results were negative and the wound was found to be free of shrapnel.

Accordingly, a decision was made to continue aerosol chelation therapy under the assumption that the DTPA agents would continue to prevent the spread of internal contamination. The patient then received a daily chelation treatment for the next four days. After completion of the treatment on the second day, September 13th, a radiological survey discovered that the DPM counts were still increasing. With the wound counts still at elevated levels, the threat of internal contamination still existed. In an effort to control the translocation of the radiological contamination from the wound to the circulatory system, the decision was made to immediately remove the nail. Preparations were made at a local hospital for the surgery to be performed on an "out patient" basis. The nail and surrounding tissue were excised and the wound was sealed with two sutures. All material used in the surgical procedure, as well as the excised material, were retained and underwent a radiological survey. A tabulation of the results of the various surveys are presented in Table 6.2-1. The area was dressed with an antibiotic ointment (TEFLON) and a thick dressing was applied. Prescribed medications included Cipro, Darvol and Phenaren. The

DATE	RESULT Am-241 (nCi)	Implied Result of Pu (Applying Reported Ratio)	DETECTOR TYPE/ LOCATION
09/05 - 09/13/1991	**36.50**	**54.75**	Result based on average of highest wound count results prior to surgical excision
09/13/1991	**21.65**	**32.475**	Activity of material excised from wound site (thumbnail, tissue, rinse solutions, gauze, sponges, etc.)
09/13/1991	**7.32**	**10.98**	Wound count result immediately following excision. Thumb was wrapped in 4" x 4" gauze pad and thumb cot. No correction was determined for attenuation of bandages
09/14/1991	**6.92**	**10.38**	Wound count of thumb w/o bandages
09/15/1991	**6.76**	**10.14**	Wound count of thumb w/o bandages
09/16/1991	**7.60**	**11.4**	Wound count of thumb w/o bandages
09/19/1991	**9.60**	**14.4**	Wound count of thumb w/o bandages
09/20/1991	**4.30**	**6.45**	Activity of scabbing and sutures removed from the wound site
09/23/1991	**11.15**	**16.725**	Wound count of thumb w/o bandages
09/24/1991	**11.02**	**16.53**	Wound count of thumb w/o bandages
10/02/1991	**10.19**	**15.285**	Wound count of thumb w/o bandages
10/07/1991	**10.20**	**15.3**	Wound count of thumb w/o bandages
10/10/1991	**10.03**	**15.045**	Wound count of thumb w/o bandages
10/23/1991	**10.19**	**15.285**	Wound count of thumb w/o bandages
12/11/1991	**6.60**	**9.9**	Wound count of thumb w/o bandages
02/06/1991	**8.20**	**12.3**	Wound count of thumb w/o bandages

Pu-239: Am-241 ratio reported by Employer = 1.5:1.0

THE ABOVE RESULTS WERE TAKEN AT THE FACILITY USING A THIN WINDOW Be GERMANIUM DETECTOR.

Table 6.2-1: Wound Count Results

THE RESULTS HAVE BEEN CORRECTED FROM THE ORIGINAL REPORTED RESULTS FOR DISCREPENCIES BETWEEN RESULTS REPORTED BY AN INVESTIGATING NATIONAL LABORATORY.

INVESTIGATION OF THESE DISCREPENCIES REVEALED THAT THE STANDARD USED AT THE FACILITY FOR CALIBRATION OF THE UTILIZED COUNTER PRODUCED A DEAD TIME IN THE DETECTION EQUIPMENT OF 25% OR GREATER, WITH A RESULT OF DECREASED EFFICIENCY FOR THE COUNTING SYSTEM.

Table 6.2-1:Wound Count Results (cont.)

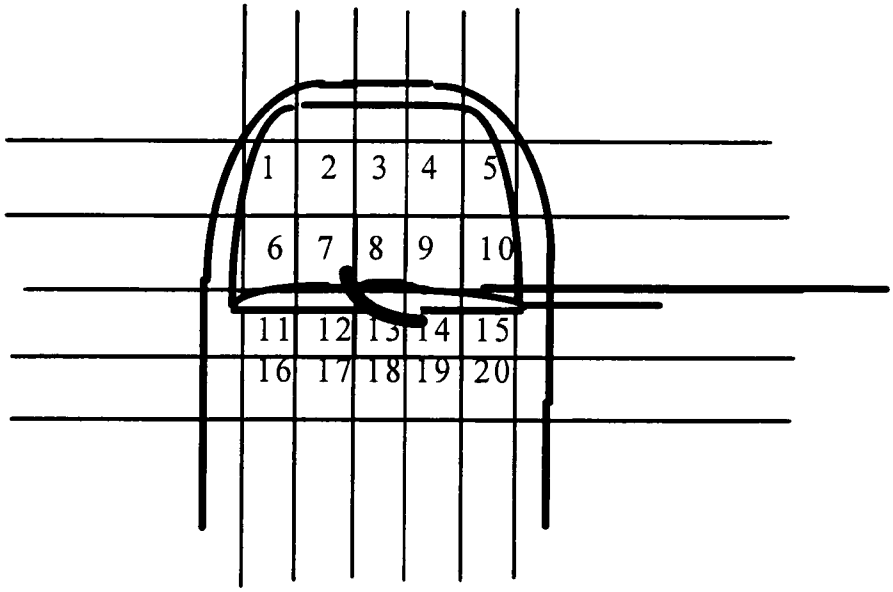
patient received instructions from the physician to return the following day, September 14th, for a change of dressing on the wound.

The patient received a second chelation treatment on September 14 and returned to the hospital to have the wound examined. Noting that the injury was healing nicely, the area was cleaned with water and a sterile solvent antibiotic ointment was applied. TELFA and a finger cot dressing was placed around the wound area. Contemplating the nausea and sweating the patient was experiencing, the physician suspected that the patient might be allergic to the prescribed Demoral . The physician changed the prescribed medication to Tylox in hopes of relieving the patient's symptoms.

Zn-DTPA was administered again the next day (September 15) in an effort to counteract the effects of zinc depletion often observed with prolonged use of Ca-DTPA. The following day, September 16th, the patient received the final chelation treatment. Additional concerns were expressed that day regarding the patient's high blood pressure, which had been consistent throughout the therapy. The attending physician prescribed 50 mg of Tenornen in an effort to overcome the problem.

The patient returned to the physician three days later (September 19). The physician removed the wound dressing to observe the injured area. After a consultation with medical personnel at the Hanford facility, a special radiological survey was taken. The procedure involved a very concise mapping of the wound activity. The pattern can be seen in Figure 6.2-2. In this way, personnel obtained a more accurate picture of exactly which regions of the thumb still contained radiological activity and

LEFT THUMB



Wound mapping was performed with a collimator

The injured area was partitioned using a 0.5 x 0.5 cm grid

Each count was taken for 600 seconds

Counts were taken on Sept. 26, 1991

Figure 6.2-2: Wound Mapping

AREA	COUNT (600 sec)
1	0
2	18
3	14
4	22
5	not counted
6	3
7	18
8	0
9	0
10	not counted
11	0
12	0
13	13
14	19
15	not counted
16	not counted
17	28
18	0
19	0
20	not counted

Table 6.2-2: Wound Count Results

Figure 6.2-3 presents a simulated three-dimensional presentation of the wound counting data imposed on a diagram of the thumb. In this way, areas of elevated activity can be noted in regards to the actual wound site. After the counting procedure was completed, the physician removed the external sutures the wound received after the nail and associated tissues were excised. During this time, the physicians also removed the scabbing which had formed on the cut. A radiological survey of the extracted scab discovered that it contained approximately half of the contamination that still remained in the wound. The patient returned the next day to have the wound redressed.

On September 23rd, a radiological survey was performed on the patient's lymph node located near the left clavicle. Lymph nodes act as a blood filter, filtering contaminants out of the circulatory system. Because of this characteristic, the lymph nodes often accumulate any radiological contamination which enters the blood. This inspection detected approximately 0.5 nCi of radiological material amassed in this area. Meanwhile, after inspecting the injured thumb, the doctor believed that the wound still contained a suture from the surgery earlier in the month. If the suture was not soon dissolved by biological processes, the suture would have to be removed by surgical means.

The wounded thumb underwent another radiological survey upon the patient's return to the physician's office the next day. Alarmingly, despite the fact that a significant amount of radiological material had been removed with the scabbing less than a week before, the counts were still increasing. The same phenomenon was noticed two days later after a survey

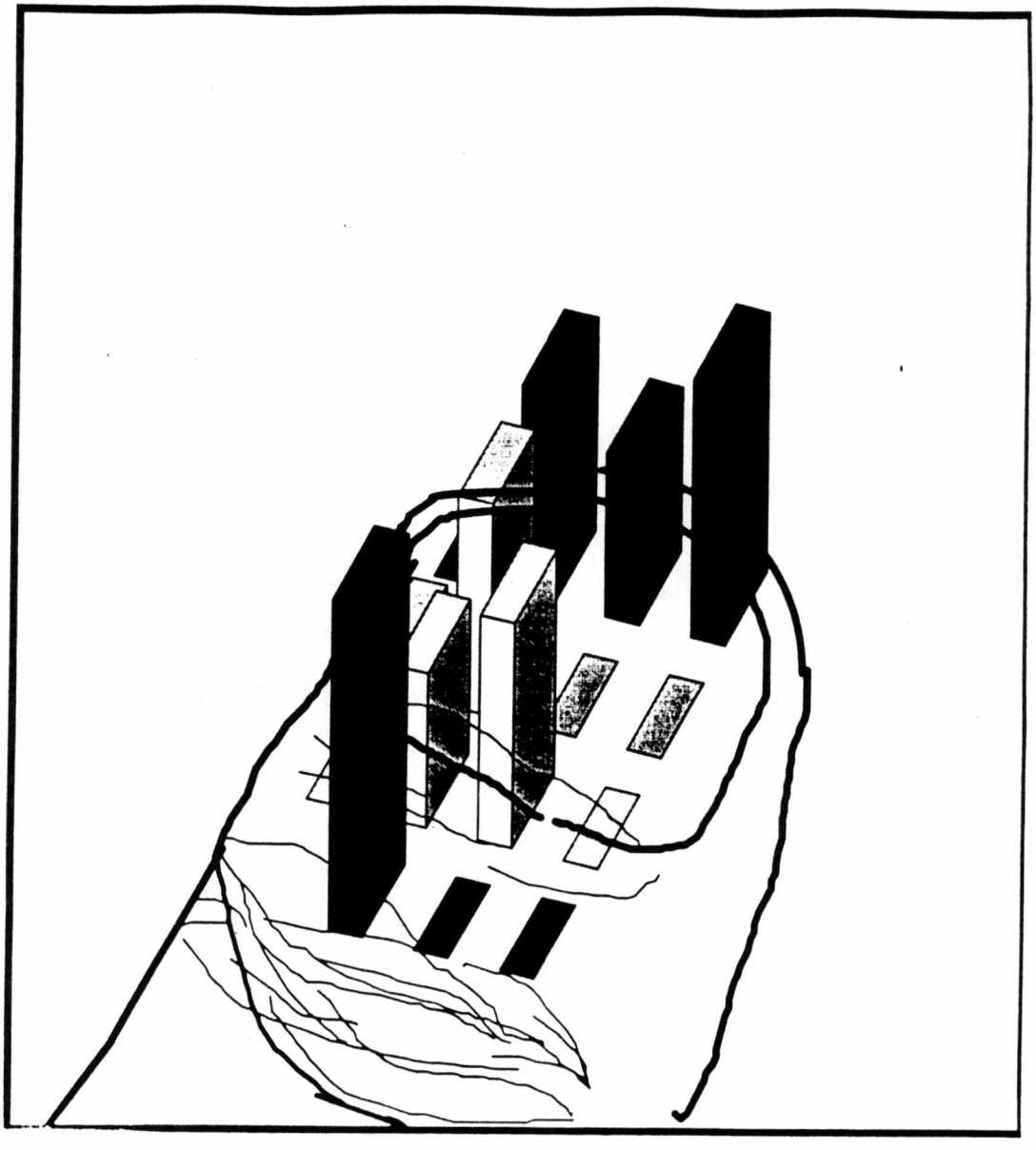


Figure 6.2-3: Simulated 3D Surface Map of Contaminated Wound Area

on September 26th. At that time, the thumb was cited as "oozing" around the cuticle . Moreover, the sutured area had opened. The physician removed the scabbing and the remaining suture. Next, after cleaning the wound, antibiotic ointment and a bandage was applied to the wound. Concerning the patient's consistent high blood pressure, the doctor changed the prescribed medication to Zestril (10 mg). Halcion was also prescribed to counter the sleeping trouble the patient was experiencing.

The thumb continued to heal well the next couple of weeks. The only problem occurred early in October when another remaining suture was discovered. After deciding that biological means were not sufficient to dissolve it, the suture was surgically removed December 2nd. The patient remained on blood pressure medicine through the end of the year.

As the 1991 plutonium wound treatment schedule demonstrates (summarized in Table 6.2-3), the 1991 plutonium wound patient received an initial chelation with Ca-DTPA then received five subsequent chelations with Zn-DTPA. However, one aspect of the treatment which makes this case unique is the use of a chelation ointment- a rarity in treatment procedures. Since then, the chelation ointment has not been used in any other contamination case due to the lack of potency of the treatment. In this case, Dr. Goans from REAC/TS implies that the chelation ointment had no effect on the excretion of the plutonium (1997). Chelation ointment is no longer included in treatment regimens for victims of contamination injuries.

The treatment schedule summarizes the various procedures, the times each action was taken and any medications administered or prescribed. It also includes any notable events or comments by attending personnel

DATE	TIME	TREATMENT
Sept. 5, 1991	9:15 AM	Vigorous rubbing, rinsing with sterile saline solution
	9:20 AM	Washing with lotionized body shampoo, then rinsed with alconex detergent
	9:39 AM	Ca-DTPA initiated, administered via nebulizer
	9:55 AM	Ca-DTPA ointment applied
	10:10 AM	Ca-DTPA ointment applied
	10:15 AM	Ca-DTPA ointment applied
	10:25 AM	Ca-DTPA complete
	10:30 AM	Area dressed with antibiotic ointment and bandaged
Sept. 10, 1991	AM	Patient instructed to soak finger in very warm salt water
Sept. 12, 1991	AM	X-ray of thumb
	3:18 PM	Zn-DTPA treatment began (nebulizer)
	3:39 PM	Zn-DTPA completed
Sept. 13, 1991	11:50 AM	Zn-DTPA treatment initiated (nebulizer)
	12:38 PM	Zn-DTPA complete Nail Removed, 2 Sutures Antibiotic ointment (Teflon) and dressing applied Prescription for Cipro, Darvol and Phenaren

Table 6.2-3: Summary of Treatment Schedule

DATE	TIME	TREATMENT
Sept. 14, 1991	10:10 AM	Chelation started
	10:50 AM	Chelation complete
	11:15 AM	Dressing Changed, wound cleaned with water and sterile solvent antibiotic ointment
Sept. 15, 1991	2:00 PM	Zn-DTPA started
	2:45 PM	Zn-DTPA complete
Sept. 16, 1991	8:39 AM	Chelation started
	8:55 AM	Chelation ended
		Tenormen prescribed
Sept. 19, 1991		Sutures and scab removed
Sept. 20, 1991		Redressed wound
Sept. 24, 1991		Physician doubles prescription for Ienorin to 100 mg daily.
Sept. 26, 1991	11:00 AM	Applied antibiotic ointment and BandAid. Blood pressure medicine changed to Zestril (10 mg) and Halcion is prescribed for sleep. Scabbing and 1 suture removed: wound is cleaned by physician.
Oct. 2, 1991		Wound is covered with a BandAid.
Oct. 18,1991		BP medicine prescribed for next three months
Dec. 2, 1991		Sutures removed

Table 6.2-3: Summary of Treatment Schedule (cont.)

6. 3 Excretion Data

The urinary excretion of the individual was strictly monitored. Periodically, 24-hour urinary excretions were collected after the incident. This collected material underwent radiological surveys to determine the content of plutonium and americium. Naturally, the data points are more concentrated immediately after the incident and become more sparse as time elapsed. This data can be found in Table 6.3-1.

For a more visual presentation, the information is graphed in Figure 6.3-1. As the figure shows, the Pu-239/240 clearly dominates the excretion data. The two excretion curves for the two plutonium isotopes follow the same general pattern. Both curves peak and decrease simultaneously. The only distinctive difference lies in the fact that the Pu-238 exists at a diminished level. However, this difference diminishes about thirty days after the discovery of the wound.

At the same time, the americium does not appear until early October, almost a month after the event. Americium has a half-life of 432.2 years (Shleien 1992). It is a daughter product included in the decay of Plutonium-241, which has a half-life of 14.4 years (Shleien 1992).

Date	Days Post Intake	Isotope	Result (DPM/L)	Uncertainty (1 σ)	Total Sample (L)
09/05/1991	0.5	Pu-238 Pu-239/240	9.99 37.1	0.509 1.83	1.73
09/06/1991	1.0	Pu-238 Pu-239/240	2.56 9.34	0.174 0.593	1.96
09/07/1991	2.0	Pu-238 Pu-239/240	3.79 15.6	0.251 0.981	1.87
09/08/1991	3.0	Pu-238 Pu-239/240	3.17 13.0	0.206 0.796	1.88
09/09/1991	4.0	Pu-238 Pu-239/240	1.18 5.29	0.108 0.408	1.98
09/10/1991	5.0	Pu-238 Pu-239/240	1.464 6.519	0.104 0.409	1.89
09/11/1991	6.0	Pu-238 Pu-239/240	0.887 4.164	0.0687 0.0267	1.74
09/12/1991	7.0	Pu-238 Pu-239/240	4.879 22.13	0.309 1.35	1.89
09/13/1991	8.0	Pu-238 Pu-239/240	4.679 20.34	0.291 1.218	2.04
09/14/1991	9.0	Pu-238 Pu-239/240	6.336 26.79	0.4384 1.786	1.88
09/15/1991	10.0	Pu-238 Pu-239/240	4.023 16.59	0.2837 1.11	2.01
09/16/1991	11.0	Pu-238 Pu-239/240	3.559 13.87	0.2987 0.9478	1.86
09/17/1991	12.0	Pu-238 Pu-239/240	4.62 19.95	0.4162 1.478	1.89
09/18/1991	13.0	Pu-238 Pu-239/240	2.297 10.89	0.2575 0.887	1.92
09/18/1991	13.5	Pu-238 Pu-239/240	1.401 6.455	0.147 0.4714	1.97
09/19/1991	14.0	Pu-238 Pu-239/240	1.551 7.250	0.1607 0.534	2.15

Table 6.3-1: Urinary Excretion Data Collected From Patient

Date	Days Post Intake	Isotope	Result (DPM/L)	Uncertainty (1 σ)	Total Sample (L)
09/20/1991	15.0	Pu-238 Pu-239/240	2.155 9.645	0.2171 0.7209	2.00
09/20/1991	15.5	Pu-238 Pu-239/240	1.368 5.296	0.1362 0.3828	2.11
09/21/1991	16.0	Pu-238 Pu-239/240	1.222 6.212	0.126 0.4349	2.00
09/22/1991	17.0	Pu-238 Pu-239/240	0.954 4.895	0.1262 0.4028	1.91
09/24/1991	19.0	Pu-238 Pu-239/240	1.084 5.292	0.1155 0.3772	2.00
09/25/1991	20.0	Pu-238 Pu-239/240	0.757 3.078	0.8830 0.2346	1.93
09/27/1991	22.0	Pu-238 Pu-239/240	0.647 2.98	0.0568 0.179	1.91
09/28/1991	23.0	Pu-238 Pu-239/240	0.451 1.994	0.0394 0.117	1.95
10/05/1991	30.0	Pu-238 Pu-239/240 Am-241	0.241 1.16 0.704	0.0191 0.0676 0.0441	2.02
10/12/1991	37.0	Pu-238 Pu-239/240 Am-241	0.0947 0.405 0.511	0.0227 0.0648 0.0395	1.81
10/19/1991	44.0	Pu-238 Pu-239/240 Am-241	0.152 0.685 0.562	0.0256 0.0667 0.0494	1.27
11/02/1991	58.0	Pu-238 Pu-239/240 Am-241	0.0705 0.346 0.175	0.0106 0.0279 0.0253	1.31
12/01/1991	87.0	Pu-238 Pu-239/240 Am-241	0.105 0.575 ????	0.0227 0.0654 ????	1.96

Table 6.3-1: Urinary Excretion Data Collected From Patient (cont.)

Date	Days Post Intake	Isotope	Result (DPM/L)	Uncertainty (1 σ)	Total Sample (L)
12/28/1991	114.0	Pu-238 Pu-239/240 Am-241	0.0629 0.417 0.257	0.00906 0.0365 0.0283	2.00
1/26/1992	143.0	Pu-238 Pu-239/240 Am-241	0.0534 0.36 0.215	0.00902 0.0348 0.0211	2.04
04/18/1992	226.0	Pu-238 Pu-239/240	0.0477 0.368	0.00722 0.0318	2.07
08/02/92	332.0	Pu-238 Pu-239/240	0.0404 0.258	0.00642 0.0232	1.90
11/22/1992	444.0	Pu-238 Pu-239/240	0.0503 0.385	0.00776 0.0333	1.72
03/01/1993	543.0	Pu-238 Pu-239/240	0.0355 0.243	0.00525 0.0197	1.89
06/14/1993	648	Pu-238 Pu-239/240	0.0553 0.319	0.00717 0.0257	1.93
02/18/1995	1262	Pu-238 Pu-239/240 Am-241	0.0825 0.508 0.163	0.0148 0.0518 0.0229	1.77

Table 6.3-1: Urinary Excretion Data Collected From Patient (cont.)

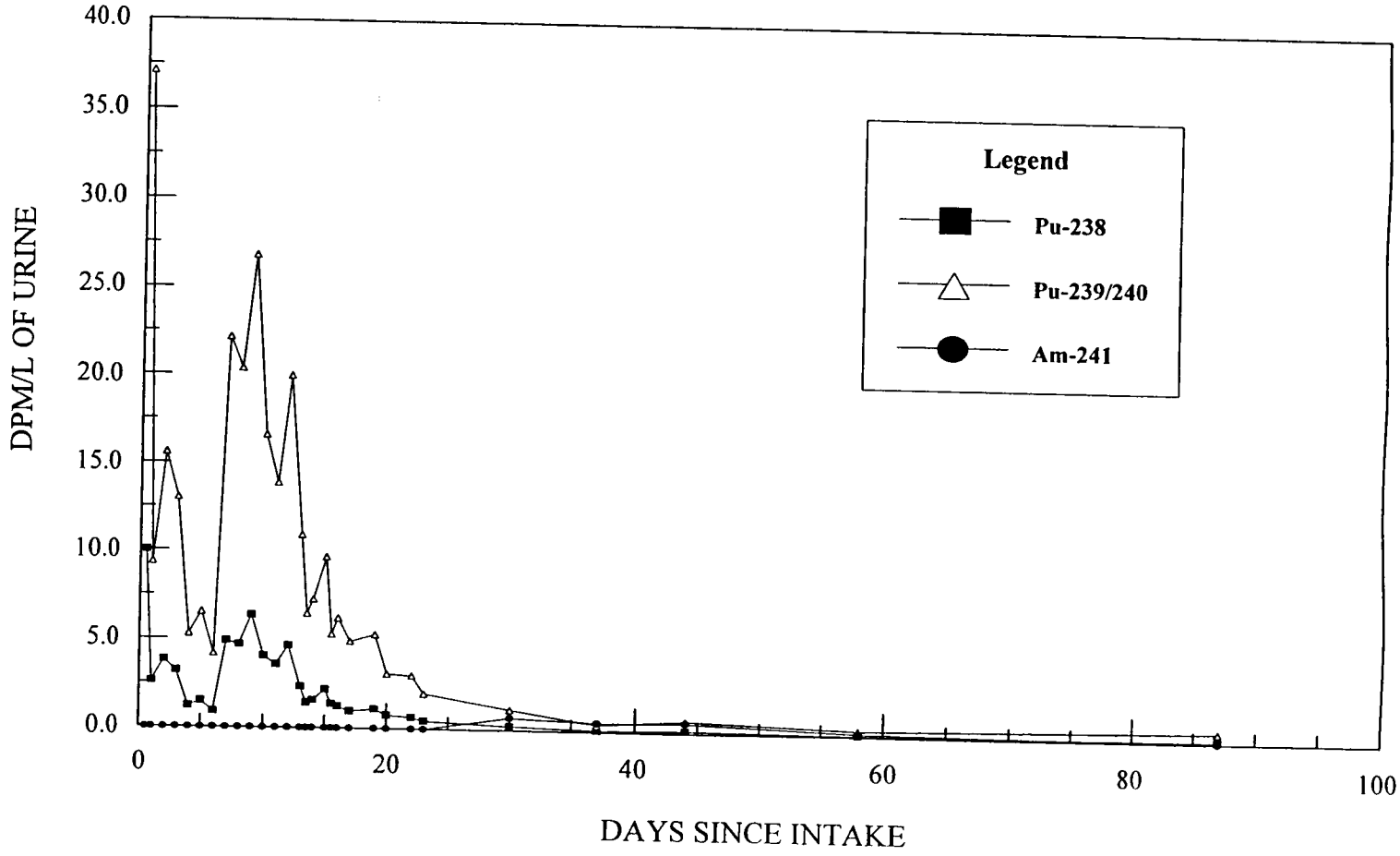


Figure 6.3-1: Urinary Excretion Results

7. ANALYSIS

7. 1 Treatment Procedures

In this section, an analysis of the treatment procedures administered to the 1991 Plutonium Wound Incident patient will be performed in an effort to establish the effectiveness of each procedure. Figure 7.1-1 summarizes the effectiveness of each medical procedure based on the amount of the contamination removed as a result of the treatment. The evaluation was performed by Skrable Enterprises (Skrable, 1992). Each section of the chart represents the percentage of the initial intake thought to be removed by the procedure. As the chart shows, surgery was the most effective in removing contamination. After an extensive analysis of the urinary and fecal excretion data in conjuncture with the wound counting data, personnel at Skrable Enterprises estimated that the initial intake for the 1991 wound incident was 36.5 nCi of Americium-241 and 66.65 nCi of plutonium (238, 239 and 240 combined) (Skrable, 1992).

Using their intake estimate along with their treatment analysis, an estimate of the contamination that each treatment procedure removed can be formulated. Following the Skrable recommendations, the amount of material removed from the wound by surgery should be 72.205 nCi. This amount would consist of 25.55 nCi of Am-241 and 46.655 nCi of plutonium.

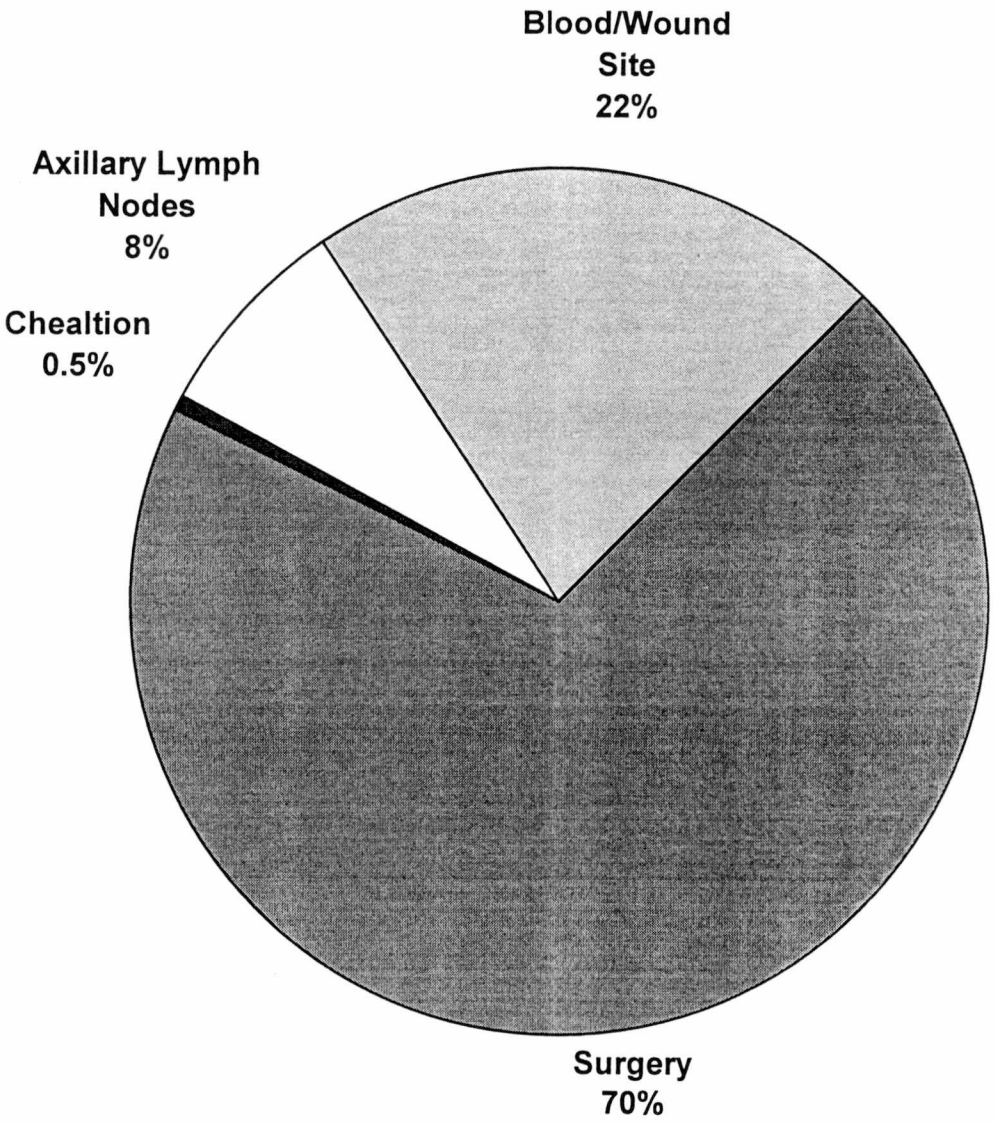


Figure 7.1-1: Treatment Effectiveness

Chelation would have removed 18.25 nCi of the americium and 33.325 nCi of plutonium for a total of 51.575 nCi of radiological material. With 8% thought to have been transferred to the lymph nodes (29.2 nCi Am-241, 53.32 nCi Pu, 82.52 nCi total), the remaining 22% is either absorbed into the blood or is fixed at the wound site. If so, 8.03 nCi of Am-241 and 14.663 nCi of plutonium would remain in the wound or would have been absorbed into the blood. These amounts are calculated using the plutonium/americium ratio estimated by Skrable Enterprises.

7. 2 Wound Clearance

It is also important to note the transfer of the radiological material from the wound into the blood. As the contaminated metal punctured the Special Operator's thumb, the radiological material was deposited beneath the surface of the skin. Normally, the majority of this material will be centralized at the bottom of the wound canal, at the deepest point of the puncture. If not removed, the material will eventually find its way into the bloodstream, where it will be deposited throughout the body. By knowing how fast the material is leaving the wound site, the quantity of material that reaches various organs, like the lymph nodes, at a particular time can be calculated.

This theory would prove very beneficial for cases like the 1991 wound incident where the initial intake is not known. Knowledge of how fast the material is leaving the wound allows measurements of the amount of

radionuclide being translocated to a particular organ to indicate the quantity of the initial intake.

However, in this instance, the analysis becomes difficult due to the influence of the various treatment procedures. Since surgical excision of material was involved, several of the data points must be omitted from the analysis. Hence, the first seven points of the wound mapping count will be excluded. A graph of the remaining points can be found in Figure 7.2-1. Including the data would severely distort the analysis because the excised activity would incorrectly be attributed to the influence of the other treatments or diffusion to the bloodstream.

By finding a mathematical expression that will relate these points, the physiology of the plutonium in the contaminated wound can be chronicled. Figure 7.2-2 depicts two such expressions inserted into the plot of the data points from the wound mapping surveys. The data for the plots is listed in Table 6.2-1 in Chapter 6. This data was fitted by a two-exponential function using a non-linear least square procedure. As seen in the figure, two fits were performed: one including the total data set and the second excluding an outlying point reported on December 11th, 1991. The curve based on the complete data set (excluding the first seven days) was then assumed to describe the clearance from the wound site to blood.

Remembering to drop the first seven wound surveys, the measurement from December 11, 1991 is clearly much smaller than the values for the other points. By including this point in the data set, the relationship that best describes the association among the points is a double exponential. As a result, the mathematical expression which best fits the data set is:

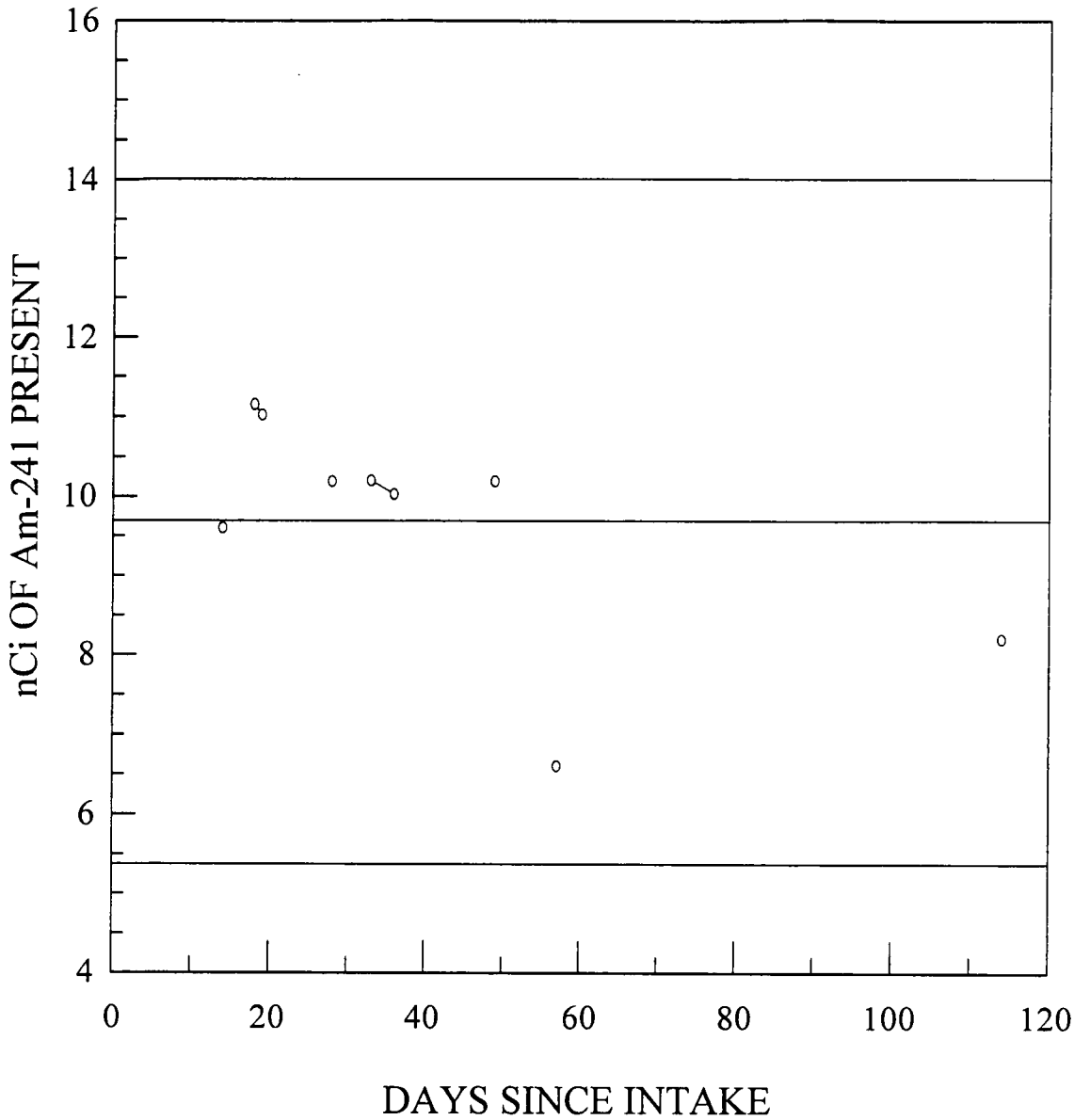
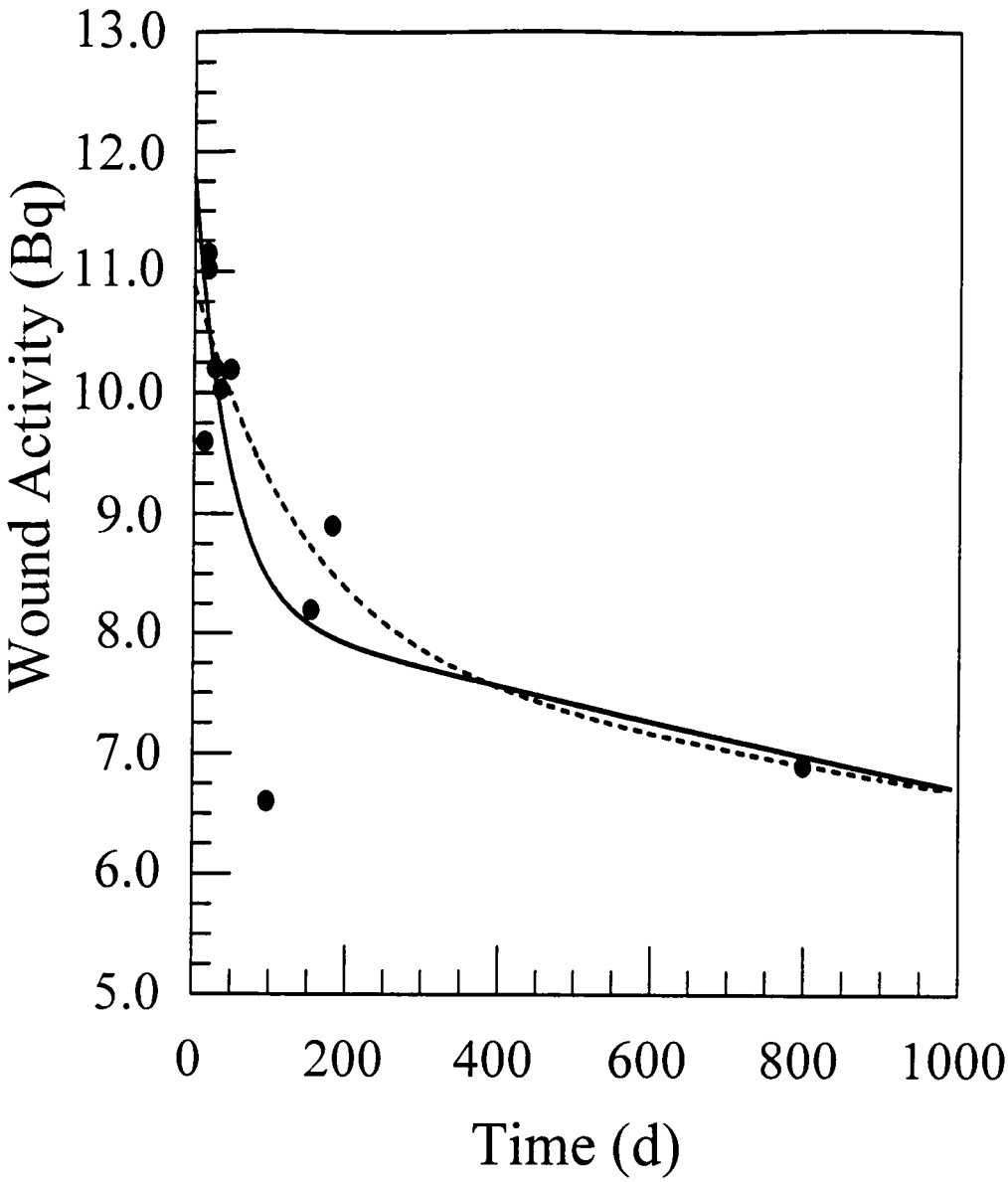


Figure 7.2-1: Wound Count Results (Excluding First Seven Points)



LEGEND:

DOTTED: INCLUDES OUTLIER

SOLID: EXCLUDES OUTLIER

Figure 7.2-2: Wound Clearance Expressions

$$\text{Activity} = 3.60e^{-0.022t} + 8.19e^{-0.0002t}$$

Following the common practice in statistical methods of dropping outliers, data points which seem to stray from the normal association among a data set, this expression changes slightly. Outlying data points can be dropped on the basis of possible systematic or operator error. By ignoring that December 11th, 1991 data point, the equation becomes:

$$\text{Activity} = 3.06e^{-0.067t} + 7.82e^{-0.00015t}$$

Both of these curves follow a double exponential fit. The values change by a minuscule amount by when the outlying data point is neglected. Yet, the difference makes the curve defined by the second expression less dramatic than the first. By eliminating the outlier, the curve becomes less steep and flatter. Including the point makes the slope of the curve steeper and the initial decline more dramatic.

7. 3 Comparison of Measured Versus Predicted Data

To estimate the efficiency of the chelation therapy, a comparison is made with the body's normal ability to excrete plutonium. To be truly effective, chelation agents should drastically increase the rate at which radionuclides are excreted by the human body. To compensate for the lack of normal, unchelated excretion data, the original ACTLITE computer code is used to produce the urinary excretion data. The ACTLITE code is

based upon the solver for the differential equations describing the behavior of the plutonium inside the body as reported by Leggett, Eckerman and Williams (1993).

The ICRP model for systemic plutonium (ICRP 1993) and the ACTLITE computer code which produced the prediction excretion data up to this point are based upon an injection of one becquerel into a human subject; therefore, the model results are in terms of "fraction of a becquerel". The facility data has units of "DPM/L" where "L" represents liters excreted per day, reflecting the total daily urinary excretion on the day the data was reported. This data was converted to express the activity excreted per day ($Bq\ d^{-1}$).

In order to obtain the total number of becquerels excreted each day, the measured data (with units of DPM/L) must be multiplied by the number of liters of urine excreted each day. These conversions are detailed in Table 7.3-1.

Meanwhile, the data from the prediction model demands a more strenuous procedure. The simplest way to correlate these data sets is to normalize one to the other. A comparison of the overall excretion curves for both the measured data and the ICRP model for unchelated excretion is shown in Figure 7.3-1.

As the figure indicates, there are several disagreements between the two curves, especially early in the treatment period. The major contributor to these differences is the various therapies the patient underwent including surgical extraction. In affect, the excretion rate was hastened by the chelation agents. Following the advice of Jech, et al. (1972), "reasonable_

Days Since Intake	Pu-238 (DPM/L)	Pu-239/240 (DPM/L)	Am-241 (DPM/L)	Urine Sample (L)	Total Pu-238 (Bq)	Total Pu-239/240 (Bq)	Total Am-241 (Bq)
0.5	9.99	37.1	0	1.730	0.28805	1.0697	0
1	2.56	9.34	0	1.960	0.083627	0.3051	0
2	3.79	25.1	0	1.870	0.11812	0.4862	0
3	3.17	13.0	0	1.880	0.099327	0.4073	0
4	1.18	5.29	0	1.980	0.03894	0.1746	0
5	1.464	6.519	0	1.890	0.046116	0.2053	0
6	88.7	4.164	0	1.743	0.025723	0.1208	0
7	4.879	22.13	0	1.894	0.15369	0.6971	0
8	4.679	20.34	0	2.041	0.15909	0.6916	0
9	6.336	26.79	0	1.877	0.19853	0.8394	0
10	4.023	16.59	0	2.008	0.13477	0.5558	0
11	3.559	13.87	0	1.860	0.11033	0.4300	0
12	4.62	19.95	0	1.891	0.14553	0.6284	0
13	2.297	10.89	0	1.924	0.073504	0.3485	0
13.5	1.401	6.455	0	1.969	0.045999	0.2119	0
14	1.551	7.250	0	2.146	0.055577	0.2598	0
15	2.155	9.645	0	2.004	0.0718333	0.3215	0
15.5	1.368	5.296	0	2.107	0.048108	0.1862	0
16	1.222	6.212	0	2.000	0.40733	0.2071	0
17	.954	4.895	0	1.909	0.030369	0.1558	0
19	1.084	5.292	0	2.002	0.036133	0.1764	0
20	.757	3.078	0	1.925	0.024350	0.0990	0
22	.647	2.98	0	1.909	0.020596	0.0949	0

Table 7.3-1: Conversion of Urine Data

Days Since Intake	Pu-238 (DPM/L)	Pu-239/240 (DPM?L)	Am-241 (DPM/L)	Urine Sample (L)	Total Pu-238 (Bq)	Total Pu-239/240 (Bq)	Total Am-241 (Bq)
23	.451	1.994	0	1.954	0.014657	0.0648	0
30	.241	1.16	.704	2.020	0.0081137	0.0391	0.0237
37	0.0947	0.405	0.511	1.810	0.0028568	0.0122	0.0154
44	0.152	0.685	0.562	1.270	0.003173	0.0145	0.0119
58	0.0705	0.346	0.175	1.310	0.0015392	0.0076	0.0038
87	0.105	0.575	0	1.960	0.0034300	0.0188	0
114	0.629	0.417	0.257	2.000	0.0020967	0.0139	0.0086
143	0.0534	0.360	0.215	2.040	0.0018156	0.0127	0.0073
226	0.0477	0.368	0	2.070	0.006456	0.0082	0
332	0.0404	0.258	0	1.900	0.0012793	0.0110	0
444	0.0503	0.385	0	1.720	0.0014419	0.0077	0
543	0.0355	0.243	0	1.890	0.0011182	0.0077	0
648	0.0553	0.319	0	1.930	0.106729	0.0103	0
1262	0.0825	0.508	0.163	1.77	0.146025	0.0150	0.0048

Table 7.3-1: Conversion of Urine Data (cont.)

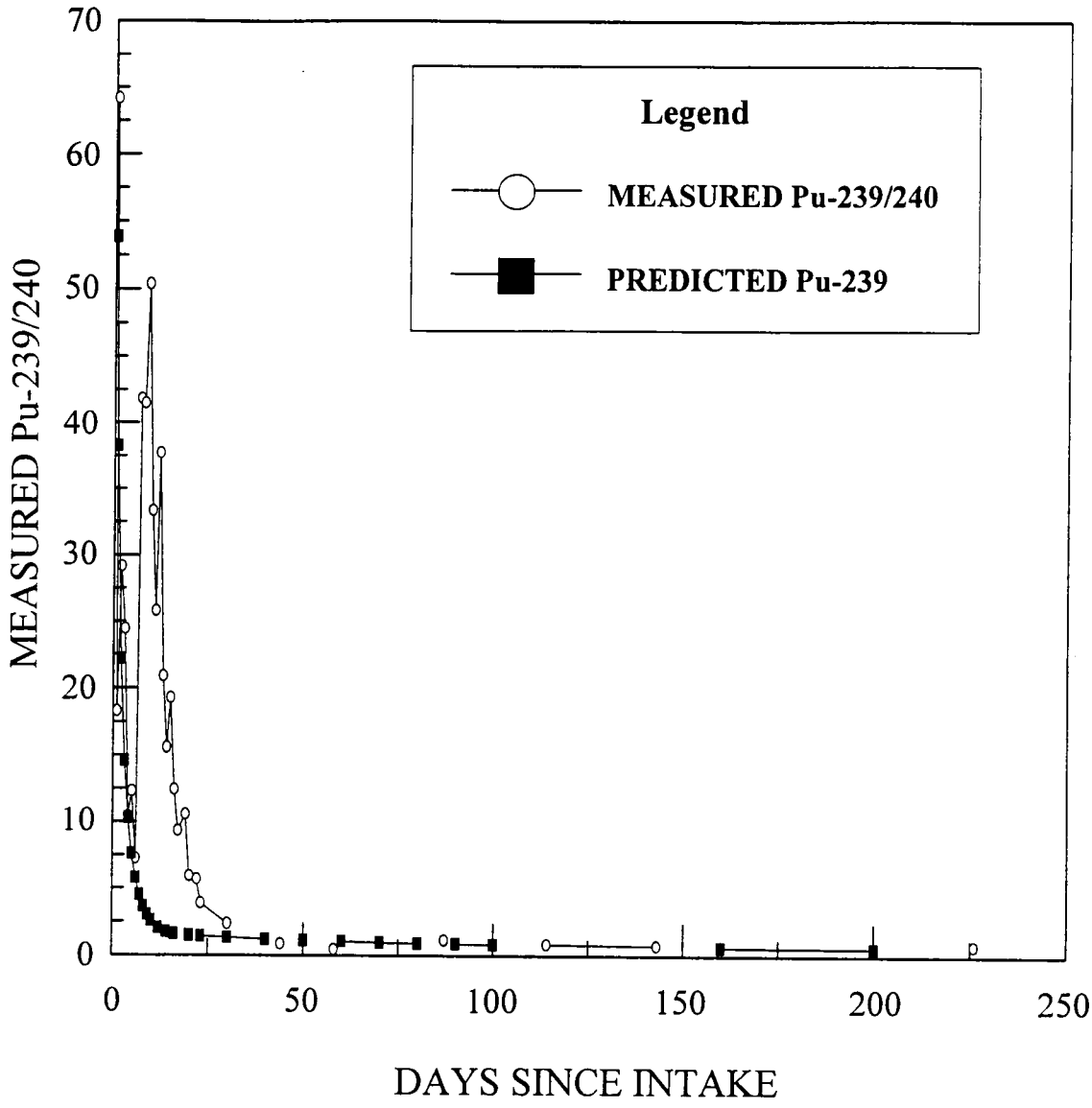


Figure 7.3-1: Measured Data Versus Predicted Data

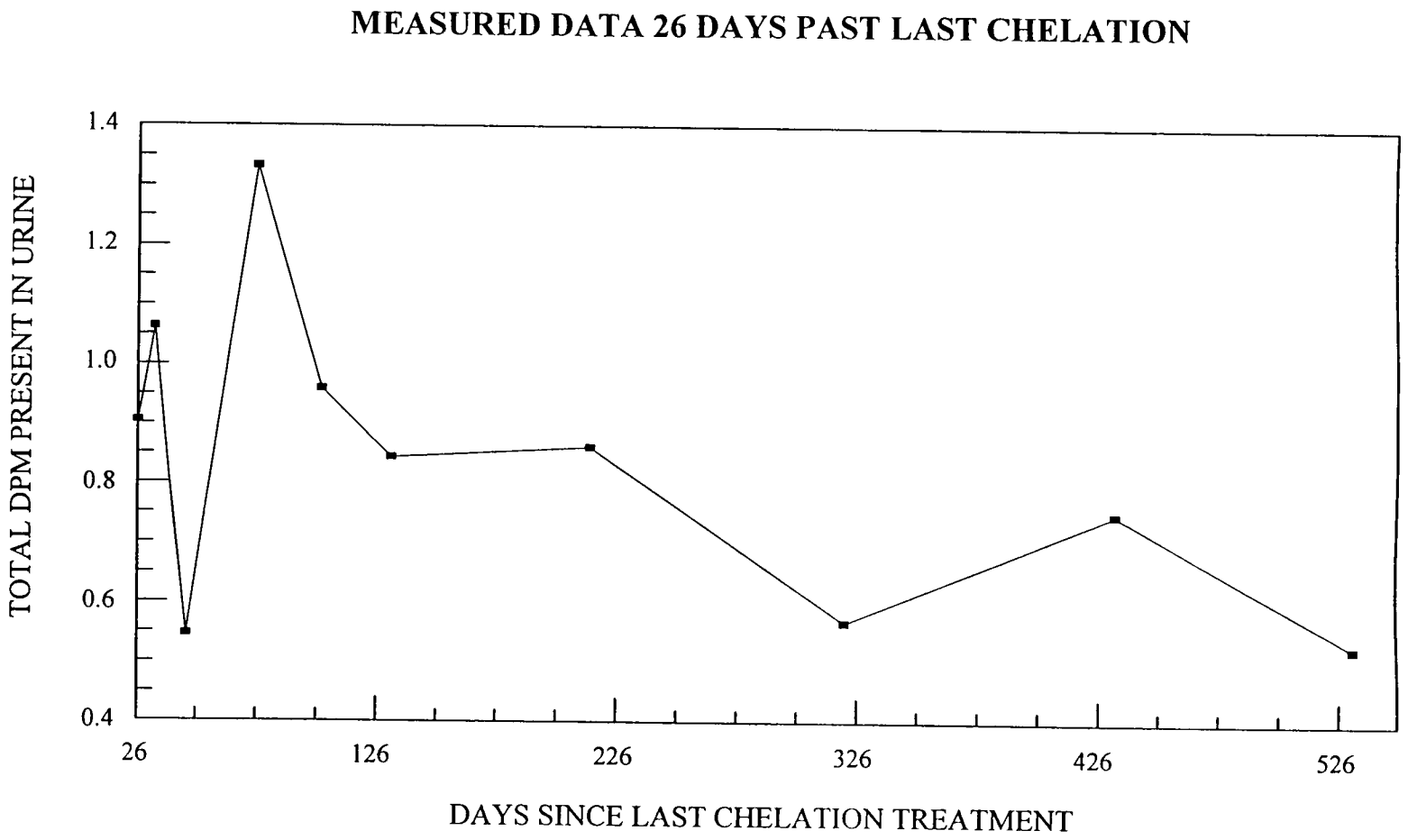


Figure 7.3-2: Measured Plutonium Excretion 26 Days After Last Chelation Treatment

estimates of the effects of DTPA on excretion rate cannot be made for at least 20 days after treatment". Since the 1991 wound case involves multiple chelation treatments, the data for observing the effects of DTPA therapy on urinary excretion rates will be taken 20 days after the chelation, which occurred September 16, 1991. Twenty days after this date was October 6, 1991. However, the closest data record was October 12, 1991. This was 26 days after the last chelation. A plot of this data is seen in Figure 7.3-2.

The next figure (7.3-3) is a plot of the ACTLITE code prediction for excretion. Plotting the measured and predicted data on the same plot, the chelation effects are more than noticeable (Figure 7.3-4). One prominent peak is centered on December 28, 1991, about 114 days after the wound occurred and 103 days after the last chelation treatment. This peak correlates with another event that happened about this same time. The patient had a minor surgery earlier that same month to remove a suture that remained in the wound after having the thumbnail removed approximately three months earlier. It is speculated that when the suture was removed, plutonium which had previously been bound at the wound site was released into the bloodstream. Thus, it became susceptible to the influence of the DTPA agents and was excreted at an elevated rate.

The effects of DTPA therapy are quite extensive. In fact, the benefits of a chelation last about 100 days (LaBone 1994). After that time period, the excretion rates return to the pre-chelation levels. Research shows that "urine excretion rates after completion of treatment return to near predicted levels within 15-25 days, but remain slightly elevated for another 100 or more days" (Jech, Anderson and Heid 1972). Considering these facts, data for the excretion of plutonium should not be considered reliable until 100 days after

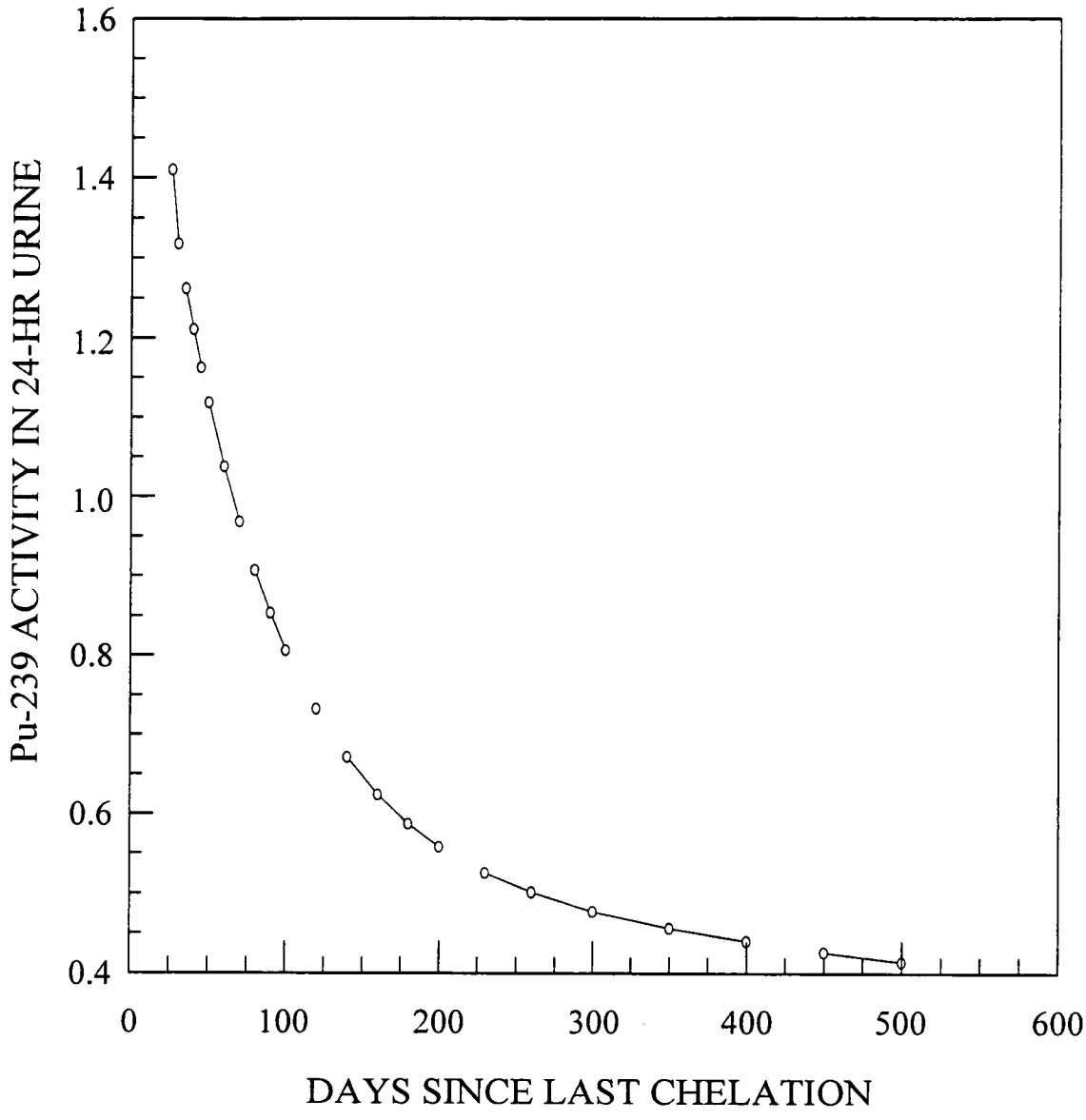


Figure 7.3-3: Predicted Plutonium Excretion 20 Days After Last Chelation Treatment

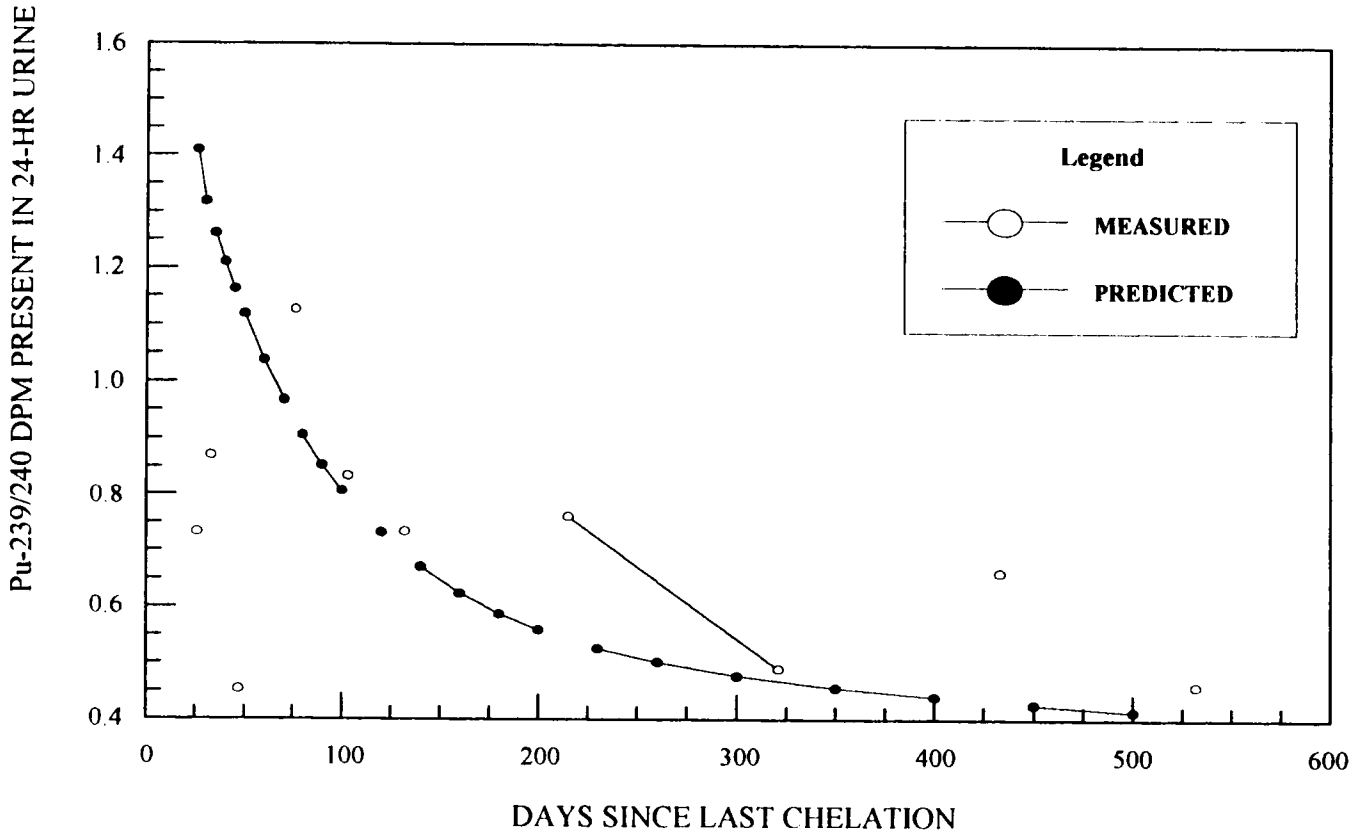


Figure 7.3-3: Predicted Plutonium Excretion 20 Days After Last Chelation Treatment

the last DTPA treatment. This time period is sufficient for the demise of the chelation effects and allow excretion rates to return to normal.

Theoretically, with the demise of the effects of the DTPA , the two curves should be identical. However, due to the scarcity of the data 100 days past the end of treatment with DTPA, the analysis will begin with urine samples 80 days after the last chelation treatment. The last chelation agent was administered September 16, 1991. Eighty days subsequent to this date would be December 5th, 1991.

Unfortunately, no sample was taken by attending personnel on this day. Using extrapolation techniques, a rate of plutonium excretion on that day would probably have been about 0.477 DPM/L. Moreover, the average sample size of the urine samples collected by facility personnel was 1.899 liters. Multiplying these factors together produces a figure of 0.906 DPM. Presumably, this is the extrapolated amount of excreted DPM from the victim 80 days after the last chelation treatment.

From the ICRP model, the predicted amount of plutonium eliminated from the body of an unchelated exposure victim, 80 days post intake, is 0.000105900 DPM given an intake of 1 becquerel. Normalizing the predicted data to the extrapolated measured data, in order for the ICRP model to predict an excretion of 0.906 DPM 80 days past intake, the initial intake would have to be 8555.241 DPM.

As the plot(s) clearly show, some discrepancies still exists between the measured data and the excretion rates predicted by the ICRP model even after the surgical effects are eliminated. There exists several spikes in the measured excretion rate curve which distort the plot. These spikes begin around day seven (87 days post last chelation treatment) and continue until

about day 30 (110 days post last chelation therapy). The last chelation treatment occurred 11 days after the intake. This would suggests that these spikes begin 98 days after the wound was discovered and end about 121 days after the discovery.

7. 4 Explanations of Discrepancies Between ACTLITE Predicted Urinary Excretion and Measured Data

Reviewing the treatment schedule, there exists elements which might explain these variations between the predicted and measured data. Approximately three months after the event, the victim underwent a small surgical procedure to remove a suture which failed to dissolve on its own. This factor might contribute to the presence of the spikes in the measured data excretion curve. The survey might have mobilized some plutonium which was bound to the wound site. Under normal circumstances, the radionuclide would have remained at the site and not have entered the bloodstream. However, removal of the suture disturbed the area around the wound, allowing the bound plutonium to enter the circulatory system where it was filtered out by the kidney or liver and excreted in the urine. Hence, more plutonium than predicted was excreted, inducing a positive sweep in the curve. However, the suture extraction was a minor surgical procedure. Lasting only a short period of time and involving almost trivial surgical procedures, a very modest amount of plutonium was probably released into the blood. As a result, the curve quickly reaches its peak and begins to decline as the amount of unbound plutonium in the bloodstream dissipates.

Nevertheless, with data analysis beginning 100 days after the last chelation treatment, the curves become very similar. (Figure 7.3-5).

There are also several factors associated with DTPA therapy which might explain the discrepancies between the measured excretion data and the rates predicted by the ICRP model. For one, "plutonium elimination after DTPA treatment is apparently increased by at least two mechanisms with half-lives of approximately 12-hours and 7 days" (Jolly, et al. 1972). The latter may be directly related to the excretion of water from the body. The average biological body water half-life of 9.5 ± 4.1 days (Jech, et al. 1972). Clearly, the 7-day half-life observed with the DTPA treated excretion rate is well within the range of the half-life of water. On the other hand, explanation for the 12-hour half-life "is not apparent" (Jech, et al. 1972). Research continues in an effort to completely understand the kinetics of chelation therapy.

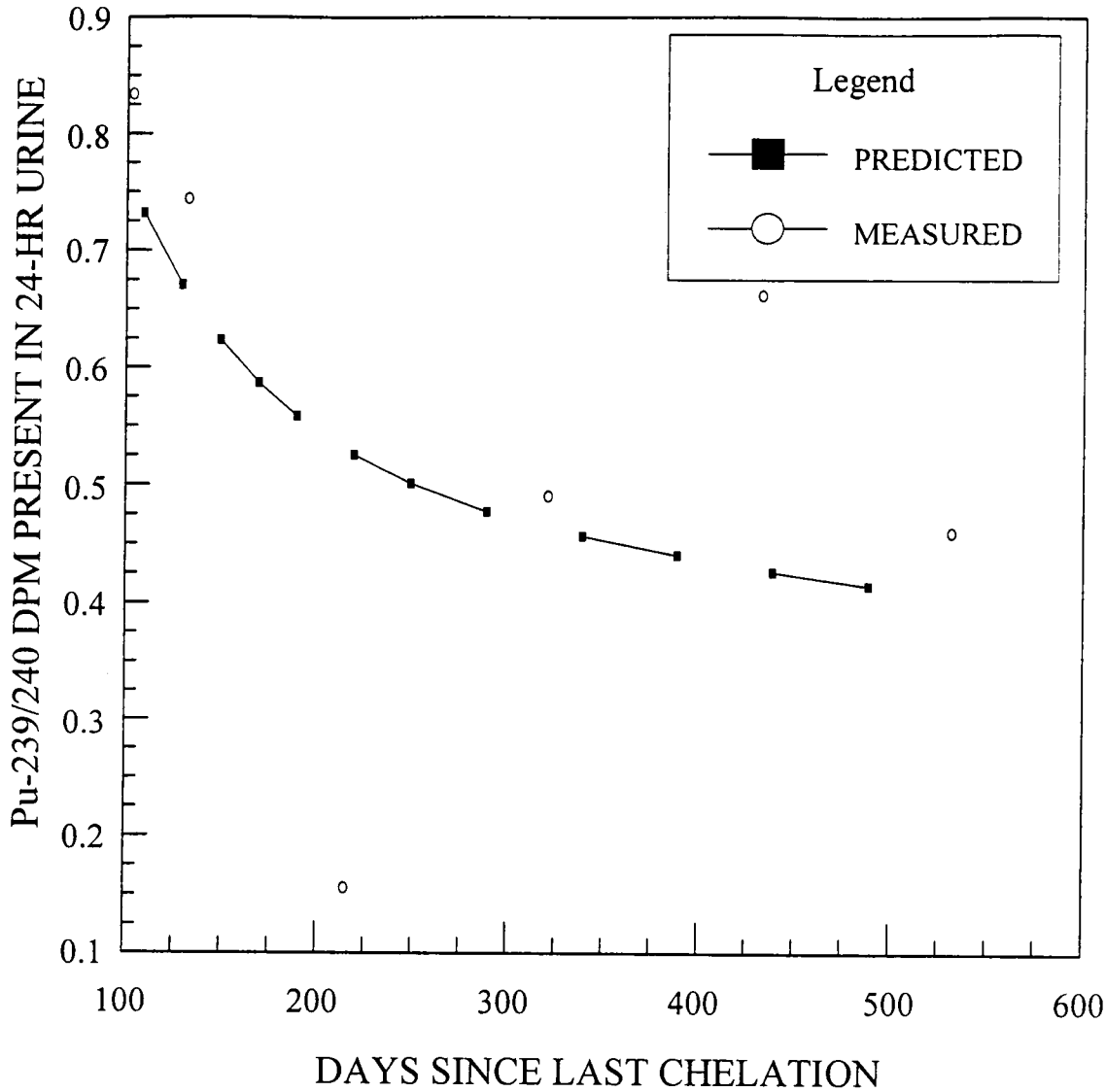


Figure 7.3-5: Measured Data Versus Predicted Data 100 Days After Last Chelation

8. PCWOUND COMPUTER CODE

Up to this point, the data for the excretion model was produced by the computer code ACTLITE. Dr. K. F. Eckerman, Research Group Leader of the Life Science Division of the Oak Ridge National Laboratory, created the computer code . ACTLITE is a simplified version of ACTACAL, another code created by Eckerman. Both are based upon the ICRP model for radionuclide excretion from an unchelated contamination victim. However, to be effective for cases involving chelation therapy and surgery, the ACTLITE code must be modified. The ACTLITE program is proven effective for only natural excretion of radionuclides.

In the early days of dealing with contamination victims, where physicians depended upon the body's natural excretion for removal of the contamination, the ACTLITE program was an efficient tool. However, as more contamination cases occurred, and the hazards of such intakes were more evident, there evolved new treatment procedures. For instance, in the event of a contaminated wound incident, surgical procedures will be used to remove the localized contamination at the puncture site. Along the same lines, medical advances have produced chelation agents which can speed the excretion process. For a case where a contamination victim has been administered chelation agents, the ACTLITE program would underestimate the amount of radionuclide excreted on a given day.

Unlike ACTLITE, the radiological material excised by surgery are also compensated for in the PCWOUND code. The PCWOUND code is a special version of the ACTLITE code developed in an earlier work (Leggett, Eckerman and Williams 1993) that predicts the urinary excretion

of radionuclides resulting from a contaminated wound. PCWOUND takes into account the effects of therapeutic procedures like chelation therapy and surgery.

During these procedures, the source of the contamination may be removed as well as the contamination bound to extracted tissue. As a result, there is no possible way to correlate an intake with the amount of material surgically removed. Besides, the variability (treatment procedures, wound depth, etc...) in each different instance prevents any corroboration. As a result, only estimates can be made before the surgery as to the amount of contamination that will be excised.

However, after the surgery, measurements can be made of the excised tissue and scabbing from the surgery to obtain a more accurate count. This will give a more accurate account of the success of the surgery. In the PCWOUND code, these extracted amounts are considered as an instantaneous removal in the intake model (Section 8.1)

The PCWOUND computer code was developed during this work to compensate for the elements missing in the ACTLITE program needed to analyze contaminated wound incidents where chelation and surgery were involved. Refer to Appendix A for a listing of the code and input files. Keep in mind the fact that the PCWOUND code is not a finished product but merely a trial attempt to establish the feasibility of devising a model for predicting the urinary excretion of radionuclides from a contaminated wound patient considering the effects of the chelation therapy or surgical excision of radionuclear materials from the wound site.

8. 1 Intake Adaption

In order to be suitable for incidents involving contaminated wounds where chelation therapy and surgical excision of materials are utilized, the computer code must consider an intake differently. The ACTLITE code considers the intake as one mass of matter with no differentiation. However, the new model divides the intake into two compartments. The compartments, Wound 1 and Wound 2, represent two different rates of transfer of the radiological contamination from the wound site into the bloodstream. The material in the first compartment is rapidly transferred while the Wound 2 compartment is a "slow feed" of a chronic nature to the bloodstream. A visual representation is displayed in Figure 8.1-1. A provision is also included in the figure for surgical removal as represented by the transfers to "Excreta".

8. 2 Systemic Component Adaptations

The systemic component of the ACTLITE model consists of several components which represent various vital organs, tissues and structures of the human body. These components are assigned a retention and excretion rate according to their human body counterpart. The components consists of eight large categories: massive soft tissues, blood, kidneys, urinary bladder, liver, gastrointestinal, gonads and skeleton. The blood, gastrointestinal tract, gonads and the urinary bladder are undivided

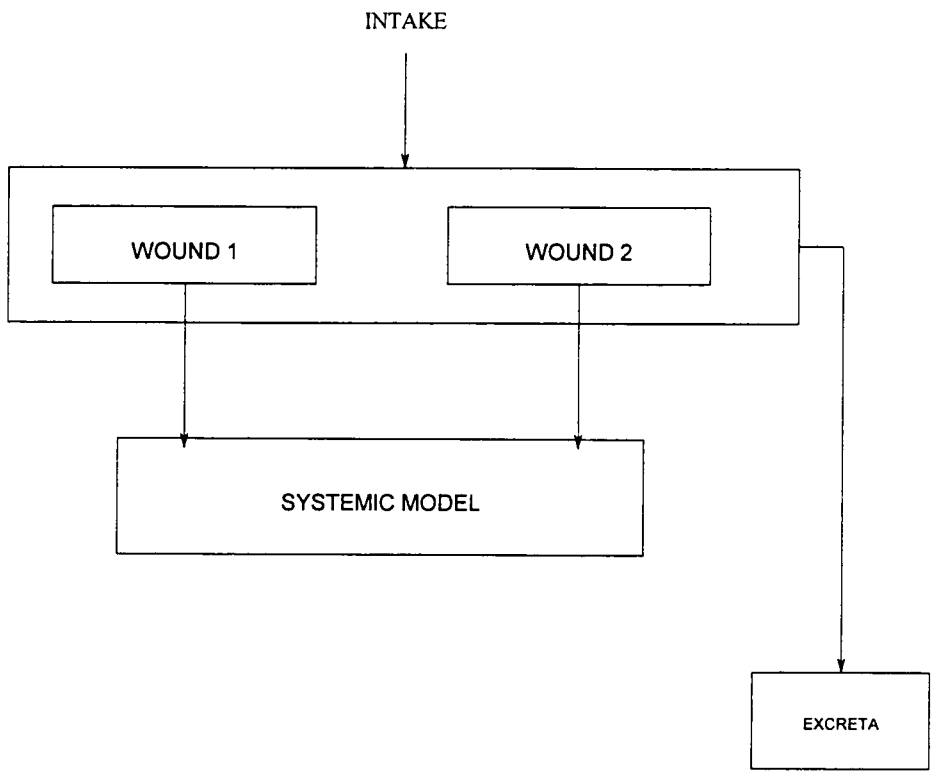


Figure 8.1-1: Intake Model For PCWOUND

portions. The remaining parts are further divided into small contributors. A diagram of this model is displayed in Figure 8.2-1.

The total systemic model in the ACTLITE code consists of 17 compartments and 32 possible pathways between them through which the radiological contamination can be traced. The massive soft tissue consists of three subdivisions: the rapid turnover (ST0), Intermediate Turnover (ST1) and Slow Turnover (ST2). The kidneys consists of a urinary section and other kidney tissues. The liver is partitioned into Liver 1 and Liver 2.

Lastly, the skeleton has six subdivisions: cortical volume, cortical surface, cortical marrow, trabecular volume, trabecular surface and trabecular marrow. By further diversification of these components, doses to specific parts of the organs or structures can be estimated. Otherwise, in the case of the bone, an estimate would have to be made concerning dose to the cortical marrow. Not knowing the independent retention rate for cortical marrow, an assumption has been made as to how much of the total dose to the bone can be attributed to the cortical marrow. This assumption provides an opportunity for error and, as a consequence, erroneous evaluations and treatments.

A diagram of the adapted ACTLITE systemic component for the computer code used in the PCWOUND code is presented in Figure 8.2-2. The adapted code looks very similar to the original ACTLITE code except for a few additions. The ovals at the bottom of the diagram were added to account for the chelation therapy. There are also duplicate boxes for the urine and extracellular fluid compartments. In each case, one is an oval and the other is a rectangle. The oval shaped compartments signify urine or extracellular associated purely with the kinetics of the DTPA (either Ca-

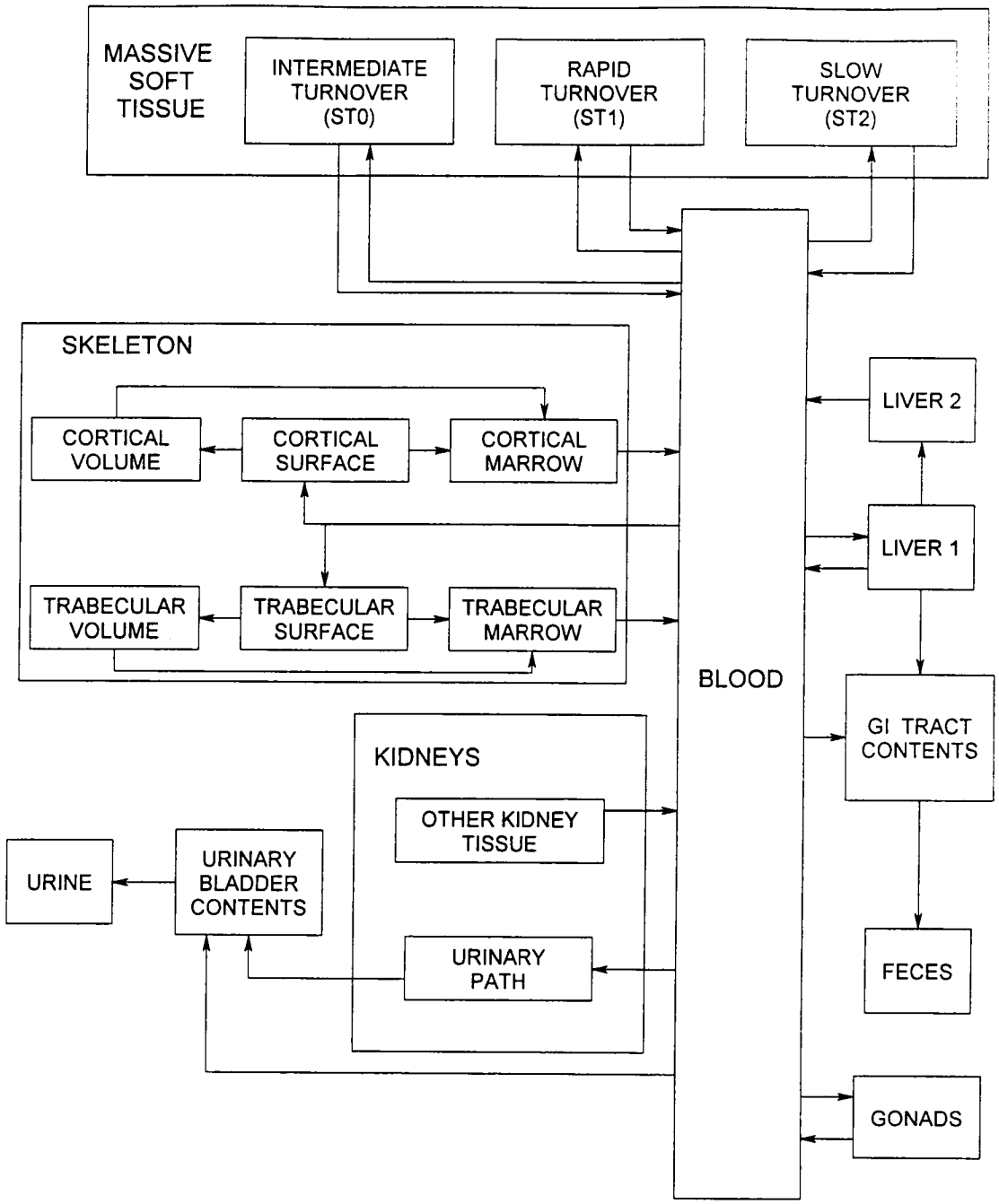


Figure 8.2-1: Schematic of the ICRP Plutonium Biokinetic Model (ICRP 1993).

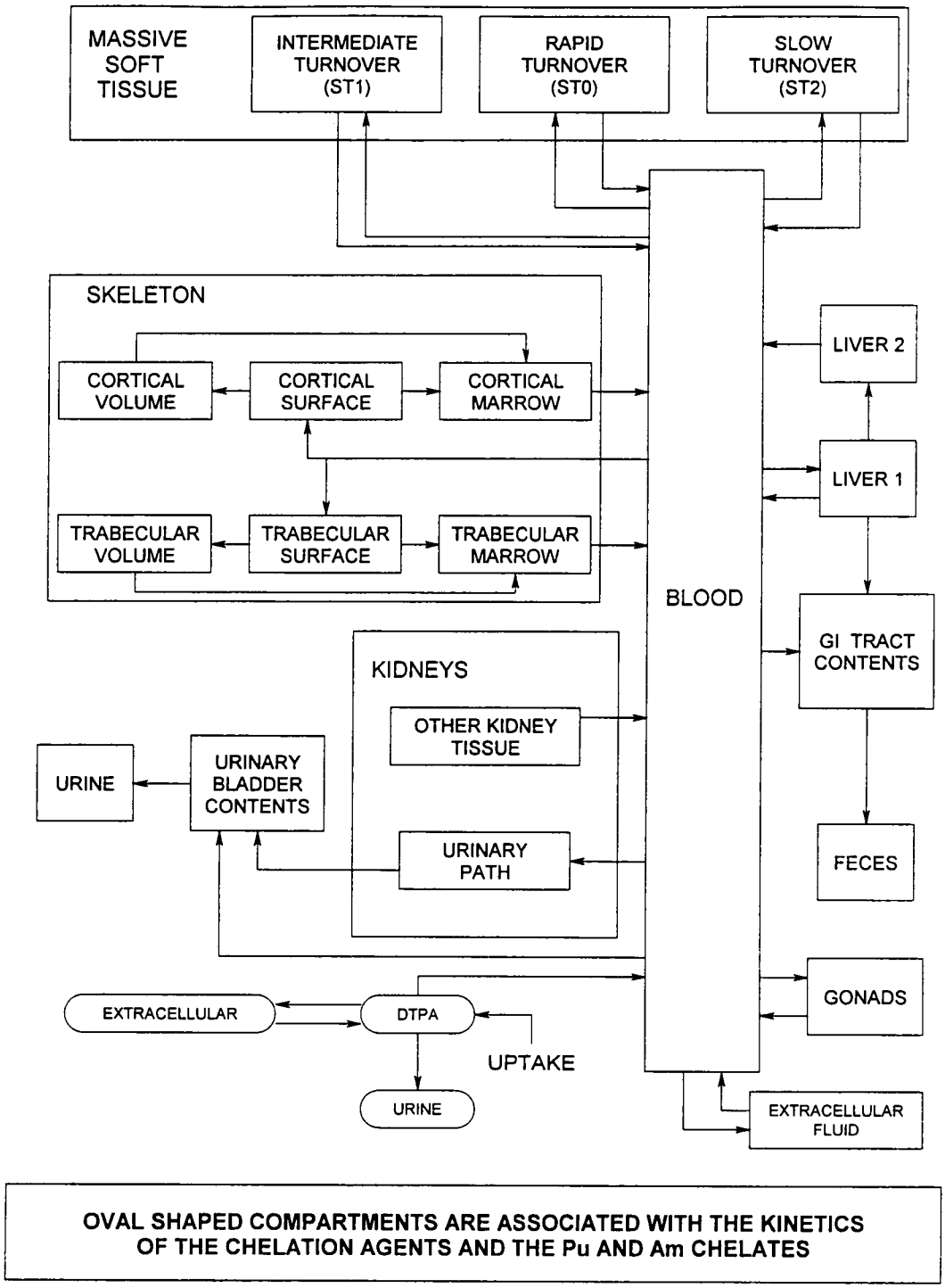


Figure 8.2-2: Schematic of PCWOUND Computer Code

DTPA or Zn-DTPA). The rectangles are associated with normal bodily functions.

Another characteristic of the codes is the translocation parameters. Each pathway between compartments has its own distinct parameter. This statistic describes the rate of translocation between the twocompartments (i and j). These parameters are unique for each different radionuclide. For this contaminated wound case, the two radionuclides of interest are plutonium and americium. The parameters used by the code for each of these radionuclides are tabulated in Table 8.2-1 and Table 8.2-2. The left column lists the source region of the pathway (j), not to be confused with the source organ. This is merely the compartment from which the radionuclide has entered and is slowly leaving. The middle column is the target region (i)- the region which the radiological material is headed from the region listed in the left column. Finally, the third column is the characteristic rate of translocation from the compartment in the left column to the compartment in the middle column. The rate has units of fraction of activity in compartment "j" excreted per day.

8. 3 Kinetics of the PCWOUND Code

The behavior of the contaminant is expressed as a set of coupled differential equations. These equations express the rate of change in the activity present in each compartment. The activity in any compartment is governed by the following linear ordinary differential equation:

From	To	Transfer (/d)
Blood	->Liver_1	1.9410E-01
Blood	->Other_0	2.7730E-01
Blood	->Other_1	8.0600E-02
Blood	->Other_2	1.2900E-02
Blood	->C_Bone-S	1.2940E-01
Blood	->T_Bone-S	1.9410E-01
Blood	->Kidneys_1	6.4700E-03
Blood	->Kidneys_2	3.2300E-03
Blood	->ULI_Cont	1.2900E-02
Blood	->Testes	2.3000E-04
Blood	->UB_Cont	1.2900E-02
Liver_1	->Liver_2	1.7700E-03
Liver_1	->SI_Cont	1.3300E-04
Liver_2	->Blood	2.1100E-04
Other_0	->Blood	6.9300E-01
Other_1	->Blood	4.7500E-04
Other_1	->UB_Cont	4.7500E-04
Other_2	->Blood	1.9000E-05
C_Bone-S	->C_Bone-S_1	8.2100E-05
C_Bone-S	->C_Bone-V	4.1100E-05
C_Bone-S_1	->Blood	7.6000E-03
C_Bone-V	->C_Bone-S_1	8.2100E-05
R_Marrow	->Blood	7.6000E-03
T_Bone-S	->R_Marrow	4.9300E-04
T_Bone-S	->T_Bone-V	2.4700E-04
T_Bone-V	->R_Marrow	4.9300E-04
Kidneys_1	->UB_Cont	1.3860E-02
Kidneys_2	->Blood	1.3900E-03
Testes	->Blood	1.9000E-04
SI_Cont	->ULI_Cont	6.0
SI_Cont	->Blood	3.0000E-03
ULI_Cont	->LLI_Cont	1.8
LLI_Cont	->Feces	1.0
UB_Cont	->Urine	12.

Table 8.2-1: Biokinetic Parameters for Model of Systemic Plutonium (ICRP 1993)

From	To	Transfer (/d)
Blood	->Liver_1	1.1600E+01
Blood	->Other_0	1.0000E+01
Blood	->Other_1	1.6700E+00
Blood	->Other_2	4.6600E-01
Blood	->C_Bone-S	3.4900E+00
Blood	->T_Bone-S	3.4900E+00
Blood	->Kidneys_1	4.6600E-01
Blood	->Kidneys_2	1.1600E-01
Blood	->ULI_Cont	3.0300E-01
Blood	->Testes	8.2000E-03
Blood	->UB_Cont	1.6300E+00
Liver_1	->Blood	1.8500E-03
Liver_1	->SI_Cont	4.9000E-05
Other_0	->Blood	1.3860E+00
Other_1	->Blood	1.3900E-02
Other_2	->Blood	1.9000E-05
C_Bone-S_1	->Blood	7.6000E-03
C_Bone-S	->C_Bone-S_1	8.2100E-05
C_Bone-S	->C_Bone-V	4.1100E-05
C_Bone-V	->C_Bone-S_1	8.2100E-05
R_Marrow	->Blood	7.6000E-03
T_Bone-S	->R_Marrow	4.9300E-04
T_Bone-S	->T_Bone-V	2.4700E-04
T_Bone-V	->R_Marrow	4.9300E-04
Kidneys_1	->UB_Cont	9.9000E-02
Kidneys_2	->Blood	1.3900E-03
Testes	->Blood	1.9000E-04
SI_Cont	->ULI_Cont	6.0
SI_Cont	->Blood	3.0000E-03
ULI_Cont	->LLI_Cont	1.8
LLI_Cont	->Feces	1.0
UB_Cont	->Urine	12.

Table 8.2-1: Biokinetic Parameters for Model of Systemic Plutonium (ICRP 1993)

$$\frac{d}{dt} A_i = \sum_{\substack{j=1 \\ j \neq i}}^{n} \lambda_{ij} A_j - A_i \sum_{\substack{j=1 \\ j \neq i}}^{n} \lambda_{ji}$$

where A represents the activity in the respective compartment and λ_{ij} represents the transfer rate to compartment i from compartment j. The numerical values for these parameters are previously given in Table 8.2-1 and 8.2-2.

PCWOUND and ACTLITE both calculate activities for fixed time periods following a contamination incident. This is accomplished by performing the calculations over a series of time intervals. These intervals, or steps, are used to calculate the quantity of the radionuclide transported both into and out of a specific organ or structure, retention in a single or numerous compartments or excretion through the urine or feces on a specific day.

The results of these computer codes can be advantageous in two respects. For a known intake, the model can predict approximately how much of a radionuclide will be deposited in any compartment, the number of decays of the radionuclide in the compartment, and the amount that will be excreted following an intake by an untreated individual. The data can be used to structure a treatment procedure concentrated on the areas of highest retention.

At the same time, for an unknown intake, the model analysis is simply reversed. Urine or feces samples can be taken and measured for

radionuclide content. Once the treatment data must also be entered into PCWOUND and the excretion rate is known, the model can be used to calculate what the initial intake must have been at t=0 (when the event occurred) in order for the patient to have excreted amount X (measured activity in the sample) of the radionuclide at time Y (when the sample was taken). In this way, unknown intakes can be estimated and the biological hazard which would result can be considered and the proper treatment administered.

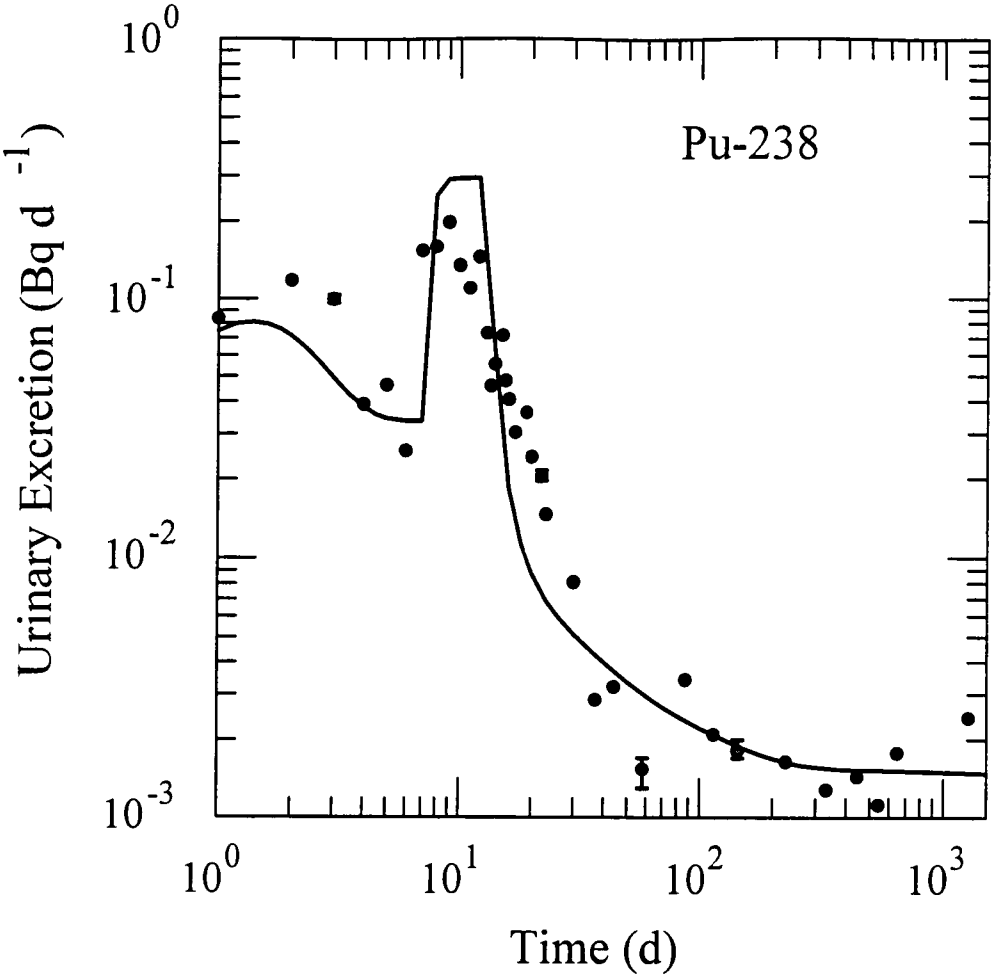
The program also offers many other features. For instance, the model can be adapted for a variety of age ranges (where the transfer rate changes with age) and is also gender dependent (varying such parameters as target organs for each gender). In this way, doses due to radiological contamination to organs such as the gonads or breasts can be either considered or deleted, depending upon the gender of the victim. Also, the program is designed to mimic the intake of a wide range of radionuclides as well. All of these factors make the PCWOUND program an effective tool for analysis of radionuclide contamination.

In order to produce estimates for comparison with the measured data, the ACTLITE program considers the effects of a one becquerel injection to an adult male. In this case, the only pathway considered by the program is urinary excretion. The data for fecal excretion as well as the retention of the radionuclide (plutonium) in the various organs and body structures are not considered.

8. 4 PCWOUND Results

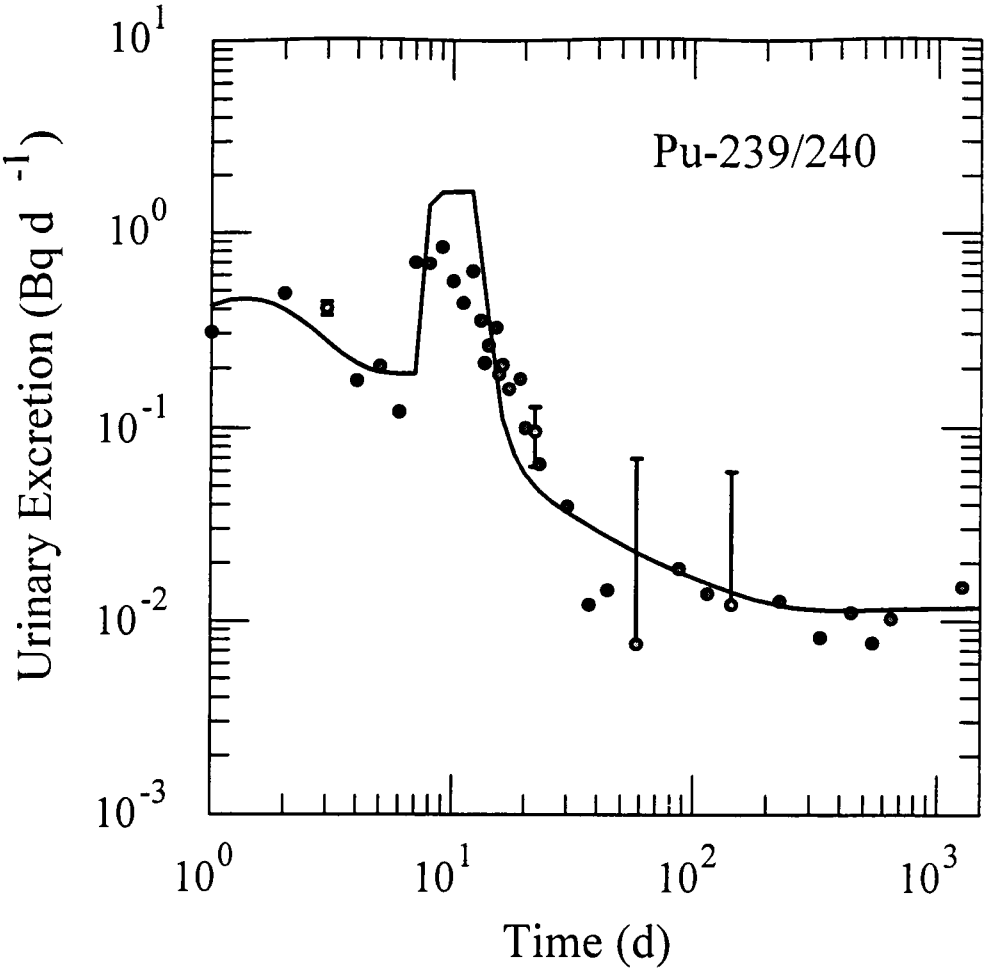
Figures 8.4-1, 8.4-2 and 8.4-3 are examples of excretion curves predicted by the PCWOUND program. The figures include the measured urinary excretion data for Plutonium-238, Plutonium-239/240 and Americium-241, respectively, from the 1991 plutonium wound incident as a series of data points plotted on the appropriate graph. Each figure also displays an imposed curve which represents the excretion curve for each radionuclide as predicted by the PCWOUND computer code.

In each case, the excretion curve traverses the data points, indicating a good correlation for each radionuclide.



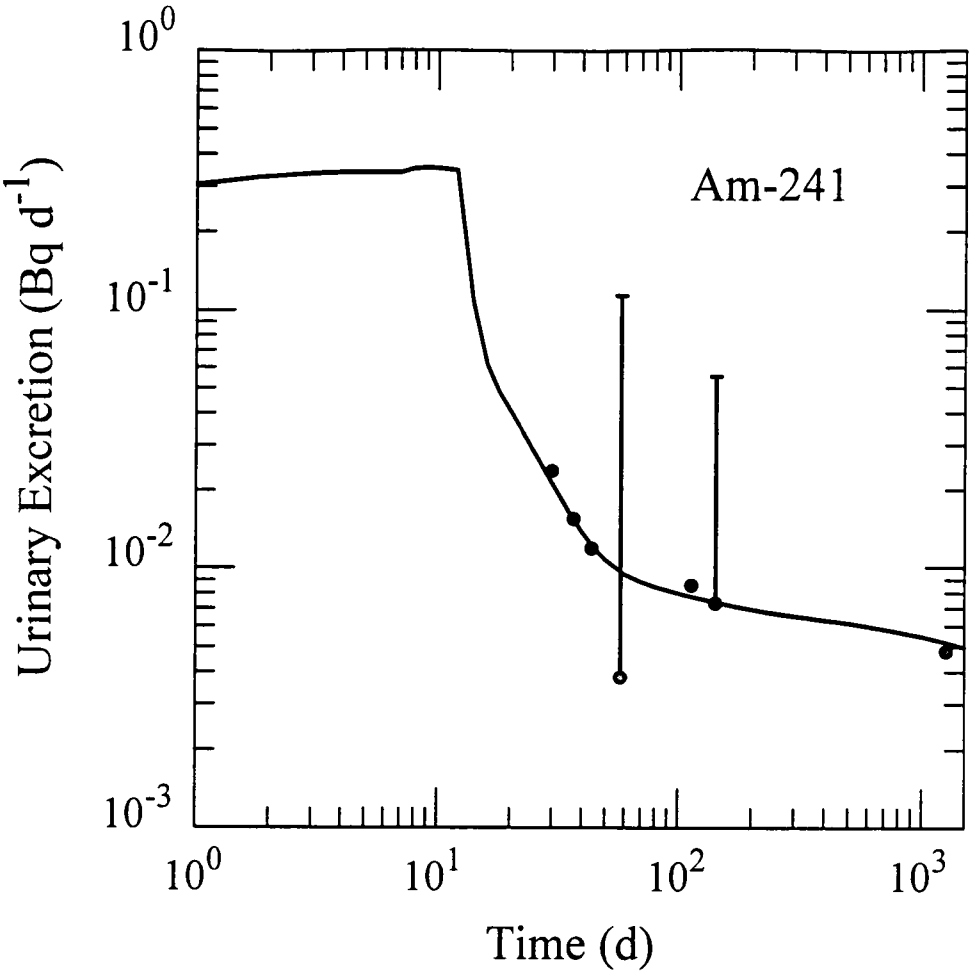
LEGEND: Points represents measured data from 1991 Plutonium Wound Case.
Function is produced from the PCWOUND code
Error bars have been imposed on various measured data points.

Figure 8.4-1: PCWOUND Predicted Excretion Curve For Pu-238



LEGEND: Points represents measured data from 1991 Plutonium Wound Case.
Function is produced from the PCWOUND code
Error bars have been imposed on various measured data points.
Large error bars may be one-sided where axis limits does not allow the full bar to be displayed.

Figure 8.4-2: PCWOUND Predicted Excretion Curve For Pu-239/240



LEGEND: Points represents measured data from 1991 Plutonium Wound Case.

Function is produced from the PCWOUND code

Error bars have been imposed on various measured data points.

Large error bars may be one-sided where axis limits does not allow the full bar to be displayed.

Figure 8.4-3: PCWOUND Excretion Curve For Am-241

9. INTAKE ESTIMATES AND DOSE ASSESSMENT

From the comparisons of the PCWOUND simulations of the urinary excretion (which considers the DTPA treatment as well as the surgical excision which the patient received) with the measured excretion data from the 1991 plutonium wound patient, an estimate of the initial intakes can be made. From this PCWOUND simulation of the 1991 Plutonium Wound case, the following intakes (amount of activity in the wound at time zero) were estimated:

Pu-238.....400 Bq.....10.8 nCi
Pu-239/240.....2240 Bq.....60.5 nCi
Am-241.....1060 Bq.....28.7 nCi

The individual is assumed to be a 45 year-old male with a life expectancy of 30 years. PCWOUND also computes the number of nuclear decays in the various compartments as needed for the dose assessment. The number of nuclear transformations over the 30 year period following the incident are given in Table 9-1. The equivalent dose in tissue is computed as:

$$H_t = \sum_s \sum_j U_{j,s} SEE(T \leftarrow S)_j$$

where $U_{j,s}$ is the number of nuclear transformations of the radionuclide j in organ s and $SEE(T \leftarrow S)_j$ is the equivalent dose in T per nuclear

transformation of radionuclide *j* occurring in *S*. The SEE_s for plutonium and americium were computed using SEECAL (Christy and Eckerman 1993).

The effective dose is the product of the equivalent dose (weighted absorbed dose) and the tissue weighting factor (Raabe 1994). The weighting factors are assigned by the ICRP and reflect the susceptibility of that particular organ or tissue to cancer. The cell labeled "remainder" under the "Organ" column represents all other organs and tissues not previously listed. The dose assessment is displayed in Table 9-2.

The highest dose is credited to the bone surface. This is not surprising considering the kinetics of plutonium as previously discussed. And due to its biological physiology, the liver receives the second highest dose. As a result of serving as a blood filter, the liver stores much of the contamination found in the blood; hence, it becomes a site of higher concentrations of the radionuclides.

The red bone marrow and the testes are next highest. However, their dose relies not on concentration of the nuclear material as much as the highly sensitive cells produced at these sites. Red bone marrow produces red blood cells while the testes produces sperm cells for reproduction. These two types of cells are highly sensitive to radiation. People receiving large doses of radiation experience low amounts of red blood cells directly attributed to damaged red bone marrow. Men who receive high doses will experience the depleted red blood cell count as well as suppressed sperm cell levels. These are two prime examples why internal radiological contamination demands such extreme measures of protection and treatment.

ORGAN	Pu-238	Pu-239/240	Am-241
Blood	1.804E+06	2.208E+07	1.792E+08
Other	2.242E+09	3.456E+09	2.779E+10
Liver	1.074E+10	1.417E+10	1.139E+11
T_Bone-S	7.906E+09	5.262E+09	4.260E+10
T_Bone-V	3.421E+09	2.212E+09	1.780E+10
C_Bone-S	2.808E+10	1.192E+10	9.590E+10
C_Bone-V	4.306E+09	1.745E+09	1.382E+10
Kidneys	1.537E+08	5.918E+07	4.795E+08
R_Mar row	7.287E+08	4.798E+08	3.874E+08
Testes	5.279E+07	1.711E+07	1.375E+08
SI_Cont	8.726E+04	4.838E+04	3.905E+05
ULI_Cont	5.962E+05	3.197E+05	2.583E+06
LLI_Cont	1.071E+06	5.702E+05	4.657E+06
UB_Cont	3.162E+05	1.184E+05	9.245E+05

Table 9-1: Number of Nuclear Transformations

ORGAN	Dose (Sv)	Dose (REM)
Adrenals	0.00957	0.957
Urinary Bladder Wall	0.00957	0.957
Bone Surface	6.84	684.0
Brain	0.00957	0.957
Stomach Wall	0.00957	0.957
Small Intestines Wall	0.00957	0.957
Upper Large Intestines	0.00957	0.957
Lower Large Intestines	0.00957	0.957
Kidneys	0.0383	3.83
Liver	1.31	131.0
Lung Tissue	0.00957	9.57
Muscle	0.00957	9.57
Pancreas	0.00957	9.57
Red Marrow	0.343	343
Skin	0.00957	9.57
Spleen	0.00957	9.57
Testes	0.102	10.2
Thymus	0.00957	9.57
Thyroid	0.00957	9.57
Remainder	0.00986	9.86
Effective	0.181	18.1

Table 9-2: Dose Assessment

10. CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

This work demonstrated that chelation and surgical procedures can be embodied within a contemporary biokinetic model in order to properly characterize the uptake of radionuclides by blood in contaminated wound cases. A computer code, PCWOUND, was developed that overcomes the limitations of the empirical model of by Hall, et al. (1982). The code has been validated by a comparison of predicted activities over time with data from an actual wound incident. As a result, the estimates for the intake and the dose estimates presented in this thesis are 4-5 times lower than previously suggested estimates.

Meanwhile, this research suggests topics for future work. Additional effort should be devoted towards modeling the different routes of administration of the chelating agents. In this work, only the behavior of the chelation therapy after its introduction into blood is considered. Once in the blood, no effort is currently made to address possible differences in the biokinetics and efficiencies between Ca-DTPA and Zn-DTPA.

The PCWOUND computer code needs further testing. The code should be used with additional wound cases to insure its legitimacy. Procedures should be developed for statistical management of the estimated intakes derived from PCWOUND. In this work, no attempts were made to treat the intake calculations in a statistical manner. Also, an effort should be made to carryout wound analysis when an actual case presents itself as the information is being generated. This work involved processing nearly three years of information from a second person viewpoint.

For personnel managing future cases involving contaminated wounds, this work offers suggestions for handling such events. First, an isotopic analysis should be performed on any materials excised from a wound or from samples taken from the environment which the worker was utilizing during the time of the incident. Urinary excretion data should be obtained at least monthly for workers who have had significant intakes (intakes beyond Annual Limit on Intake) while the worker remains employed by the facility. Instruments for wound analysis should be calibrated and available at any facility handling transuranic materials. Lastly, capabilities for detection of L_γ x-rays and low energy photons should be available at all facilities handling transuranics and the procedures should be written to deal with "dead time losses" and other complications which may lead to misinterpretation of the collected data.

In summary, this work has demonstrated the feasibility of developing a wound model which includes consideration of both surgical and chelation therapies. As such this thesis provides the critical first step in advancing such a tool for the health physics community.

11. EPILOGUE

Unfortunately, there have not been any recent evaluations performed on this individual. The most recent analysis was performed over a year ago after yet another incident involving the individual. In this case, the individual, while working on another decommissioning project, was helping with the excavation of buried waste. After loading a dump truck full of soil, the tailgate became lodged and was unable to properly latch. Trying to rectify the situation, the individual began trying to remove the obstructions. Suddenly, the heavy metal tailgate dislodged itself and came crashing down on the individual's thumb- the same thumb which had suffered the contaminated wound. As a result of this accident, the individual lost the tip of the thumb. Ironically, if the surgeons had removed about 1/8" more of the thumb, they would have amputated the contaminated injury along with the remaining material deposited within the wound.

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REFERENCES

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APPENDIX

APPENDIX A

The PCWOUND code was developed in this work from the ACTLITE code. PCWOUND solves a system of differential equations using the method of Leggett, et al. (1993). The code is written in FORTRAN and was compiled using the Microsoft 5.1 FORTRAN compiler and linker. The code uses some common exceptions to standard FORTRAN; e.g., DO - END DO statements. In addition, some routines specific to Microsoft are used to get the data and time information and to obtain the command line arguments.

PCWOUND runs on a personnel computers, under DOS, with a 486 or higher CPU and at least 16 Mbytes of RAM. The user is prompted regarding the name of the data set describing the chelation/surgical therapy for the specific case. The biokinetic file describing the behavior of the material is specified on the command line. For example, entering at the DOS prompt

PCWOUND PU-WOUND

runs PCWOUND using the biokinetics of the wound and systemic region contained in the file PU-WOUND (the extension DAT is assumed).

This version of PCWOUND was written for this research. PCWOUND and its data files reported here should be considered to in its development phase

and hence has not been subjected to extensive testing nor quality assurance. Some of the parameter values for the chelation agents used here may be specific to this application and thus should not be considered to be generally applicable. Potential users of this version of PCWOUND must establish the applicability of the code to their particular problem.

APPENDIX A

```
*-----------------------------------------------------------------------
*                                                                      *
      Program PCWOUND
*                                                                      *
*     An age-independent, striped-down, version of ACTACAL.                  *
*     K.F. Eckerman & Brian Bailey                                     *
*     Microsoft FORTRAN 5.1                                            *
*-----------------------------------------------------------------------
*
      include 'pcwound.cmn'
      include 'iolist.cmn'
*
      character*66 Mess
      character*8 fname
      integer*2 istatus
      logical*1 answer, chelflg
      dimension wrtime(mwrite), a(2*mcomp)
      common/timit/ delt0, delt1, delt2, delt3, delt4, delt5, ncycle,
     :              mcyc1, mcyc2, mcyc3, mcyc4
      common/iconds/y(mcomp), yw(mcomp)
      common/chelate/ tadm(40), amount(40), effect(40), tsur(40),
     :                arem(40), awound, nadm, nsur, chelflg
      equivalence (y(1), a(1))
      equivalence (yw(1), a(mcomp + 1))
      parameter (zero = 0.0, maxtit = 9)
      call cls
      write(*,'(" PCWOUND:",t11,"Excretion calculations",/t11,
     :        " Authors:",t11,"K.F. Eckerman & B. Bailey",
     :        /t11,"Oak Ridge National Laboratory",
     :         /t11,"Oak Ridge, TN 37831-6383"/)')
      numarg = nargs()
      if (numarg .eq. 1) then
        write(*,*) ' Usage: PCWOUND FileName w/o extension. Extension'
        write(*,*) '        INP will be assumed. The output file will'
        write(*,*) '        be names FileName.ACT.'
```

```
      stop
    else
      call getarg(1, fname, istatus)
    end if
    open(olog, file=fname(:len_trim(fname)) // '.log')
*
*    Read times at which activities will be printed, the
*    vector wrtime(i), i=1, numtim.
*
    numtim = mwrite
    call readtim(wrtime, numtim)
*
*    read time step information
*
    call timin
    write(olog,'(a)') 'Activities written to file: ' //
   :   fname(:len_trim(fname)) // '.act'
*
*    zero arrays and get kinetic data for the problem
*
    do i = 1, 2*mcomp
      a(i) = zero
    end do
    do i = 1, mcomp
      cname(i) = ' '
      do  j = 1, mcomp
        irmatrix(i, j) = 0
      end do
    end do
*
    call moddat (fname)
*
    mess = 'Read chelation data set '
    if (answer(mess, 'y'))then
      chelflg = .true.
      write(*,'(a\)')' Chelation Data File (ext dat assumed) -> '
      read(*,'(bn, a8)') fname
      open(14, file=fname(:len_trim(fname)) // '.dat')
```

```
 read (14,'(a60)') mess
 do while (mess(:5) .NE. 'WOUND')
   read (14,'(a60)') mess
 end do
 read(mess,'(5x,e10.0)') Awound
 write(olog,*) 'Initial wound activity - ', Awound
 do while (mess(:5) .NE. 'START')
   read (14,'(a60)') mess
 end do
 i1 = 0
 i2 = 0
 read (14,'(a60)') mess
 do while (mess(:3) .ne. 'END')
   if (mess(:2) .eq. 'Zn' .or. mess(:2) .eq. 'Ca') then
     i1 = i1 + 1
     read(mess,'(2x, 3E8.0)') Tadm(i1), Amount(i1), effect(i1)
     write(*,*) 'i =', i1, Tadm(i1), Amount(i1), effect(i1)
   elseif (mess(:2) .eq. 'Su') then
     i2 = i2 + 1
     read(mess,'(2x, 2E8.0)') Tsur(i2), Arem(i2)
   else
     write(*,*) mess
     write(*,*) 'Error in ', fname(:len_trim(fname)) // '.dat'
     stop 1
   end if
   read (14,'(a60)') mess
 end do
 close(unit=14)
 nadm = i1
 nsur = i2
 if (nadm .gt. 0) then
   write(olog, *) 'Chelation Therapy'
   do i = 1, nadm
     write(olog, *)'i =', i, Tadm(i), Amount(i), effect(i)
   end do
 end if
 if (nsur .gt. 0) then
   write(olog, *) 'Surgical Removal'
```

```
          do i = 1, nsur
            write(olog, *)'i =', i, Tsur(i), Arem(i)
          end do
        end if
      else
        chelflg = .false.
      end if
      call trace
      write(olog,'("Biokinetics")')
      write(olog,'(" Number of compartment =",i4)') ncomp
      call printc
      open(oact, file=fname(:len_trim(fname)) // '.act')
      open(ocpt2, file=fname(:len_trim(fname)) // '.cpt')
      open(oext, file=fname(:len_trim(fname)) // '.ext')
      call compute(wrtime, numtim)
      write(olog,'(a)') 'Computations ended normally.'
      close(unit = oact)
      close(unit = ocpt2)
      close(unit = oext)
  500 continue
      close (unit=21)
      end
*-----------------------------------------------------------------------*
*                                                                       *
        subroutine compute(wrtime, numtim)
*                                                                       *
*-----------------------------------------------------------------------*
*
*     author:   k. f. eckerman
*     date:     10/04/94
      include 'pcwound.cmn'
      include 'iolist.cmn'
*
      integer timex
      dimension wrtime(mwrite), yww(mcomp)
      real*8 days, y0, p, r, dt, a, aw, zerod
      common/iconds/y(mcomp), yw(mcomp)
      integer*2 ifeed, iout, nfeed, nout
```

```
      common/feed/ifeed(mtran, mcomp), iout(mtran, mcomp),
nfeed(mcomp),
     :          nout(mcomp), nentry
      common/timit/ delt0, delt1, delt2, delt3, delt4, delt5, ncycle,
     :           mcyc1, mcyc2, mcyc3, mcyc4
      common/activity/ y0, p, r, dt, a, aw
      logical*1 chelflg
      common/chelate/ tadm(40), amount(40), effect(40), tsur(40),
     :           arem(40), awound, nadm, nsur, chelflg
      logical test
      parameter (zero=0.0, one=1.0, zerod=0.0d0)
*
*     do some start up items
*
      howold = 7300.
      iprnt = 1
      write(olog,'("Total number of transfers =",i3)') nentry
*
*     begin calculations
*
      days = zerod
      delt = zero
      do icomp = 1, ncomp
        y(icomp) = 0.0
        yww(icomp) = 0.0
      end do
      if (Awound .eq. 0.0) Awound = 1.0
      iw1 = invect(cname, 'wound_a   ', ncomp)
      iw2 = invect(cname, 'wound_b   ', ncomp)
      y(iw1) = Fa * Awound
      y(iw2) = Fb * Awound

      iurne = invect(cname, 'ub_cont   ', ncomp)
      ichel = invect(cname, 'dtpa      ', ncomp)
      iblood = invect(cname, 'blood     ', ncomp)
      ipuchel = invect(cname, 'pu-dtpa   ', ncomp)
      iexcreta = invect(cname, 'excreta   ', ncomp)
      if (chelflg) then
```

```
      trchel = rmatrix(irmatrix(ichel, iexcreta))
      if (tadm(1) .eq. 0.) then
        y(ichel) = amount(1)
      end if
    else
      if (ichel .ne. 0) rmatrix(irmatrix(iblood, ipuchel)) = 0.0
    end if
    write(*,*)
    write(*,'(t5,"Computations started; time post intake =",
   :            f9.2," d.")') days
    write(oact,'("   Time  ",60(1x,a10))') (cname(i), i=1,ncomp)
    write(oact,'(1pe11.3, 60e11.4)') days, (y(ij), ij = 1, ncomp)
    write(ocpt2,'("   Time  ",60(1x,a10))') (cname(i), i=1,ncomp)
    write(ocpt2,'(1pe11.3, 60e11.4)') days, (yw(ij), ij = 1, ncomp)
    write(oext,'("   Time    E_u(t)")')
    write(oext,'(1pe11.3, e11.4)') days, 0.0
    if (chelflg .and. tadm(1) .eq. 0.0) y(ichel) = 0.0
    transfer = 0.d0
    itime = timex( )
*
    do 1000 icycle = 1, 10000                              ncycle
      exhaust = zero
      if (delt0 .eq. zero) then
        if (icycle .le. mcyc1) then
          dt = dble(delt1)
        elseif (icycle .le. mcyc2) then
          dt = dble(delt2)
        elseif (icycle .le. mcyc3) then
          dt = dble(delt3)
        elseif (icycle .le. mcyc4) then
          dt = dble(delt4)
        elseif (icycle .gt. mcyc4) then
          dt = dble(delt5)
        end if
      else
        dt = dble(delt0)
      end if
*
```

```
*       days is the elapse time from acute intake.
*
        days = days + dt
        if (chelflg) then
          do iadm = 1, nadm
            if (tadm(iadm) .ge. days-dt .and.
     :          tadm(iadm) .le. days) then
*             write(olog,*) days-dt, tadm(iadm), days
              Tot = y(ichel) + amount(iadm)
              y(ichel) = tot
              transfer = effect(iadm)
              adamout = amount(iadm)
*             write(*,*)'Iadm = ', iadm,' Time =',days,' DTPA =',
*    :              y(ichel), transfer, adamout
*             pause
              exit
            end if
          end do
          if (adamout .gt. 0.0) then
            rmatrix(irmatrix(ichel, iexcreta))= trchel
            rmatrix(irmatrix(iblood, ipuchel)) =
     :            y(ichel) * transfer / tot
*           rmatrix(irmatrix(ichel, iexcreta))= trchel   ! +
*    :            y(ichel) * transfer / adamout
          else
            rmatrix(irmatrix(iblood, ipuchel)) = 0.0
            rmatrix(irmatrix(ichel, iexcreta))= trchel
          end if
*
*       surgical remove of activity
*
          do isur = 1, nsur
            if (tsur(isur) .ge. days-dt .and.
     :          tsur(isur) .le. days) then
              if (Fa * Arem(isur) .gt. y(iw1)) then
                y(iw1) = 0.
                y(iw2) = y(iw2) - Arem(isur)
                if (y(iw2) .lt. 0.) y(iw2) = 0.
```

```
              exit
            else
              y(iw1) = y(iw1) - Fa* Arem(isur)
              y(iw2) = y(iw2) - Fb* Arem(isur)
              if (y(iw1) .lt. 0.) y(iw1) = 0.
              if (y(iw2) .lt. 0.) y(iw2) = 0.
              exit
            end if
          end if
        end do

*       write(*,*) cname(iblood),'->',cname(ipuchel),'= ',
*  :       rmatrix(irmatrix(iblood, ipuchel))
*       write(*,*) cname(ichel),'->',cname(iexcreta),'= ',
*  :       rmatrix(irmatrix(ichel, iexcreta))
*       write(*,*) 'Chelate =', y(ichel)
*       call printc
*       pause
      end if
*
*     Loop over compartements
*
      do 750 icomp = 1, ncomp
*
*       Set initial condition y0 and compute inflow to p.  The inflow
*       into compartment icomp consists of:
*          1. inflow from outside the system if pflow <> 0, and
*          2. inflow from the donor compartments.
*
        y0 = dble(y(icomp))
        p = zerod
        do i = 1, nfeed(icomp)
          jcomp = ifeed(i, icomp)
          index = irmatrix(jcomp, icomp)
          p = p + dble(rmatrix(index)) * dble(yw(jcomp))
        end do
        p = p / dt
        if (y0 .ne. zerod .or. p .ne. zerod) then
```

```
          r = rad
          do i = 1, nout(icomp)
            r = r + dble(rmatrix(iout(i, icomp)))
          end do
          call actvty
        else
          a = zerod
          aw = zerod
        end if
*
*       Save the activities and cummulative activities computed for
*       the current time step.
*
        y(icomp) = a
        yw(icomp) = aw
        yww(icomp) = yww(icomp) + aw
        exhaust = exhaust + a
 750    continue
*
*     end of the icomp loop
*
*     increment howold to the right hand of the time period.
      howold = howold + dt
      test = .false.
      if (days .gt. dble(wrtime(iprnt)-0.00001)) test=.true.
        if (test) then
        write(*,'(1h+,t5,"Computations started; time post intake",
     :          " =", f9.2)') days
        write(oact,'(1pe11.3, 60e11.4)') days, (y(ij), ij =1,ncomp)
        write(ocpt2,'(1pe11.3, 60e11.4)') days,(yww(ij),ij =1,ncomp)
        write(oext,'(1pe11.3, e11.4)') days, 12. * y(iurne)
        iprnt = iprnt + 1
        if (exhaust .eq. zero .or. iprnt .eq. numtim) then
          write(olog,'(" Compartments are exhausted, quit.")')
          goto 1001
        end if
        if (howold .gt. 36500.) then
          write(*, '(t5,"Attained age > 100 y; computations",
```

```
     :            " halted.")')
           write(olog, '(" Attained age > 100 y; computations",
     :            " halted.")')
           go to 1001
         end if
       end if
 1000 continue
*
*    end of the icycle loop.
 1001 write(olog,'("Calculations completed over",i5," cycles.")')
     :     icycle
     write(olog,'("Data reported for",i4," time steps.")') iprnt
     itime = timex( )/100
     write(*,'(t5,"System of",i3,
     :" compartments &",i4," transfers solved in", i4,
     :" s.")') ncomp, ntrans, itime
     write(olog,'("Computational time =",i8," s.")') itime
*
     return
     end

*-----------------------------------------------------------------------*
*                                                                       *
                  subroutine printc
*                                                                       *
*-----------------------------------------------------------------------*
*
*    author:   k. f. eckerman
*    date:     10/04/94
     include 'pcwound.cmn'
     include 'iolist.cmn'
*
     do i = 1, mcomp
       do j = 1, mcomp
         ic = irmatrix(i, j)
         if (ic .ne. 0) then
           write(olog, 300) cname(i), i, cname(j), j, rmatrix(ic)
         end if
```

```
      end do
    end do
    return
*
 300 format(a10,'(',i2,')--> ',a10,'(',i2,') ',1p10e10.3)
    end
*-----------------------------------------------------------------------*
*                                                                       *
                  subroutine trace
*                                                                       *
*-----------------------------------------------------------------------*
*    author:  k. f. eckerman
*    date:    10/04/94
*
*    routine determines the interconnection of compartments such that
*    the computations need only run over the feeder compartments for
*    a given compartment. The nonzero removal coefficients for each
*    compartment are identified.
*
    include 'pcwound.cmn'
*
    integer*2 ifeed, iout, nfeed, nout
    include 'iolist.cmn'
    common/feed/ifeed(mtran, mcomp), iout(mtran, mcomp),
nfeed(mcomp),
   :        nout(mcomp), nentry
*
*   This block sets up the information needed to determine the removal
*   coefficients from the compartment of interest. The matrix iout(i,j)
*   will contain the index into the rmatrix of the ith removal pathway
*   from the jth compartment. The number of nonzero removal coefficients
*   from the jth compartment is nout(j).
*
    nentry = 0
    do icomp = 1, ncomp
      n = 0
      do jcomp = 1, ncomp
        index = irmatrix(icomp, jcomp)
```

```
          if(index .ne. 0) then
            n = n + 1
            if (n .gt. mtran) goto 70
            iout(n, icomp) = int2(index)
          end if
        end do
        nout(icomp) = int2(n)
        nentry = nentry + n
      end do
*
*     This block of code sets up the information needed to determine the
*     inflow rate into the compartment of interest.  The matrix ifeed(i,j)
*     contains the index in the rmatrix of the ith compartment feeding the
*     jth compartment.  The number of compartments feeding the jth
*     compartment is nfeed(j).
*
      do jcomp = 1, ncomp
        n = 0
        do icomp = 1, ncomp
          index = irmatrix(icomp, jcomp)
          if (index .ne. 0) then
            n = n + 1
            if (n .gt. mtran) goto 80
            ifeed(n, jcomp) = int2(icomp)
          end if
        end do
        nfeed(jcomp) = int2(n)
      end do
      return
   70 write(olog,'(" The number of outflows from ", a10,
     :           " exceeds mtran!")') cname(icomp)
      write(olog,'(" Fatal error, please check biokinetic files.")')
      write(*, '(" The number of outflows from ", a10,
     :           " exceeds mtran!")') cname(icomp)
      write(*,'(" Fatal error, please check biokinetic files.")')
      stop 1
   80 write(olog,'(" The number of inflows into ", a10,
     :           " exceeds mtran!")') cname(jcomp)
```

```
      write(olog,'(" Fatal error, please check biokinetic files.")')
      write(*, '(" The number of inflows into ", a10,
     :           " exceeds mtran!")') cname(icomp)
      write(*,'(" Fatal error, please check biokinetic files.")')
      stop 1
      end
*-----------------------------------------------------------------------*
*                                                                       *
                    subroutine actvty
*                                                                       *
*-----------------------------------------------------------------------*
*     author:  k. f. eckerman
*     date:    10/04/94
*     routine to compute activity a and integrated activity aw assuming
*     initial content y0, inflow rate p, removal rate r, and time step t.
*
      real*8 y0, p, r, t, a, aw, zero, one, two, dx, eps, eps1, q
      real*8 por, half
      logical*1 first
      common/activity/ y0, p, r, t, a, aw
      parameter (zero = 0.0d0, half = 0.5d0, one = 1.0d0, two = 2.0d0)
      data first /.true./
      if (first) then
        eps = one
 10     eps = eps / two
        if (eps + one .gt. one) goto 10
        eps1 = dsqrt(eps)
        first = .false.
      end if
      if (r .gt. zero) then
        dx = t * r
        por = p / r
        if (dx .gt. 50.0d0) then
          a = por
          aw = (y0 - por + p * t) / r
        elseif (dx .lt. eps1) then
          q = t * (one - half * dx)
          a = y0 * dexp(-dx) + p * q
```

```
        aw = (y0 - por) * q + por * t
      else
        q = dexp(-dx)
        a = (y0 - por) * q + por
        aw = ((y0 - por) * (one - q) + p * t) / r
      end if
    else
      a = y0 + p * t
      aw = t * (y0 + half * p * t)
    end if
    if (a .le. eps) a = zero
    return
    end


*-----------------------------------------------------------------------*
*                                                                       *
          subroutine moddat (fname)
*                                                                       *
*-----------------------------------------------------------------------*
*    author:   k. f. eckerman
*    date:     10/04/94
*    description of call variables:
*    fname - name of input file
*
    include 'pcwound.cmn'
    include 'iolist.cmn'
*
    character*80 card
    character*12 fname12
    character*10 lcase, dmmy1, dmmy2, unscore
    character*8 fname
*
*    open file
*
    fname12 = fname(:len_trim(fname)) // '.inp'
    open(igit, file = fname12, status='old')
*
```

```
      rad = 0.0
      read(igit,'(a80)') card
      do while (card(:3) .ne. 'COM')
        if (card(:5) .eq. 'THALF') then
          read(card, '(5x,e16.0)') T12
          rad = 0.6931471 / t12
        else if (card(:5) .eq. 'WOUND') then
          read(card, '(10x,2e10.0)') Fa, Fb
        end if
        read(igit,'(a80)') card
      end do
      ncomp = 0
      read(igit,'(a80)') card
      i = 0
      do while (card(:5) .ne. 'END L')
        i = i + 1
        read(card, '(a10,2e10.0)') dmmy1, a0(i), p0(i)
        dmmy1 = unscore(lcase(dmmy1))
        i1 = len_trim(dmmy1)
        call bldvect(cname, dmmy1, i1, ncomp)
        read(igit,'(a80)') card
      end do
*
*     Read the transfer rates between the compartments.
*     ntrans is the number of transfers.
      read(igit, '(a10)') dmmy1
      ntrans = 0
      read(igit, '(a80)') card
      do while (card(:3) .ne. 'EOF')
        read(card, '(a10,2x,a10,e16.0)') dmmy1, dmmy2, r
        ntrans = ntrans + 1
        rmatrix(ntrans) = r
        dmmy1 = unscore(lcase(dmmy1))
        dmmy2 = unscore(lcase(dmmy2))
        i1 = invect(cname, dmmy1, ncomp)
        i2 = invect(cname, dmmy2, ncomp)
*       write(*,*) i1, dmmy1, i2, dmmy2
        irmatrix(i1, i2) = int2(ntrans)
```

```
      read(igit, '(a80)') card
    end do
    close(unit = igit)
    if (rad .ne. 0.0) write(*,'(" Thalf =",1pe11.4)') t12
*   write(*,'(4(3x,a10))') (cname(i), i=1, ncomp)
    return
    end
*-----------------------------------------------------------------------*
*                                                                       *
          subroutine readtim(wrtime, numtim)
*                                                                       *
*-----------------------------------------------------------------------*
*
*   author:  k. f. eckerman
*   date:    10/04/94
    include 'iolist.cmn'
    dimension wrtime(*)
*
*   Read the times at which the activities will be printed, the
*   array wrtime(i), i = 1, numtim.
*
    open(itim, file = 'writim.dat', status='old')
    numtim0 = numtim
    read(itim, *) numtim
    if (numtim .gt. numtim0) then
      write(olog,'(" Error: Number of times in WRITIM.DAT exceeds th
   :e program dimensions.")')
      write(olog,'(" Maximium number of time is", i4)') numtim0
      write(*,'(" Error: Number of times in WRITIM.DAT exceeds the p
   :rogram dimensions.")')
      write(*,'(" Maximium number of time is", i4)') numtim0
      stop 1
    end if
    do i = 1, numtim
      read(itim, *) wrtime(i)
    end do
    close(unit = itim)
    return
```

```
      end
*-----------------------------------------------------------------------*
*                                                                       *
                  subroutine timin
*                                                                       *
*-----------------------------------------------------------------------*
*
*     author:   k. f. eckerman
*     date:     10/04/94
      include 'pcwound.cmn'
      include 'iolist.cmn'
      common/timit/ delt0, delt1, delt2, delt3, delt4, delt5, ncycle,
     :              mcyc1, mcyc2, mcyc3, mcyc4
*
      open(itim, file='timin.dat', status='old')
      read(itim,*) delt0, delt1, delt2, delt3, delt4, delt5
      read(itim,*) ncycle, mcyc1, mcyc2, mcyc3, mcyc4
      close(unit = itim)
      return
      end
*-----------------------------------------------------------------------*
*                                                                       *
      integer function invect(clist, citem, n)
*                                                                       *
*-----------------------------------------------------------------------*
*     author:   k. f. eckerman
*     date:     10/04/94
*     purpose:  function returns the index of citem in the array clist(m).
*               if citem is not in clist a zero is returned.
*
      character*(*) citem, clist(*)
      if (n .eq. 0) then
       write(*,'(" Error in invect,  no elements in array")')
       stop 1
      else
       ilen = len_trim(citem)
       do i = 1, n
         itest = len_trim(clist(i))
```

```
        if (itest .eq. ilen) then
          if (clist(i) .eq. citem(:ilen)) then
            invect = i
            return
          end if
        end if
      end do
*
*     return 0 to calling routine when item not found in array.
*
      invect = 0
    end if
    return
    end
*-----------------------------------------------------------------------*
*                                                                       *
        character*(*) function unscore (a)
*                                                                       *
*-----------------------------------------------------------------------*
*    author:   k. f. eckerman
*    date:     08/20/93
*    purpose:  replace blank by underscorce character
*
    character*(*) a
    unscore = a
    do i = 1, len_trim(a)
      if (unscore(i:i) .eq. ' ') unscore(i:i) = '_'
    end do
    return
    end

*-----------------------------------------------------------------------*
*                                                                       *
        subroutine bldvect(clist, citem, ilen, n)
*                                                                       *
*-----------------------------------------------------------------------*
*    author:   k. f. eckerman
*    date:     02/13/95
```

```
*    purpose:  routine build the character vector clist(n).  ilen
*              should be set to the length of character variable citem for
*              which the comparison is to be made.  citem is added to vector
*              of length ilen.
*
      character*(*) citem, clist(*)
      if (n .eq. 0) then
        n = 1
        clist(n) = citem(:ilen)
      else
        do i = 1, n
          itest = len_trim(clist(i))
          if (itest .eq. ilen) then
            if (clist(i) .eq. citem(:ilen)) return
          end if
        end do
        n = n + 1
        clist(n) = citem(:ilen)
      end if
      return
      end
*-----------------------------------------------------------------------*
*                                                                       *
            character*(*) function lcase (a)
*                                                                       *
*-----------------------------------------------------------------------*
*    author:   k. f. eckerman
*    date:     10/04/94
*    purpose:  convert character variable a to lower case.
*
      character*(*) a
      lcase = a
      do i = 1, len_trim(lcase)
        ix = ichar(lcase(i:i))
        if (ix .gt. 64 .and. ix .lt. 91) then
          lcase(i:i) = char(ix + 32)
        end if
      end do
```

```
      return
      end

*-------------------------------------------------------------------------*
*                                                                         *
            character*(*) function ucase (a)
*                                                                         *
*-------------------------------------------------------------------------*
*     author:  k. f. eckerman
*     date:    10/04/94
*     convert character variable a to upper case.
*
      character*(*) a
      ucase = a
      do i = 1, len_trim(ucase)
        ix = ichar(ucase(i:i))
        if (ix .gt. 96 .and. ix .lt. 123) then
          ucase(i:i) = char(ix - 32)
        end if
      end do
      return
      end

*-------------------------------------------------------------------------*
*                                                                         *
              integer function timex ( )
*                                                                         *
*-------------------------------------------------------------------------*
*     author:  k. f. eckerman
*     date:    03/13/94
*     purpose:  function returns the elasped time between calls in 100th
*               of a second. this procedure is only valid for elasped times
*               less that 24 hours. the following statement can be used to
*               print the elapsped time after the second call to timex:
*               write(*,'(" elapsed time (100 s) =",i8)') timex( )
*
      integer*2 ihr, imin, isec, i100s
      integer*4 idelt, itold, isecd, itime
```

```
      logical*1 first
      parameter(isecd = 8640000)
      save first, itold
      data first /.true./
*
      call gettim(ihr, imin, isec, i100s)
      itime = i100s + 100 * (isec + 60 * (imin + 60 * ihr))
*
*     if first set idelt to zero, first to false, store itime as
*     itold and return.  if not first compute elapsed time, idelt.
*
      if (first) then
        idelt = 0
        first = .false.
        itold = itime
      else
        if (itime .lt. itold) then
*
*           if current time is less than time of previous call,
*           a new day has begun, thus add isecd to current itime.
*
          idelt = itime + isecd - itold
        else
          idelt = itime - itold
        end if
        itold = itime
      end if
      timex = idelt
      return
      end
*-----------------------------------------------------------------------*
*                                                                       *
                      subroutine Cls
*                                                                       *
*-----------------------------------------------------------------------*
*     author:   k. f. eckerman
*     date:     01/13/92
*     routine to clear screen
```

```
      write(*,*) char(27),'[2J'
      return
      end
*-----------------------------------------------------------------------
      logical*1 function answer(mess, default)
*-----------------------------------------------------------------------
*  routine:  answer
*  author:   k. f. eckerman
*  date:     09/20/91
*  purpose:  obtain a yes/no response to the question given in mess.
*            note the routine attached a (y/[n])? or ([y]/y)? to the
*            message based on the default variable.  the functions
*            returns a logical true.
*
      character*1 anx, default
      character*40 mess
      ilen = len_trim(mess)
*
*     since each write moves use down 1 we need to back up two lines.
*     save cursor position in case we need to return to here.
*
      write(*,*) char(27) // '[2A'
      write(*,*) char(27) // '[s'
*
   10 if (default .eq. 'n') then
        write(*,'(a\)') ' '// mess(:ilen) //' (y/[n])? '// default
      else
        write(*,'(a\)') ' '// mess(:ilen) //' ([y]/n)? '// default
      endif
*
*     move cursor back one character
*
      write(*,'(a\)') char(27) // '[1D'
*
*     get user input
*
      read (*,'(a1)') anx
*
```

```
*     process the input considering the default.
*
      if (anx .eq. ' ') then
        if (default .eq. 'y') then
          answer = .true.
        else
          answer = .false.
        endif
      elseif (anx .eq. 'Y' .or. anx .eq. 'y') then
        answer = .true.
      elseif (anx .eq. 'N' .or. anx .eq. 'n') then
        answer = .false.
      else
*
*       if the user gave us an incorrect response we need to
*       note it, and restore the cursor before go to 10.
*
        write(*,*)' Incorrect response, try again.'
        write(*,*) char(27) // '[u'
        go to 10
*
      endif
*
*     clear any warning text and back up the cursor two lines
*
      write(*,*) char(27)//'[K'
      write(*,*) char(27) // '[2A'
      return
      end
```

APPENDIX A

```
character*6 proot
 integer*2 itim, igit, ilng, ibio, idex
 parameter(itim=20, igit=21, ilng=22, ibio=23, idex=24)
 common/root/proot
 integer*2 ocpt, ostm, olog, oact, ocpt2, oext
 parameter(ocpt=11, ostm=12, olog=13, oact=14, ocpt2=15, oext=16)
```

APPENDIX A

```
*  The following parameter values give the maximium dimensions of the
*  arrays of pcwound.  To increase the problem size simply edit this
*  file and recompile pcwound.        k.f. eckerman & brian bailey
*
*     mcomp is the maximium number of compartments in the kinetics
*     mtran is the maximium number of transfers from any compartment
*     mrank is the maximium number of transfers in the kinetics.
*     mwrite maxium number of write times; i.e. entries in wrtim.dat
*
      integer*2 mcomp, mtran, mrank, mwrite
      parameter(mcomp = 60, mtran = 50, mrank = 200, mwrite = 150)
*
      character*10 cname
      real*8 rad
      real rmatrix
      integer*2 irmatrix
*
*     description of common block metdat
*
*     the square matrix irmatrix(i,j) contains the index, ic, into the
*     rmatrix for the transfer rate from compartment i to j at age iage
*     for species ispec.  The transfer is rmatrix(ic, iage, ispec).
*     the vector iother(mcomp) is the list of csour source regions that
*     are part of the systemic pool, their are noth such entries.
*
      common/metdat/rmatrix(mrank), rad, irmatrix(mcomp, mcomp),
     :     cname(mcomp), a0(mcomp), p0(mcomp), iorder(mcomp), tauw,
     :     fa, fb, ncomp, ntrans
```

APPENDIX A

0.0, 0.001, 0.01, 0.1, 1., 10 DELT0, DELT1, 2, 3, 4, 5
8857, 1000, 1900, 2800, 6700
NCYCLE,ICYC1,ICYC2,ICYC3,ICYC4

TIME STEPS
129
0.001
0.002
0.003
0.004
0.005
0.006
0.007
0.008
0.009
0.01
0.012
0.014
0.016
0.018
0.020
0.023
0.026
0.03
0.035
0.04
0.045
0.05
0.06
0.07
0.08

0.09

0.1
0.12
0.14
0.16
0.18
0.2
0.23
0.26
0.3
0.35
0.4
0.45
0.5
0.6
0.7
0.8
0.9
1.0
1.2
1.4
1.6
1.8
2.0
2.3
2.6
3.0
3.5
4.0
4.5
5.0
6.0
7.0
8.0
9.0
10.
12.

13.
14.

16.
18.
20.
23.
26.
30.
35.
40.
45.
50.
60.
70.
80.
90.
100.
120.
140.
160.
180.
200.
230.
260.
300.
350.
400.
450.
500.
600.
700.
800.
900.
1000.
1200.
1400.
1600.

1800.
2000.
2300.

2600.
3000.
3500.
4000.
4500.
5000.
6000.
7000.
8000.
9000.
10000.
11000.
12000.
13000.
14000.
15000.
16000.
17000.
18250.
19500.
21000.
22500.
24000.
25550.
27500.
30000.
33000.
36501.

APPENDIX A

This is a Pu-239/240 data file for Pu worker.

We assume the initial wound contained 36.5 nCi Am-241 or 1350 Bq. The Pu to Am ratio is taken as 2 with about 83% of the Pu activity being Pu-239/240.

Thus the initial Pu-239/240 content of the wound was 2240 Bq.

WOUND 2240.

START

Ca 0.0 1.0 0.3

Zn 7.0 1.0 0.3

Zn 8.0 1.0 0.3

Zn 9.0 1.0 0.3

Zn 10.0 1.0 0.3

Zn 11.0 1.0 0.3

Su 13.0 1330.

Su 14.0 264.

END

Note above format is (a2, 3e8.0).

APPENDIX A

This is a Am-241 data file for Pu worker.

We assume the initial wound contained 36.5 nCi Am-241 or 1350 Bq.

WOUND 1060.

START

Ca 0.0 1.0 0.3

Zn 7.0 1.0 0.3

Zn 8.0 1.0 0.3

Zn 9.0 1.0 0.3

Zn 10.0 1.0 0.3

Zn 11.0 1.0 0.3

Su 13.0 801.

Su 14.0 159.

END

Note above format is (a2, 3e8.0).

VITA

Brian Bailey was born Labor Day, September 4th, 1972 in Akron, Ohio. He spent the first seven years of his life there until his family moved to Minnora, West Virginia. There, he finished his elementary and high school years. After high school graduation, he spent a year away from educational pursuits and was employed by a pipeline construction company. The following August, he enrolled at Marshall University in Huntington, West Virginia. There he was a full-time student and worked part-time at the Marshall University Physical Plant. In May, 1995 he graduated Cum Laude with a degree in Physics. Once again, he took a year off of educational pursuits and remained at the Marshall University Physical Plant where he earned a full-time position as the Draft Specialist. In July, 1996, Brian was awarded a Department of Energy Applied Health Physics Fellowship through the Oak Ridge Institute for Science and Education. This fellowship allowed him to enroll as a full-time student at the University of Tennessee. He spent the next two years at the university pursuing a Master of Science Degree in Nuclear and Radiological Engineering which he received in August, 1998. With degree in hand, he plans on starting work for H. & R. Technical Associates in Oak Ridge, Tennessee in early August.