UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D. C. 20555

MAY 1 1987

MEMORANDUM FOR: Thomas E. Murley, Director
Office of Nuclear Reactor Regulation

Hugh L. Thompson, Jr., Director
Office of Nuclear Material Safety and Safeguards

FROM: Eric S. Beckjord, Director
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SUBJECT: RESEARCH INFORMATION LETTER NUMBER 150, "RESULTS OF GROUND-WATER INTERDICTIVE STRATEGY RESEARCH FOR SEVERE NUCLEAR ACCIDENTS"

Abstract

Based upon NRC staff studies during the TMI incident and subsequent technical assistance work at Argonne National Laboratory, a comprehensive study of ground-water interdictive strategies was performed at Pacific Northwest Laboratory (PNL). PNL researchers evaluated the feasibility of using mitigative techniques to control radionuclide migration in ground water following a severe accident at a commercial nuclear power reactor. The two types of severe accidents investigated were containment basemat penetration by: (1) core-melt debris which slowly cools and leaches radionuclides to the subsurface environment, and (2) sump water without full penetration of the core mass. Six generic hydrogeologic site classifications were developed from an evaluation of previously submitted data pertaining to the hydrogeologic properties of all existing and proposed commercial reactor sites. One-dimensional radionuclide transport analyses were conducted on each of the individual reactor sites grouped into the six generic classifications to determine the generic characteristics of radionuclide discharge to an accessible environment for each group of sites. Mitigative techniques were identified, and then evaluated for their suitability to site specific and severe power plant accident conditions. Feasible mitigative techniques, and associated constraints on their feasibility were determined for the six hydrogeologic site classifications. The researchers showed that certain hydrogeologic settings are more sensitive to contaminant transport offsite, and that certain settings would not be capable of effective ground-water interdiction. Two case studies were conducted at nuclear power plant sites to examine their hydrogeologic characteristics and to investigate and examine its effect on various mitigative techniques. The impact of plant structures on the various mitigative techniques was studied in a related case study. Mitigative strategies were evaluated for their effectiveness in reducing contaminant transport offsite. Numerical simulation results indicate that the mitigative techniques could significantly increase ground-water travel times and reduce contaminant migration rates. The research study demonstrated the value of the developed interdictive strategy for severe accident analysis and provides guidance for selecting the most appropriate mitigative techniques based upon site hydrologic characteristics, accident conditions, plant structures and ground-water flow and transport modeling.

INTRODUCTION

1. Background

A core-melt accident could release radioactive contaminants to ground water. Isolation of the contaminated ground water beneath a failed reactor building would be necessary to protect regional water supplies. The "Liquid Pathway Generic Study" (NUREG-0440) (See Reference 6), which was published in February 1978, compared the consequences of a core-melt accident at a floating nuclear plant with those from a land-based plant. This report was the most comprehensive NRC staff study prior to the Three Mile Island (TMI) accident on liquid pathway consequences from a core-melt accident. During the accident at TMI in 1979, NRR hydrologists evaluated the potential for contaminant migration offsite, and the feasibility of containing contaminated ground water onsite (Nicholson, 1979, See Reference 7). Since that accident, NRR ground-water-related activities have focused almost entirely on evaluating environmental impacts of postulated accidents involving releases of radioactive materials to ground water.

2. Regulatory Basis

NRC regulations relevant to ground-water protection for nuclear power plants are contained in 10 CFR Part 100. Paragraph (§) 100.10 identifies specific ground-water pathway concerns. Following the TMI accident, the "Report of the Siting Policy Task Force" (NUREG-0625), which drew upon the "Lessons Learned Study" by the NRC staff, recommended that Part 100 be revised by requiring "reasonable assurance that interdictive measures are feasible to limit ground-water contamination resulting from Class-9 accidents at nuclear power plants." (Class-9 accidents comprise a class of accidental releases of radionuclides to ground water as a result of partial or total melting of the reactor core, and breaching of the containment vessel.) An in-depth evaluation of this recommendation was deferred until research on source terms and ground-water mitigative techniques was completed.

3. Regulatory Review

Since July 1980, the NRR staff has evaluated radiological exposure pathways to humans from postulated core-melt accidents for environmental impact statements. These evaluations have included the ground-water pathway. Standard procedures for assessing the consequences of ground-water pathway releases have been under development by the NRR staff since July 1980, and were recently published in NUREG-1165, "Environmental Standard Review Plan for ES Section 7.1.1 - Environmental Impacts of Postulated Accidents Involving Releases of Radioactive Materials to Ground Water" (See Reference 12). This NUREG lists the types of information to be used by NRR staff in evaluating the ground-water pathways, and highlights useful references for the evaluation. It also provides procedures for consistent staff reviews of applicant's analyses of radiological impacts involving releases to ground water. NUREG-1054, "Simplified Analysis for Liquid Pathway Studies" (See Reference 2), provides procedures for calculating doses to humans and making comparisons with generic sites, and also includes a computer code for the radionuclide transport analysis.

4. Previous Studies

Based upon the NRR staff analysis of the TMI accident, (Nicholson, 1979), the NRR staff identified installation of bentonite slurry walls as one possible means of isolating contaminated ground water, and awarded a technical assistance contract to Argonne National Laboratory (ANL) to determine the feasibility of using slurry walls. Results of the Argonne study were submitted May 1982 in an unpublished report entitled "Accident Mitigation: Slurry Wall Barriers." In a follow-up study, ANL staff investigated alternative methods of isolating and controlling contaminated ground water including (1) ground-water freezing, (2) aquifer dewatering, (3) water injection, (4) recovery drain systems, (5) recovery well systems, (6) grouting, and (7) sheeting piling. In September 1982, ANL submitted their follow-up report entitled "Accident Mitigation: Alternative Methods for Isolating Contaminated Ground Water." Although these investigations showed that some of the methods could be effective in isolating contamination, the report concluded that the performance of mitigative measures is highly dependent on site-specific factors. Since the ANL studies did not use ground-water models to evaluate the appropriateness of various mitigative methods to specific site and accident conditions, a more comprehensive research study was begun at Pacific Northwest Laboratory (PNL) in August 1982.

5. PNL Study

Because of the unresolved issues in licensing reviews and proposed rulemaking recommendations, NRC's Research office contracted with PNL to conduct ground-water studies of implementing various interdictive strategies and to identify and assess generic site conditions that may require the use of mitigative techniques in the event of a severe accident. This research information letter outlines the major conclusions and lessons learned from the PNL study which is contained in their report, "Mitigative Techniques for Ground-Water Contamination Associated with Severe Nuclear Accidents" (NUREG/CR-4251 Volumes 1 and 2). This report provides detailed information about mitigative techniques for controlling contaminated ground water, including various strategies and computer codes that would provide a technical basis for selecting appropriate and feasible techniques, and site specific emergency response activities.

PNL STUDY OVERVIEW

1. Purpose

Pacific Northwest Laboratory conducted a study of available mitigative techniques for controlling contaminated ground water resulting from postulated severe commercial nuclear power plant accidents. The purpose of the study was to evaluate the feasibility and desirability of using specific ground-water contaminant mitigation techniques (e.g., constructed barriers to subsurface flow and transport, and hydraulic barriers created by ground-water withdrawal and/or injection) to control radionuclide migration in ground-water flow systems following a core-melt accident. The terms "severe accident" and "core-melt accident" as used in the study were synonymous, and are defined as that accident in which molten nuclear fuel, reactor components, and/or sump water exit the containment structure through the basemat.

2. Objectives

The objectives of the PNL study were:

a. Identification of hydrogeologic factors that affect the source term release to the surrounding geologic media, and subsequent ground-water migration of the radionuclides following a severe nuclear accident,

b. Evaluation of the feasibility of interdicting radionuclide contaminants for a variety of generic hydrogeologic conditions based upon analysis of power plant sites in the United States,

c. Development and demonstration of the methodology for both characterizing the hydrogeologic site conditions, and then evaluating the likelihood of contaminant transport for various interdictive methods, and

d. Development and demonstration of the methodology for evaluating the feasibility, design, implementation, and performance assessment of various mitigative schemes using site-specific information.

3. Accomplishment of Objectives

The first two objectives were accomplished by conducting a generic analysis of ground-water flow and transport conditions following a severe accident. This information is contained in Volume 1 of NUREG/CR-4251 and represents an inductive process wherein a large volume of diverse information is reduced to generalized or generic descriptions of a core-melt accident. The common properties concerning core-melt formation, contaminant migration and arrivals at an accessible environment were combined to form a generic hydrogeologic classification system. Ninety-seven existing and proposed nuclear power plant sites in the United States were classified by this scheme. A large body of geologic and hydrologic information is included in the PNL report (NUREG/CR-4251) for the convenience of the nontechnical reader and to serve as a reference guide to further discussions. Table 1 of this Research Information Letter (RIL) lists the important parameters for characterizing plant sites. Information on these parameters would be necessary baseline data for modeling and evaluating the possible ground-water pathways which would be used for developing an appropriate interdictive strategy.

The third and fourth objectives were accomplished by conducting three site-specific case studies which are contained in Volume 2 of NUREG/CR-4251. Different aspects of selection, design, and implementation of mitigative techniques were incorporated into the three case studies. Results from the case studies provide insight into the site-specific conditions that would need to be considered following a severe accident. The three case studies examined mitigative techniques in greater detail than was possible in the generic analysis contained in Volume 1 of NUREG/CR-4251. The case studies also served to confirm the conclusions of the generic analysis. Determination of an appropriate method to interdict ground-water contaminants, and of the design of the appropriate methods can only be made at the case study level of analysis. The individual hydrogeologic and plant features considered in each of the three case studies are given in Table 2.

Table 1 Important Parameters for Characterizing Plant Sites

Hydrogeologic Characteristics	Geochemical Data
Hydraulic Conductivity	Soil pH
Anisotropy of Hydraulic Properties	Ion-Exchange Capacity
Effective Porosity	Surface-water Chemistry
Hydraulic Potential	Ground-water Chemistry
Flow Directions	Sorption-Desorption Values of Hydrogeologic Units
Hydrodynamic Dispersion	
Moisture Retention Curves	Source Term Data
Infiltration Rates and Capacities	
Specific Water Capacity	Radionuclide Inventory
Ground-Water Recharge	Time History of Liquid Release
Grain-size Distribution, Density, and Strength	Core Debris - Geologic Interface
Distance to Surface-Water Discharge Points	Material Zone Boundaries

Table 2 Case Study Hydrogeologic and Plant Features

Case Study No.	Site Name	Topics Considered
1	South Texas Plant	Unconsolidated hydrogeologic media, hydrogeologic characterization, evaluation of mitigative methods
2	South Texas Plant	Evaluation of the impact of plant structures on implementing various mitigative techniques, mitigative scheme selection
3	Marble Hill, Indiana	Consolidated and fractured hydrogeologic unit, anisotropic flow field, plant structures

PNL ANALYSIS OF GENERIC SITE AND ACCIDENT CONDITIONS

The following discussion is an edited summary taken from the PNL report (NUREG/CR-4251) which should be referred to for detailed data and analysis.

1. Introduction

The severity of ground-water contamination and subsequent discharge of radionuclides to the surface environment is, in part, a function of the hydrogeology of the site. The hydrogeology of the site affects the radionuclide release rate, subsequent transport time to the accessible environment, and the ability to mitigate environmental impacts due to the accident. Therefore, the analysis of liquid pathway contamination resulting from a severe accident is primarily a study of ground-water flow, leaching and subsequent transport of the radionuclides to surface and ground-water bodies.

The two types of accidents investigated were containment basemat penetration by: (1) molten fuel and other core debris, which slowly cools and leaches radionuclides to the subsurface environment, and (2) contaminated sump water. The release and transport of radionuclides following a core-melt accident is a complex process which is dependent on many accident and site-specific parameters and events. These processes were defined in as much detail and as accurately as possible given the absence of real data (prior to the Chernobyl accident). Where there is uncertainty in the examination, conservative yet realistic parameter estimates were made.

The escape of the contaminants by release from containment (i.e., leach rate) to the surrounding geologic media, and the discharge to the accessible environment, was described as an activity flux rate in picocuries/year. The environmental contact point was assumed to be the nearest surface-water body. The major topics and findings of the PNL analysis of generic site and accident conditions are presented by topic in the following sections.

2. Leach Release from Core Debris

The chemical composition of the aggregate in the concrete basemat and the underlying geologic materials will have a large influence on the rate of leaching solid material released to the ground water. For example, calcine debris derived from concrete and carbonate rock are envisioned to have the following features:

- relatively porous with a high surface area,
- contain a high density of radionuclides per unit volume,
- melt to a depth of about 3 meters below the basemat,
- release radionuclides to the ground-water flow system through a diffusion process, and
- attain a peak release rate for strontium-90 of about 1 - 10 x 10^{17} pCi/yr.

On the other hand, silicic debris produced by the melting of sand or igneous rock should have the following features by comparison:

- more glass-like with a porosity and permeability determined by the density of the fracture network,
- a relatively lower surface area and porosity,
- a larger melt zone extending to 10 meters below the basemat,
- release radionuclides through a dissolution process, and
- a peak release rate for strontium-90 of about 2 x 10^{15} pCi/yr.

As a result of these fundamentally different characteristics and leach mechanisms, calcine debris would release radionuclides at a rate two orders of magnitude greater than silicic debris. The composition of a severe melt debris would be an admixture of both silicic and calcine components resulting in a leach rate between the two limiting cases presented.

Both calcine and silicic debris would leach release radionuclides to a ground-water flow system for long periods of time. The quantity of radionuclides released by leaching would eventually reach insignificant levels because of radioactive decay and a decreasing leach release rate. Based on the calculated leach rates and a ground-water velocity of 1 m/yr, the concentration of strontium-90 adjacent to the melt debris would reach 10 CFR 20 limits of 300 pCi/ℓ about 800 years and 1,100 years after the accident for a silicic and a calcine melt, respectively.

3. Sump Water Release Rate

Sump water drainage rates through the containment basemat and core-melt debris would be highly site and accident specific. Feasible rates based on the hydraulic properties of each site indicate that sump water drainage can potentially release radionuclides at a greater rate than core melt leaching. However, the actual drainage rate could be considerably more to much less than predicted. The time over which an actual sump water release would occur is a period of days to months. Very slow drainage rates could allow removal of liquid contaminant from the containment structure before it entered the ground-water flow system. Conversely, a release of sump water driven by a pressurized containment dome (pressurized water reactors only) could produce a rapid hydraulic spreading of contaminant and decrease the travel time to the surface environment. This would result in the largest possible radiological flux to the ground-water environment and the greatest need for contaminant interdiction.

4. Generic Hydrogeologic Classification of Nuclear Power Plant Sites

A hydrogeologic classification system for contaminant interdiction at nuclear power plants must consider the hydrogeologic factors of the plant site and the interaction of the core-melt debris with the underlying geologic media and then the eventual contaminant arrival at land surface. The three hydrogeologic factors for this classification scheme are:

a. The mineralogy of the contaminants source for the determination of leach rate;

b. Feasibility of contaminant mitigation in different geologic environments (i.e., consolidated and unconsolidated materials); and

c. Hydraulic transport parameters to land surface.

The six types of generic sites derived from application of the classification scheme to proposed and existing nuclear power plant sites in the United States were:

a. Fractured consolidated crystalline silicates,
b. Fractured and solutioned consolidated carbonates,
c. Porous consolidated silicates,
d. Porous consolidated carbonates,
e. Porous unconsolidated silicates, and
f. Fractured consolidated silicates-shale.

Assigning representative or "average" hydraulic parameters to each generic classification and subsequently generating "average" radionuclide discharges to a surface-water body based upon these assigned values was not attempted because of the wide range of hydraulic values among hydrogeologically similar sites, averaged parameters that are inversely related (e.g., hydraulic gradients and permeabilities) may not produce an average result, and the variability of transport within a given hydrogeologic classification would be lost.

Numerical simulation of individual sites and analysis of the results by generic groups are applicable and demonstrate the large differences in contaminant release and transport among and within the generic classifications. The major findings of the generic hydrogeologic analysis were that:

a. The discharge of radionuclides to the surface-water environment is more a function of site hydrogeology than the type of accident scenario.

b. The range of contaminant quantities available for transport due to accident scenarios is small (several tenths of a percent) in comparison to the large range of values (up to 6 orders of magnitude) for hydrogeologic transport parameters.

c. The different accident sequences would alter the quantity of contaminant by a linear function (a percentage of the total fuel inventory) while changes in hydrogeologic parameters allow for longer transport times which would decrease the total quantity discharged to the environment exponentially.

d. The major hydrogeologic factors determining the severity of a groundwater release (listed in order of relative importance) are:

 (1) chemical composition of the containment structure basemat and underlying hydrogeologic unit,

 (2) effective porosity* of the hydrogeologic unit,

*Note: This parameter proved to be especially sensitive for fractured media since the very low effective porosities characteristic of certain fractured media created very large average interstitial velocities when calculated.

(3) sorption of contaminant by the hydrogeologic media, and

(4) hydraulic gradient and conductivity of the hydrogeologic units.

5. Indicator Radionuclides

The selection of the three radionuclides used as indicators of contamination potential was based upon their initial quantity, longevity, and mobility. The transport analysis was conducted for strontium-90, cesium-137, and ruthenium-106. Ruthenium-106 was found to be sorbed and retarded under core-melt conditions. Previous NRC studies such as the "Reactor Safety Study" (NUREG-15/014) and the "Liquid Pathway Generic Study" (NUREG-0440) assumed that 50 percent of the ruthenium was complexed by nitrate and formed a water-coincident contaminant. This assumption was based on the migration of ruthenium-106 in high nitrate-level processing wastes at the Hanford site near Richland, Washington. Nitrate concentrations found in natural ground water are not sufficient to complex and thus mobilize ruthenium-106. Retardation of ruthenium allows decay to reduce the amount of contaminant to low levels prior to reaching surface water. Only 7 percent of the nuclear power plant sites in the United States would have a discharge of ruthenium-106 before they experienced 40 half-lives of decay.

Cesium-137 would be released in the sump water from pressurized water reactors. Empirical testing indicates that cesium-137 is more strongly sorbed than strontium-90, but the retardation mechanism is phenomonologically complex and not fully described by present retardation models. Retardation of cesium-137 has been noted as being time and concentration dependent. Cesium-137 would arrive at the discharge location at 37 percent of the sites before 40 half-lives of decay.

Strontium-90 emerged as the preferred contaminant indicator for determining the relative sensitivity of ground-water transport conditions for a core-melt accident. Strontium would be released in sump water and as leachate from the core debris. It is more mobile than cesium-137 and would arrive at the discharge location at relatively early times and at activity rates comparable to the cesium-137 in a sump water release. Strontium-90 could be expected to arrive at a surface-water body at 55 percent of the sites prior to 40 half-lives of decay.

6. Contaminant Discharge to Accessible Environments

In the PNL report, the generic discharges of contaminants are examined at two basic levels. The first level determines whether the contaminant will arrive within a short time at a high flux, or at a much longer time at an insignificant level. A conservative definition of significance is based on a 40 half-life travel time to surface water. Over this time period, radionuclides are decayed to very low levels or fall into the category of a nonimminent situation requiring mitigation. The analysis of significant discharges to the environment demonstrates that:

- 43 percent of the 97 sites analyzed do not produce a significant discharge to a surface-water body that would require immediate contaminant interdiction to prevent severe environmental consequences;

- interdiction would be desirable at 85 percent (28 of the 33 sites analyzed) of the fractured geologic sites; and

- interdiction of contaminant would be desirable at 42 percent (27 of the 64 sites analyzed) of the nonfractured sites.

Within the first level of analysis, the generic sites are ranked as to their relative environmental sensitivity to a core-melt accident by comparison of the percentages of sites that would result in a significant radionuclide discharge and those that would produce a minor discharge. The ranked generic sites are presented with the percentage of significant discharges in Table 3.

Table 3 Generic Sensitivity to a Severe Nuclear Accident

Rank	Generic classification	Percent of sites with significant surface water discharge*
1	Fractured Consolidated Crystalline Silicates	94
2	Fractured and Solutioned Consolidated Carbonates	83
3	Fractured Shale	60
4	Porous Unconsolidated Silicates	49
5	Porous Consolidated Silicates	38
6	Porous Consolidated Carbonates	20

*All three indicator radionuclides considered.

The second level of analysis of generic sites was more detailed and examined the generic trends in arrival times and discharge fluxes of the significant discharges. Observations of consequences without any mitigative effort indicated that:

- for individual sites in the fractured media classifications, the earliest time of contaminant arrival is at about 6 months for carbonates and 8 months for silicates;

- at 90 percent of the sites, contaminant arrival at a surface-water body would be greater than 5 years, allowing detailed monitoring, simulation, and planning to precede mitigative actions;

- the generic average of arrival times at a surface water body ranged from 5 years in fractured and solutioned carbonates to over 200 years for porous consolidated silicates;

- the greatest radionuclide flux entering a surface water body is 2.5 x 10^{17} pCi/yr produced by a sump water release of cesium-137 in a fractured and solutioned carbonate;

- peak flux rates of cesium-137 and strontium-90 in sump water discharges are similar (2 x 10^{16} pCi/yr) for contaminant arrival times of less than 30 years;

- silicic media have a peak contaminant discharge 100 times less than carbonate media because of the difference in leach rates; and

- although the core debris contains 10 times more strontium-90 than the sump water, the more rapid release of sump water produces a higher radionuclide flux to the environment.

When there are no trends in first arrival times or quantity of radiological outflow within a hydrogeologic classification, the site-specific hydraulic parameters and/or reactor siting (i.e., distance to surface water) are more important than generic classification. This situation occurs for porous consolidated carbonates and fractured shale. These sites are best evaluated for environmental sensitivity by observing the percentage of sites that produce a significant discharge (i.e., prior to 40 half-lives of decay).

PNL ANALYSIS OF MITIGATIVE TECHNIQUES FOR CONTAMINANT INTERDICTION

There are two general classes of ground-water contaminant interdictive techniques that may be used to mitigate the environmental effects of a severe nuclear accident: (1) static or passive techniques, and (2) dynamic or active strategies. The individual techniques or schemes that comprise each class are designed to interact directly with ground-water flow, and consequently the contaminant being transported, to achieve an acceptable level of contaminant retention. The following discussion is an edited summary taken from the PNL report section on mitigative techniques. Detailed information on the techniques presently available, and their capabilities for specific hydrogeologic conditions is provided in Chapter 4 of NUREG/CR-4251, Volume 1.

1. Static Barriers

Static or passive mitigative techniques are typically engineered and constructed barriers to contaminated ground-water flow. The primary objectives of a constructed barrier are to redirect the ground-water flow away from potentially accessible surface environments or to retard the flow, and allow radioactive decay to reduce the environmental hazard. Achievement of these objectives usually results in ground water being forced to follow more circuitous routes with longer travel times or at slower migration rates. Constructed barriers are considered static ground-water contaminant mitigations techniques because once in place they are not readily adaptable to changing conditions of ground-water contamination. Engineered/constructed barriers do not normally require a significant amount of maintenance or energy. Three basic types of constructed barriers were analyzed for their feasibility and suitability as mitigation measures for ground-water contamination resulting from a severe power plant accident: grout curtain cut-off walls, slurry trench cut-off walls, and steel sheet piling. (For more details see Chapter 4 of NUREG/CR-4251, Volume 1.)

2. Dynamic Barriers

Dynamic or active ground-water contaminant mitigation techniques are primarily conceptual strategies for actively influencing the state of ground-water contamination. Active influence is accomplished by either changing the ground-water flow regime by pumping and/or injection, directly treating the contaminated ground water or combinations of both approaches. Active ground-water contaminant mitigation schemes are generally better able to respond to changes in the state of ground-water contamination than static barriers. However, dynamic schemes typically have relatively
high maintenance costs. Also extensive monitoring feedback is usually recommended to ensure adequate performance. The dynamic ground-water contaminant mitigation schemes analyzed for their feasibility and applicability were:

a. Ground-water withdrawal schemes for potentiometric-surface adjustment, in order to prevent:

   (1) discharge to receiving surface-water body,
   (2) saturated conditions for the core-melt debris, and
   (3) contaminants moving through leaky aquifers*;

b. Ground-water withdrawal and/or injection schemes to control the contaminant plume by:

   (1) withdrawal and injection,
   (2) withdrawal without injection,
   (3) withdrawal with surface treatment and recharge, and
   (4) injection only;

c. Subsurface drains;

d. Selective filtration via permeable treatment beds;

e. Ground-water freezing; and

f. Air injection to form a permeability barrier.

3. Feasibility Criteria

The PNL study concluded that there are mitigative techniques presently available that are feasible for controlling ground-water transport. Their effectiveness, however, is very dependent upon the site characterization data, and

*Leaky aquifer is defined as any aquifer surrounded either above or below by aquitard(s) that can provide significant fluxes of water to the aquifer that it confines.

accident conditions (i.e., details necessary to select, design, construct, and implement the various mitigative techniques). Chapter 4 of the PNL report provides detailed discussions of the feasibility and costs for the mitigative methods.

There are several important considerations for determining the suitability of mitigative techniques for controlling contaminated ground water. These considerations can be categorized as: (a) design, (b) construction, (c) performance, and (d) implementation.

a. Design considerations include the variations in specific types of techniques (e.g., particulate versus non-particulate grout), appropriate host geologic media, size, location, and orientation of the various mitigation measures and design limitations. Passive ground-water barriers (i.e., slurry trenches, grout curtains, and steel sheet piling cutoffs) have better defined engineering design considerations than typically do dynamic ground-water contaminant mitigative strategies, which are less rigorously defined from an engineering standpoint.

b. Construction considerations are a major concern in determining the feasibility of specific mitigation strategies. Construction considerations include appropriate methods of installation, limitations of construction methods, equipment required for construction, etc. Several of the mitigation strategies (i.e., slurry trenches, subsurface grouts, and permeable treatment beds) require extensive excavation. Trenching is realistically feasible only in unconsolidated media and soft, easily ripped semi-consolidated media.

c. Performance considerations include permeability reductions, durability continuity, and contaminant compatibility. All of the performance considerations vary with time. For example, steel sheet piling can be expected to corrode in approximately 40 years, thus significantly reducing its effectiveness. Durability is closely related to permeability reduction and maintenance requirements. How long a barrier will perform as designed is a function of quality control during construction and ground-water chemistry. Cement-based constructed barriers will lose their integrity more rapidly if exposed to freeze and thaw cycles or high levels of sulfate. Most, if not all, dynamic mitigation strategies are temporary and energy extensive, and their design with respect to the overall mitigation plan should reflect this condition.

d. Implementation considerations are based upon the practical engineering feasibility of the technique (e.g., the construction and implacement difficulties). These considerations include:

   (1) installation and construction time,
   (2) cost,
   (3) equipment mobilization and availability,
   (4) toxicity (some chemical grouts are toxic), and
   (5) exposure hazards to workers.

Worker safety during the installation and maintenance of a mitigation scheme is of primary concern. In most cases the closer the mitigation scheme is to the core debris, the more effective it will be. A site-specific investigation of the radionuclide hazards from core debris, contaminated ground water, and surface contamination must be conducted prior to construction activities. Another safety issue involves the safe handling, treatment, and disposal of contaminated ground water. Several of the mitigative schemes require above ground handling of contaminated ground water thus requiring special care to ensure the safety of workers and the integrity of the surface environment.

PNL CHARACTERIZATION APPROACH AND SELECTION OF GROUND-WATER FLOW AND TRANSPORT MODELS

An important aspect of selecting and implementing an interdictive strategy is the modeling of the ground-water system in and around the nuclear power plant. The first step in modeling the site is the selection of an appropriate conceptual model. Conceptual model identification for purposes of simulating subsurface contaminant migration is actually a problem of developing a relevant systems model to represent the particular plant site and ground-water system. Model identification, however, is just one aspect of developing a systems model as outlined in the following conceptual modeling scheme:

1. Define site study objectives.
2. Collect and analyze site characterizing data.
3. Formulate the conceptual model.
4. Identify process descriptive equations.
5. Select the computer codes.
6. Couple/interface the selected codes.
7. Evaluate code performance
8. Run site-specific simulations.
9. Compare results with study objectives.

The above nine steps should form the basis of guidelines for model identification and evaluation. Code selection cannot be successfully accomplished without regard for the overall simulation model that will achieve the study objectives (step 1), and an active evaluation of code simulation capabilities (step 7) is necessary to ensure a proper selection. As shown in Figure 1, these steps are involved in the development of each component of a systems model for a specific site. A conceptual model based on the site characterization data and consistent with study objectives is the hub of a systems model. Other system model components are arranged as a wheel on that hub. Clockwise progress around the wheel, following the nine steps, is required to complete the systems model. During the development of a systems simulation model, the hub may require repeated modifications and revisions to produce a well-rounded and balanced wheel. The steps and their relationship to ground-water transport modeling are discussed in greater detail in Simmons and Cole (1985).

PNL CASE STUDIES

The scope of the case studies was limited to consideration of the necessity and feasibility of mitigative techniques to reduce the environmental consequences

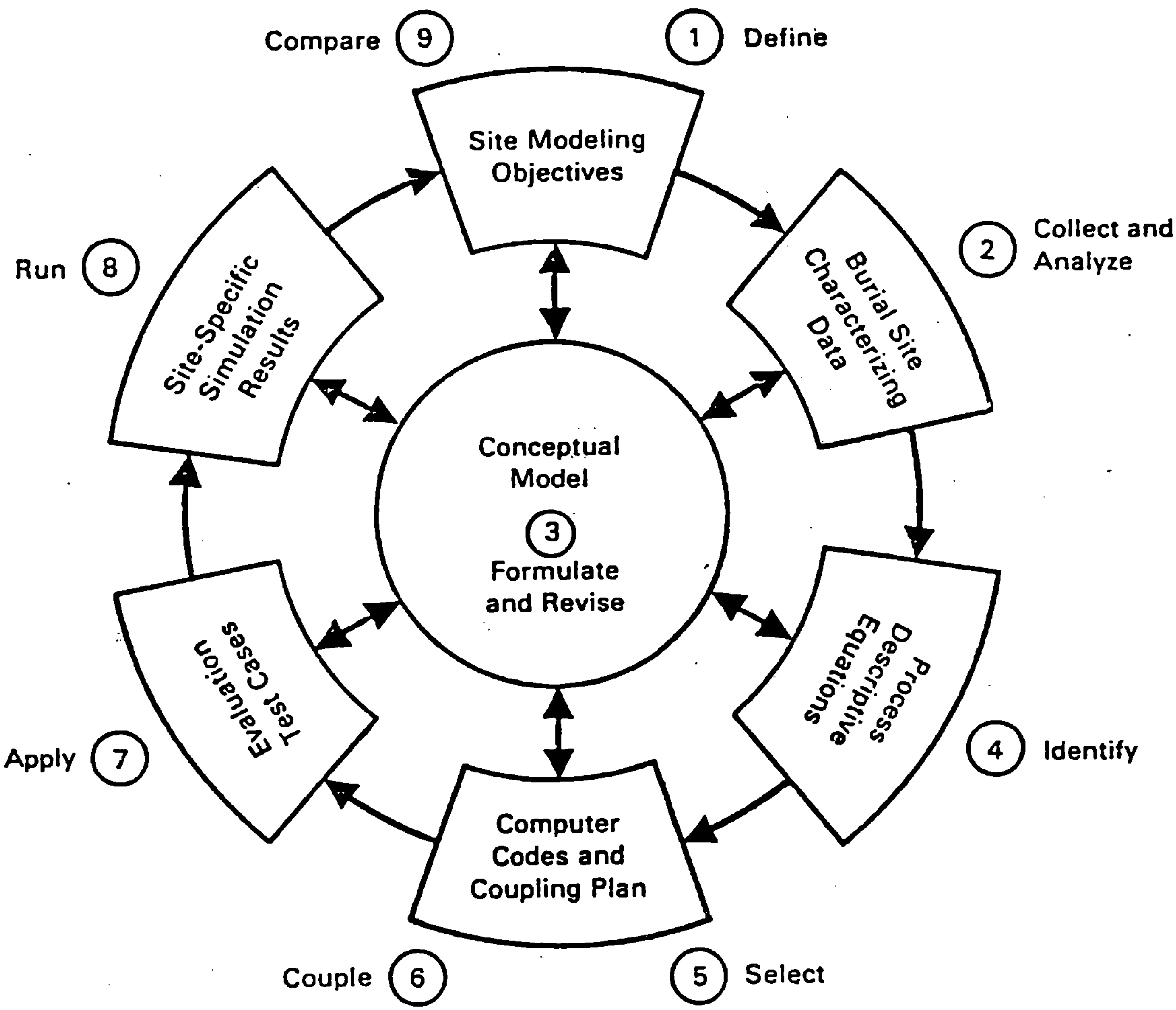

FIGURE 1. Systems Model Components. Arrows show direction for completing the systems model development steps (numbers).

along the ground-water pathway. Contaminated ground water could reach accessible environments through: (1) controlled discharge points (e.g., water supply wells), (2) uncontrolled discharge points such as springs, and (3) groundwater to surface-water flow interface at discharge locations. This study assumed that obvious available measures to protect the public, such as prohibiting the use of contaminated wells, will be taken. It also assumes that contaminants discharging through natural collection points such as springs will be collected, as necessary, and isolated from the environment. The study concentrated on actions taken to reduce radionuclide transport rates through the ground water toward surface-water bodies. Issues concerning atmospheric releases, site restoration and long-term, low-level radioactive discharges to surface water bodies were not a part of this study but are recommended for future research. Considerations for monitoring systems such as optimal placement, statistical confidence, and detailed mitigative designs were explicitly outside the statement of work as formulated by the U.S. Nuclear Regulatory Commission but would also be key elements in implementing an effective interdictive strategy. The specific case studies were the South Texas Plant site, and Marble Hill Plant site (See Table 2).

PNL STUDY CONCLUSIONS

The following discussion is taken from Chapter 9.0 "Lessons Learned and Suggestions for Future Research" of the PNL report (NUREG/CR-4251).

1. Most of the limited number of plant sites considered for case study analysis were not selected because there was insufficient hydrogeologic data to simulate ground-water flow with an acceptable degree of accuracy. Following a severe accident, the need to define the transport characteristics of the ground-water pathway would be vital to an evaluation of environmental consequences and the decision to implement mitigative techniques. Sites not sufficiently characterized before the accident would need further site characterization, possibly before a determination of mitigative alternatives and design basis could be made. Hydrogeologic testing and sampling may have to be conducted at these sites under hazardous post-accident conditions and severe time constraints. Data collection such as static water levels, hydraulic stress testing, and ground-water sample collection require quiescent initial conditions to achieve representative values.

2. The source term for core debris leaching is subject to large uncertainties. The phenomenology is one where very complex and somewhat ill-defined physical mechanisms function in a multivariable stochastic environment. The chemical and mechanical processes and interactions that control radionuclide leach rates in admixtures of glass and calcine materials are not precisely defined. These uncertainties are likely to remain a part of a core melt evaluation since the core debris will be an uncontrolled mixture of various materials (i.e., silica, calcite, steel, etc.) at each location. The thermal history of the accident may also be important because fracturing and granulation of the debris affects leach rates. The evaluation of the necessity and the design basis of a mitigative scheme could be overestimated by several orders of magnitude if a typically conservative analysis were conducted. Contaminant concentrations determined by in situ measurements

of the plume may be the only method to determine leach rates within an order of magnitude.

3. Sump water release rates for pressurized water reactors are also subject to large uncertainties and are strongly site and accident specific. Data gathered during the accident (i.e., containment pressure, standing water level, volume of water lost with time, and activity of remaining water) would provide the primary information on the release rate. Collection and interpretation of this information following an accident would be the first step in evaluation of the sump water source term. If such detailed information is unavailable, monitoring of the contaminant plume could provide the best information of the contaminant release.

4. The hydrologic unit contaminated by sump water releases at some sites would be a function of the accident processes. Accident specifics such as hydraulic driving head could determine where in the stratigraphic sequence the contaminant was placed. In these cases the contaminated unit and possibly the direction of travel would be difficult to determine prior to the accident. Mitigative actions would either be delayed for post-accident characterization or proceed under the initial assumption that all feasible units were contaminated. This would complicate mitigation efforts and possibly cause cross interference between various methods in separate hydrologic units.

5. The site- and accident-specific uncertainties discussed in topics 1, 3, and 4 above could be reduced through a program of site testing, monitoring, and evaluation. Site-specific uncertainties (e.g., direction and values of hydraulic gradient, effective porosities, hydraulic conductivities, etc.) could be reduced before an accident occurred. Accident-specific questions such as which units are contaminated and what is the release rate of radionuclides must be answered through a post-accident review of: severe accident records, sampling, and monitoring. Monitoring data collection and integration into the design of mitigative schemes would be an important element of any post-accident study, as illustrated in Section 1.5 of this report. The topic of monitoring schemes and incorporation of post-accident data into mitigative designs is explicitly outside the statement of work for this study.

6. While any severe accident would represent a potential health hazard, immediate contaminant interdiction is conservatively estimated to be unnecessary at most of the sites. The generic analysis based on an equivalent porous media approach indicates that fractured sites may be twice as likely as non-fractured sites to need implementation of a mitigative scheme. The fractured media case study demonstrates that the assumption that a fractured site responds similar to porous media can overestimate the predicted radionuclide discharges.

7. Based on limited site-specific data of all sites, sufficient time exists for mitigative techniques to be implemented at plant locations before radionuclides reach the accessible environment via the ground water pathway. However, the minimum first arrival times of contaminant at surface water bodies are estimated to be on the order of months in which case site-specific factors not addressed at those locations may be of

prime importance. Both passive (i.e., grout curtain) and active (i.e., hydraulic injection) can be used either singularly or combined into composite systems to reduce contaminant migration rates.

8. Contaminant interdictive techniques and hydrogeologic characterization methods are sufficiently developed to select and design an effective barrier to imminent environmental consequences caused by ground-water contamination resulting from a core melt accident. The generic site characterization provides a screening tool for this process. Design of mitigative schemes can only be made after consideration of site-specific factors including (1) source term, (2) ground-water flow directions and rates, (3) location of recharge and discharge areas, (4) material properties of contaminated unit(s), and (5) plant configuration.

9. The design basis of a mitigative scheme would fall into one of four classifications:

   - mitigation at the greatest level achievable given the site- and accident-specific constraints,
   - mitigation to reduce the environmental consequences of surface and ground water contact to an acceptable risk level,
   - interim mitigation to isolate the contaminant from further transport pending further analysis and evaluation or,
   - interdiction to provide long-term isolation in a portion of the ground-water system.

   The decision as to which of these options to follow would be based on site-specific considerations and include governmental, scientific and public input. Mitigative measures are not the final response to a core melt accident, but rather are part of an iterative process involving characterization, monitoring, numerical simulation, evaluation, and decision making. The level of effort and specific types of information required for this process are difficult, if not impossible, to delineate a priori. Each site and each accident would be unique, requiring a characterization and mitigative plan specifically tailored to that event. Ideally, the maximum amount of information that is feasible to collect or statistically required would be used to evaluate a core melt accident.

10. The PNL study was predominantly concerned with mitigative actions to prevent imminent environmental consequences of surface-water and ground-water contact. However, applying mitigative techniques to limit exposure risk at a surface water body may result in a long-term and/or short-term exposure risk elsewhere. By design, these risks are significantly less than not mitigating contaminant transport at the site. Mitigative strategies that contain contaminants (i.e., concentrate radionuclides in space) limit the area of contamination. Unless the interdictive scheme has an element of contaminant collection, this action elevates ground-water

concentrations inside the mitigative barriers. Inadvertent contact with this fluid could be hazardous for a long time period. In the case of core debris, radionuclides would be leach released for hundreds of years at levels that are predicted to produce ground-water concentrations at the plant site above present 10 CFR Part 20 limits.

Mitigative strategies that use contaminant collection systems would require some exposure to workers. These exposures could be tightly controlled to limit the risk to any single individual. No mitigative system presently available can indefinitely isolate the contaminant without periodic maintenance and refurbishing. Failure of a passive barrier or dewatering system would remobilize radionuclides and possibly create an exposure risk at a later time. Continued and vigilant monitoring and reevaluation of the site would be required to prevent hazardous contaminant breakouts. Each subsequent mitigative effort would use additional construction space between the contaminant source and the surface or ground-water body the mitigation is protecting. For long-term isolation of the contaminant, the site and the highly contaminated portion of the travel path must either remain under institutional control or the contaminant must be removed and placed in a disposal facility.

11. The methodologies demonstrated in this study to characterize ground-water flow systems and the selection and design of near-surface interdictive schemes are generally applicable to other near-surface sites where disposal of low-level nuclear waste and non-nuclear contaminants has taken place.

PNL SUGGESTIONS FOR FURTHER RESEARCH

The following discussion is taken from Chapter 9 of the PNL Report (NUREG/CR-4251).

1. Hydrologic data bases for all operating power plants should be suitable to establish, as possible, the contaminant flow pathways; this would include the hydraulic characterization of sites to sufficient detail that preliminary simulations of contaminant migration and mitigation are feasible without additional data collection.

   Research topics for further consideration include: establishment of hydrogeologic data requirements to provide initial selection of a mitigative technique(s) and preliminary construction designs as demonstrated by this report, and a review of all operational power plant sites for identification of locations that lack an adequate data base as defined above and have characteristics that would require a quick mitigative response to a severe accident. Selected plants would undergo further hydrogeologic data gathering and/or interpretation.

2. Very large uncertainties remain in the core-melt-debris leach release functions. A better descriptor for this process will greatly improve the understanding of which radionuclides and at what quantities the mitigative system would be expected to control. Without an accurate source term, the only method to determine the magnitude of contaminant concentrations is

through direct sampling of the plume. Additional information on contaminant source terms should be gathered through experimentation and incorporation of data currently being collected for low-level radionuclide leaching experiments at Savannah River Laboratory, under saturated conditions, and Pacific Northwest Laboratory, under partially saturated conditions. This new information should be examined and applied where relevant to leach rate estimation techniques for core melt debris.

Research topics for consideration include: short- and long-term leach rates and processes, effect of mixed debris composed of silicic and calcine materials, possible differences in leach rates of simulated core materials and manmade isolation materials (i.e., grout and glass).

3. A review of site restoration issues, processes, and feasibility should be conducted. The techniques to remove core debris and reclamation of sump water contaminants should be identified or developed to the conceptual stage. Research topics for consideration include: feasibility of core debris recovery, methodology of debris collection, identification of technology that would result in total in situ isolation of radionuclides, ultimate disposal of core debris removed from the site, worker safety, and cost effectiveness.

LICENSING IMPLICATIONS

1. At the present time, there are no ground-water flow and transport models that can simulate the severe thermal and chemical conditions in the vicinity of a postulated core-melt, nor have realistic source terms and initial conditions for the local hydrogeologic flow system been available as input to models. Therefore, very conservative models must be utilized using "best guess" estimates for both the site conditions and source terms which may not be appropriate for selecting engineered interdictive options.

2. NRR may find it valuable to review the present site data available for use in contaminant transport analysis using the research findings in Table 3 of this RIL. Sites which appear to be particularly sensitive to contaminant transport offsite via ground water such as fractured media and solutioned carbonate sites should be reviewed first. After reviewing the available site specific data, NRR may want to encourage the licensee to develop a data base for use in post-accident analyses dealing with the potential for ground-water transport offsite.

3. NRR may decide, after reviewing this RIL, to review and possibly expand the existing regulatory guidance such as ES Section 7.1.1 (which provides specific guidance to the NRC staff for assessing the ground-water pathway consequences from postulated reactor core-melt accidents) of the Environmental Standard Review Plan (NUREG-1165). This additional information should include the specific technical findings discussed in NUREG/CR-4251 on analyses of various interdictive measures for accident and site specific conditions. For instance, the question of whether there is a sufficient data base to

select and evaluate the mitigative techniques, and to assess ground-water and surface-water contamination due to both possible ground-water releases and atmospheric deposition should be reviewed as part of this exercise.

4. Results from the previous ground-water interdictive studies at Argonne National Laboratory (See References 4 and 5), Pacific Northwest Laboratory (NUREG/CR-4251), and in-house NRC staff pathway analyses (See References 2, 6, 7, and 12) indicate that although the generic average of arrival travel times at a surface-water body ranged from 5 years in fractured and solutioned carbonates, to over 200 years for porous consolidated media, for certain site conditions, the minimum ground-water travel times to the accessible environment can be on the order of months. Therefore, NRR may wish to review existing ground-water monitoring programs at the reactor sites to determine if there are adequate baseline data bases for both hydrogeologic site information, and real-time flow and transport data following an accident. Such information could assist the licensees in their selection and initiation of an appropriate interdictive strategy, so that neither overreaction which might cause unnecessary worker exposure, nor underreaction, which might increase releases, would occur.

5. NRR may wish to advise the licensees on the advantage of having flow and transport codes in a ready status to facilitate selection of an interdictive strategy, and to evaluate the effectiveness of mitigative techniques. NRR should consult with RES staff on the use of these codes or other similar ground-water flow and transport codes for both input data needs and applicability to reactor site conditions for severe accident analyses. RES staff presently maintain ground-water flow codes such as USGS-3D, and FEMWATER for saturated and unsaturated media respectively, and transport codes such as SWIFT II and FEMWASTE as part of their waste management research program.

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