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U.S. NUCLEAR REGULATORY COMMISSION

STANDARD REVIEW PLAN

OFFICE OF NUCLEAR REACTOR REGULATION

Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants

Section No. 6.5.2
Revision No. 2

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U.S. NUCLEAR REGULATORY COMMISSION

STANDARD REVIEW PLAN

OFFICE OF NUCLEAR REACTOR REGULATION

6.5.2 CONTAINMENT SPRAY AS A FISSION PRODUCT CLEANUP SYSTEM

REVIEW RESPONSIBILITIES

Primary - Chemical Engineering Branch

Secondary - Plant Systems Branch
Radiation Protection Branch

I. AREAS OF REVIEW

The containment spray and the spray additive or pH control systems are reviewed to determine the fission product removal effectiveness whenever the applicant claims a containment atmosphere fission product cleanup function for the systems. The following areas of the applicant's safety analysis report (SAR) relating to the fission product removal and control function of the containment spray system are reviewed.

1. Fission Product Removal Requirement for Containment Spray

   Sections of the SAR related to accident analyses, dose calculations, and fission product removal and control are reviewed to establish whether or not fission product scrubbing of the containment atmosphere for the mitigation of radiological consequences following a postulated accident is claimed by the applicant. This review usually covers sections in SAR Chapters 6 and 15.

2. Design Bases

   The design bases for the fission product removal function of the containment spray system are reviewed to verify that they are consistent with the assumptions made in the accident evaluations of SAR Chapter 15.

USNRC STANDARD REVIEW PLAN

Standard review plans are prepared for the guidance of the Office of Nuclear Reactor Regulation staff responsible for the review of applications to construct and operate nuclear power plants. These documents are made available to the public as part of the Commission's policy to inform the nuclear industry and the general public of regulatory procedures and policies. Standard review plans are not substitutes for regulatory guides or the Commission's regulations and compliance with them is not required. The standard review plan sections are keyed to the Standard Format and Content of Safety Analysis Reports for Nuclear Power Plants. Not all sections of the Standard Format have a corresponding review plan.

Published standard review plans will be revised periodically, as appropriate, to accommodate comments and to reflect new information and experience.

Comments and suggestions for improvement will be considered and should be sent to the U.S. Nuclear Regulatory Commission, Office of Nuclear Reactor Regulation, Washington, D.C. 20555.

3. System Design

The information on the design of the spray system, including any subsystems and supporting systems, is reviewed to familiarize the reviewer with the design and operation of the system. The information includes:

a. The description of the basic.design concept; the systems, subsystems, and support systems required to carry out the fission product scrubbing function of the system; and the components and instrumentation employed in these systems.

b. The process and instrumentation diagrams.

c. Layout drawings (plans, elevations, isometrics) of the spray distribution headers.

d. Plan views and elevations of the containment building layout.

4. Testing and Inspections

The system description is reviewed to establish the details of the preoperational test to be performed for system verification and the postoperational tests and inspections to be performed for verification of the continued status of readiness of the spray system.

5. Technical Specifications

At the operating license stage, the applicant's proposed technical specifications are reviewed to establish permissible outage times and surveillance requirements.

In addition, the reviewer will coordinate other evaluations that interface with the review of the containment spray system as follows: any chemical additive storage requirements, materials compatibility of the long-term containment sump and recirculation spray solutions, and organic material decomposition including formation of organic iodides as part of SRP Sections 6.1.1 and 6.1.2, the heat removal and hydrogen mixing function of the containment spray system and the containment sump design as part of SRP Sections 6.2.2 and 6.2.5. The acceptance criteria for the review and the methods of application are contained in the referenced SRP sections.

II. ACCEPTANCE CRITERIA

The acceptance criteria for the fission product cleanup function of the containment spray system are based on meeting the relevant requirements of the following regulations:

A. General Design Criterion 41 (Ref. 1) as it relates to containment atmosphere cleanup systems being designed to control fission product releases to the reactor containment following postulated accidents.

B. General Design Criterion 42 (Ref. 2) as it relates to containment atmosphere cleanup systems being designed to permit appropriate periodic inspections.

C. General Design Criterion 43 (Ref. 3) as it relates to containment atmosphere cleanup systems being designed for appropriate periodic functional testing.

Specific criteria necessary to meet the relevant requirements of General Design Criteria 41, 42, and 43 include:

1. Design Requirements for Fission Product Removal

The containment spray system should be designed in accordance with the requirements of Reference 4, except that requirements for any spray additive or other pH control system in this reference need not be followed.

a. System Operation

The containment spray system should be designed to be initiated automatically by an appropriate accident signal and to be transferred automatically from the injection mode to the recirculation mode to ensure continuous operation until the design objectives of the system have been achieved. In all cases, the operating period should not be less than two hours. Additives to the spray solution may be initiated manually or automatically, or may be stored in the containment sump to be dissolved during the spray injection period.

b. Coverage of Containment Building Volume

In order to ensure full spray coverage of the containment building volume, the following should be observed:

(1) The spray nozzles should be located as high in the containment building as practicable to maximize the spray drop fall distance.

(2) The layout of the spray nozzles and distribution headers should be such that the cross-sectional area of the containment building covered by the spray is as large as practicable and that a nearly homogeneous distribution of spray in the containment building space is produced. Unsprayed regions in the upper containment building and, in particular, an unsprayed annulus adjacent to the containment building liner should be avoided wherever possible.

(3) In designing the layout of the spray nozzle positions and orientations, the effect of the post-accident atmosphere should be considered, including the effects of post-accident conditions that result in the maximum possible density of the containment atmosphere.

c. Promotion of Containment Building Atmosphere Mixing

Because the effectiveness of the containment spray system depends on a well-mixed containment atmosphere, all design features enhancing post-accident mixing should be considered.

d. Spray Nozzles

The nozzles used in the containment spray system should be of a design that minimizes the possibility of clogging while producing drop sizes effective for iodine absorption. The nozzles should not have internal moving parts such as swirl vanes, turbulence promoters, etc. They should not have orifices or internal restrictions which would narrow the flow passage to less than one quarter of an inch in diameter.

e. Spray Solution

The partition of iodine between liquid and gas phases is enhanced by the alkalinity of the solution. The spray system should be designed so that the spray solution is within material compatibility constraints. Iodine scrubbing credit is given for spray solutions whose chemistry, including any additives, has been demonstrated to be effective for iodine absorption and retention under post-accident conditions.

f. Containment Sump Solution Mixing

The containment sump should be designed to permit mixing of emergency core cooling system (ECCS) and spray solutions. Drains to the engineered safety features sump should be provided for all regions of the containment which would collect a significant quantity of the spray solution. Alternatively, allowance should be made for "dead" volumes in the determination of the pH of the sump solution and the quantities of additives injected.

g. Containment Sump and Recirculation Spray Solutions

The pH of the aqueous solution collected in the containment sump after completion of injection of containment spray and ECCS water, and all additives for reactivity control, fission product removal, or other purposes, should be maintained at a level sufficiently high to provide assurance that significant long-term iodine re-evolution does not occur. Long-term iodine retention is calculated on the basis of the expected long-term partition coefficient. Long-term iodine retention may be assumed only when the equilibrium sump solution pH, after mixing and dilution with the primary coolant and ECCS injection, is above 7 (Ref. 5). This pH value should be achieved by the onset of the spray recirculation mode.

h. Storage of Additives

The design should provide facilities for the long-term storage of any spray additives. These facilities should be designed so that the additives required to achieve the design objectives of the system are stored in a state of continual readiness whenever the reactor is critical for the design life of the plant. The storage facilities should be designed to prevent freezing, precipitation, chemical reaction, and decomposition of the additives. For sodium hydroxide storage tanks, heat tracing of tanks and piping is required whenever exposure to

temperatures below 40°F is predicted. An inert cover gas should be provided for solutions that may deteriorate as a consequence of exposure to air.

i. Single Failure

The system should be able to function effectively and meet all the criteria in subsection II with a single failure of an active component in the spray system, in any of its subsystems, or in any of its support systems.

2. Testing

Tests should be performed to demonstrate that the containment spray system, as installed, meets all design requirements for an effective fission product scrubbing function. Such tests should include preoperational verification of:

a. freedom of the containment spray piping and nozzles from obstructions,

b. capability of the system to deliver the required spray flow, and

c. capability of the system to deliver spray additives (if any are needed) and to achieve the sump solution pH specified in the SAR. For a system whose performance is sensitive to the as-built piping layout, such as a gravity feed system, the testing should be performed at full flow.

3. Technical Specifications

The technical specifications should specify appropriate limiting conditions for operation, tests, and inspections to provide assurance that the system is capable of performing its design function whenever the reactor is critical. These specifications should include:

a. The operability requirements for the system, including all active and passive devices, as a limiting condition for operation (with acceptable outage times). The following items should be specifically included: containment spray pumps, additive pumps (if any), additive mixing devices (if any), valves and nozzles, additive quantity and concentration in additive storage tanks, and nitrogen (or other inert gas) pressure in additive storage tanks.

b. Periodic inspection and sampling of the contents of additive storage tanks to confirm that the additive quantity and concentrations are within the limits established by the system design.

c. Periodic testing and exercising of the active components of the system and verification that essential piping and passive devices are free of obstructions.

Acceptable methods for computing fission product removal rates by the spray system are given in subsection III.4.c, "Fission Product Cleanup Models."

While granting credit for containment spray removal of fission products in the calculations of accident doses, the acceptance criteria of containment leakage in SRP Section 6.2.1.1.A and the acceptance criteria of the engineered safety feature atmosphere cleanup systems in SRP Section 6.5.1 should still be met.

III. REVIEW PROCEDURES

The reviewer selects and emphasizes aspects covered by this SRP section as appropriate for a particular plant. The judgment of which areas need to be given attention and emphasis in the review is based on a determination of whether the material presented is similar to that recently reviewed on other plants and whether items of special safety significance are involved.

The reviewer determines whether the containment spray system is used for fission product removal purposes. SAR Chapter 15 should be reviewed to establish whether a fission product removal function for the containment spray system is assumed in accident dose evaluations. If the containment spray system is not used for mitigating radiological consequences, no further review is required under this SRP section. If the containment spray system is used for mitigation of radiological doses, then the review of the fission product removal function of the containment spray system follows the procedure outlined below.

1. System Design

Review of the system design includes an examination of the components and design features necessary to carry out the fission product scrubbing function, including:

a. Spray Solution Chemistry

The forms of iodine for which spray removal credit is claimed in the accident analyses (SAR Chapter 15) are established. Containment spray systems may be designed for removal of iodine in the elemental form, in the form of organic compounds, and in the particulate form. Spray removal credit for other particulate fission products is also established.

The systems or subsystems required to carry out the fission product scrubbing function of the containment spray are identified, such as the spray system, recirculation system, spray additive system, and water source. The design of the systems involved is reviewed in order to:

(1) Ascertain the effectiveness of any chemical additive for iodine removal and retention.

(2) Ascertain that the amount of additive is sufficient to meet the acceptance criteria of subsection II or that adequate justification is supplied for the iodine removal and retention effectiveness for the range of concentrations encountered. The concentrations in the storage facility, the chemical addition lines, the spray solution injection, the containment sump solution, and the recirculation spray solution should be examined. The extremes

of the additive concentrations should be determined with the most adverse combination of ECCS, spray, and additive pumps (if any) assumed to be operating, and considering a single failure of active components in the systems or subsystems.

The reviewer verifies that the stability of the containment spray and sump solutions and the corrosion, solidification, and precipitation behavior of the chemical additives have appropriately been taken into consideration for the range of concentrations encountered.

b. System Operation

The time and method of system initiation, including chemical addition, is reviewed to confirm that the acceptance criteria of subsection II are met. Automatic initiation of spray is reviewed under SRP Section 6.2.2. The system operation should be continuous until the fission product removal objectives of the system are met. The reviewer should confirm that all requirements listed in the acceptance criteria, particularly those concerning spray coverage and sump solution pH, are met during the recirculation phase. Switchover from the injection mode to the recirculation mode following initiation to the spray system operation must be automatic to prevent damage to the spray pumps through loss of suction.

c. Spray Distribution and Containment Mixing

The number and layout of the spray headers used to distribute the spray flow in the containment space are reviewed. The reviewer verifies that the layout of the headers ensures coverage of essentially the entire horizontal cross-section of the containment building with spray, under minimum spray flow conditions. The effect of the post-accident high temperature and pressure conditions in the containment atmosphere on the spray droplet trajectories should be taken into account in determining the area covered by the spray.

The layout of the containment building is reviewed to determine if any areas of the containment free space are not sprayed. The mixing rate attributed to natural convection between the sprayed and unsprayed regions of the containment building, provided that adequate flow exists between these regions, is assumed to be two turnovers of the unsprayed region(s) per hour, unless other rates are justified by the applicant. The containment building atmosphere may be considered a single, well-mixed space if the spray covers regions comprising at least 90% of the containment building space and if a ventilation system is available for adequate mixing of any unsprayed compartments.

d. Spray Nozzles

The design of the spray nozzles is reviewed to confirm that the spray nozzles are not subject to clogging from debris entering the recirculation system through the containment sump screens.

e. Containment Sump Mixing

The mixing of the spray water containing any chemical additive and water without additive (such as spilling ECCS coolant) in the containment sump is reviewed. The areas of the containment building that are exposed to the spray but are without direct drains to the recirculation sump (such as the refueling cavity) are considered. The reviewer confirms that the required sump solution concentrations are achieved within the appropriate time intervals. The pH of the sump solution should be reviewed in regard to iodine re-evolution, using the criteria given in subsection II.1.g and the procedure in subsection III.4.c.(2).

f. Storage of Additives

The design of any additive storage tank is reviewed to establish whether heat tracing is required to prevent freezing or precipitation in the tank. The reviewer determines whether an inert cover gas is provided for the tank to prevent reactions of the additive with air, such as the formation of sodium carbonate by the reaction of sodium hydroxide and carbon dioxide. Alternatively, the reviewer verifies by a conservative analysis that an inert cover gas is not required.

g. Single Failure

The system schematics are reviewed by inspection, postulating single failures of any active component in the system, including inadvertent operation of valves that are not locked open. The review is performed with respect to the fission product removal function, considering conditions that could result in fast as well as slow injection of the spray solution.

2. Testing

At the construction permit stage, the containment spray concept and the proposed tests of the system are reviewed to confirm the feasibility of verifying the design functions by appropriate testing. At the operating license stage, the proposed tests of the system and its components are reviewed to verify that the tests will demonstrate that the system, as installed, is capable of performing, within the bounds established in the description and evaluation of the system, all functions essential for effective fission product removal following postulated accidents.

3. Technical Specifications

The technical specifications are reviewed to verify that the system, as designed, is capable of meeting the design requirements and that it remains in a state of readiness whenever the reactor is critical.

a. Limiting Conditions for Operation

The limiting conditions for operation should require the operability of the containment spray pumps, all associated valves and piping, the

appropriate quantity of additives, and any metering pumps or mixing devices.

b. Tests

Preoperational testing of the system, including the additive storage tanks, pumps (if any), piping, and valves, is required. In particular, the preoperational testing should verify that the system, as installed, is capable of delivering a well-mixed solution containing all additives with concentrations falling within the design margins assumed in the dose analyses of SAR Chapter 15.

Periodic testing and exercising of all active components should include the spray pumps, metering pumps (if any), and valves. Confirmation should be made periodically that passive components, such as all essential spray and spray additive piping, and any passive mixing devices are free of obstructions. The contents of the spray additive storage tanks should be sampled and analyzed periodically to verify that the concentrations are within the established limits, that no concentration gradients exist, and that no precipitates have formed.

4. Evaluation

The fission product removal effectiveness of the system is calculated to establish the degree of dose mitigation by the containment spray system following the postulated accident. The mathematical model used for this calculation should reflect the preceding steps of the review. The analysis and assumptions are as follows:

a. The amounts of fission products assumed to be released to the containment space are obtained from Regulatory Guide 1.3 (Ref. 6) or Regulatory Guide 1.4 (Ref. 7), as appropriate. The amounts of fission product airborne inside the containment building depend upon plate-out on interior surfaces, removal by the spray and action of other engineered safety features present, radioactive decay, and outleakage from the containment building.

b. The removal of fission products from the containment atmosphere by the spray is considered a first-order removal process. The removal coefficient λ (lambda) for each of the sprayed regions of the containment is computed. Removal coefficients representing time-dependent wall plate-out are also calculated. The coefficients for spray removal and wall plate-out are summed. The removal lambdas are input parameters of a computer model for dose calculation.

c. Fission Product Cleanup Models

The reviewer estimates the area of the interior surfaces of the containment building which could be washed by the spray system, the volume flow rate of the system (assuming single failure), the average drop fall height and the mass-mean diameter of the spray drops,

from inspection of the information in the SAR. The effectiveness of a containment spray system may be estimated by considering the chemical and physical processes that could occur during an accident in which the system operates. Models containing such considerations are reviewed on case-by-case bases. In the absence of detailed models, the following simplifications may be used:

Experimental results (Refs. 8, 9, and 11) and computer simulations of the chemical kinetics involved (Ref. 10) show that an important factor determining the effectiveness of sprays against elemental iodine vapor is the concentration of iodine in the spray solution. Experiments with fresh sprays having no dissolved iodine were observed to be quite effective in the scrubbing of elemental iodine even at a pH as low as 5 (Refs. 9 and 11). However, solutions having dissolved iodine, such as the sump solutions that recirculate after an accident, may revolatilize iodine if the solutions are acidic (Refs. 5 and 10). Chemical additives in the spray solution have no significant effect upon aerosol particle removal because this removal process is largely mechanical in nature.

(1) Elemental iodine removal during spraying of fresh solution

During injection, the removal of elemental iodine by wall deposition may be estimated by

$$\lambda_w = K_w \, A/V$$

Here, λ_w is the first-order removal coefficient by wall deposition, A is the wetted surface area, V is the containment building net free volume, and K_w is a mass-transfer coefficient. All available experimental data are conservatively enveloped if K_w is taken to be 4.9 meters per hour (Ref. 13, page 17).

During injection, the effectiveness of the spray against elemental iodine vapor is chiefly determined by the rate at which fresh solution surface area is introduced into the containment building atmosphere. The rate of solution surface created per unit gas volume in the containment atmosphere may be estimated as (6F/VD), where F is the volume flow rate of the spray pump, V is the containment building net free volume, and D is the mass-mean diameter of the spray drops. The first-order removal coefficient by spray, λ_s, may be taken to be

$$\lambda_s = \frac{6K_g \, TF}{VD}$$

where k_g is the gas-phase mass-transfer coefficient, and T is the time of fall of the drops, which may be estimated by the ratio of the average fall height to the terminal velocity of the mass-mean drop (Ref. 14). The above expression represents a first-order approximation if a well-mixed droplet model is used for the spray efficiency. The expression is valid for λ_s

values equal to or greater than ten per hour. λ_s is to be limited to 20 per hour to prevent extrapolation beyond the existing data for boric acid solutions with a pH of 5 (Refs. 8 and 11). For λ_s values less than ten per hour, analyses using a more sophisticated expression are recommended.

(2) Elemental iodine removal during recirculation of sump solution

The sump solution at the end of injection is assumed to contain fission products washed from the reactor core as well as those removed from the containment atmosphere. The radiation absorbed by the sump solution, if the solution is acidic, would generate hydrogen peroxide (Ref. 12) in sufficient amount to react with both iodide and iodate ions and raise the possibility of elemental iodine re-evolution (Ref. 5). For sump solutions having pH values less than 7, molecular iodine vapor should be conservatively assumed to evolve into the containment atmosphere (Ref. 15).

Information on the partition coefficients for molecular iodine can be found in References 15, 16, and 17. The equilibrium partitioning of iodine between the sump liquid and the containment atmosphere is examined for the extreme additive concentrations determined in Section III.1.a.(2), in combination with the range of temperatures possible in the containment atmosphere and the sump solution. The reviewer should consider all known sources and sinks of acids and bases (e.g., alkaline earth and alkali metal oxides, nitric acid generated by radiolysis of nitrogen and water, alkaline salts or lye additives) in a post-accident containment environment. The minimum iodine partition coefficient determined for these conditions forms the basis of the ultimate iodine decontamination factor in the staff's analysis described in subsection III.4.d.

(3) Organic iodides

It is conservative to assume that organic iodides are not removed by either spray or wall deposition. Radiolytic destruction of iodomethane may be modelled, but such a model must also consider radiolytic production (Ref. 18). Engineered safety features designed to remove organic iodides are reviewed on a case-by-case basis.

(4) Particulates

The first-order removal coefficient, λ_p, for particulates may be estimated by

$$\lambda_p = \frac{3hFE}{2VD}$$

where h is the fall height of the spray drops, V is the containment building net free volume, F is the spray flow, and (E/D) is the ratio of a dimensionless collection efficiency E to the

average spray drop diameter D. Since the removal of particulate material depends markedly upon the relative sizes of the particles and the spray drops, it is convenient to combine parameters that cannot be known (Ref. 13). It is conservative to assume (E/D) to be 10 per meter initially (i.e., 1% efficiency for spray drops of one millimeter in diameter), changing abruptly to one per meter after the aerosol mass has been depleted by a factor of 50 (i.e., 98% of the suspended mass is ten times more readily removed than the remaining 2%).

d. The iodine decontamination factor, DF, is defined as the maximum iodine concentration in the containment atmosphere divided by the concentration of iodine in the containment atmosphere at some time after decontamination. DF for the containment atmosphere achieved by the containment spray system is determined from the following equation (Ref. 4):

$$DF = 1 + \frac{V_s H}{V_c}$$

where H is the effective iodine partition coefficient, V_s is the volume of liquid in containment sump and sump overflow, and V_c is the containment building net free volume less V_s.

The maximum decontamination factor is 200 for elemental iodine. The effectiveness of the spray in removing elemental iodine shall be presumed to end at that time, post-LOCA, when the maximum elemental iodine DF is reached. Because the removal mechanisms for organic iodides and particulate iodines are significantly different from and slower than that for elemental iodine, there is no need to limit the DF for organic iodides and particulate iodines.

IV. EVALUATION FINDINGS

The reviewer verifies that sufficient information has been provided by the applicant and that the review and calculations support conclusions of the following type, to be included in the staff's safety evaluation report:

The concept upon which the proposed system is based has been demonstrated to be effective for fission product removal and retention under post-accident conditions. The proposed system design is an acceptable application of this concept. The system provides suitable redundancy in components and features so that its safety function can be accomplished assuming a single failure.

The proposed preoperational tests, postoperational testing and surveillance, and proposed limiting conditions for operation of the spray system provide adequate assurance that the fission product scrubbing function of the containment spray system will meet or exceed the effectiveness assumed in the accident evaluation.

The staff concludes that the containment spray system as a fission product cleanup system is acceptable and meets the requirements of General Design Criterion 41 with respect to the iodine removal function following a postulated loss-of-coolant accident, General Design Criterion 42 with respect to the capability for periodic inspection of the system, and General Design Criterion 43 with respect to the capability for periodic testing of the system.

V. IMPLEMENTATION

The following guidance is provided to applicants and licensees about the staff's plans for using this SRP section.

Except in those cases in which the applicant proposes an acceptable alternative method for complying with specified portions of the Commission's regulations, the method described herein will be used by the staff in its evaluation of conformance with Commission regulations.

Implementation of the acceptance criteria in subsection II and the review procedures in subsection III is as follows:

1. Operating plants and applicants for operating licenses pending at the date of issue of this revision need not comply with the provisions of this revision, but may do so voluntarily.

2. Future applicants will be reviewed according to the provisions of this revision.

VI. REFERENCES

1. 10 CFR Part 50, Appendix A, General Design Criterion 41, "Containment Atmosphere Cleanup."

2. 10 CFR Part 50, Appendix A, General Design Criterion 42, "Inspection of Containment Atmosphere Cleanup Systems."

3. 10 CFR Part 50, Appendix A, General Design Criterion 43, "Testing of Containment Atmosphere Cleanup Systems."

4. ANSI/ANS 56.5-1979, "PWR and BWR Containment Spray System Design Criteria," American National Standards Institute, Inc.

5. C. C. Lin, "Chemical Effects of Gamma Radiation on Iodine in Aqueous Solutions," Journal of Inorganic and Nuclear Chemistry, 42, pages 1101-1107 (1980).

6. U.S. Nuclear Regulatory Commission, Regulatory Guide 1.3, "Assumptions Used for Evaluating the Potential Radiological Consequences of a Loss-of-Coolant Accident for Boiling Water Reactors."

7. U.S. Nuclear Regulatory Commission, Regulatory Guide 1.4, "Assumptions Used for Evaluating the Potential Radiological Consequences of a Loss-of-Coolant Accident for Pressurized Water Reactors."

8. R. K. Hilliard, A. K. Postma, J. D. McCormack, L. F. Coleman, and C. E. Lunderman, "Removal of Iodine and Particles From Containment Atmospheres - Containment Systems Experiments", Pacific Northwest Laboratories Report, BNWL-1244, February 1970.

9. S. Barsali, F. Bosalini, F. Fineschi, B. Guerrini, S. Lanza, M. Mazzini, and R. Mirandola, "Removal of Iodine by Sprays in the PSICO 10 Model Containment Vessel", Nuclear Technology, 23, pages 146-156 (August 1974).

10. M. F. Albert, "The Absorption of Gaseous Iodine by Water Droplets", U.S. Nuclear Regulatory Commission Report, NUREG/CR-4081, July 1985.

11. A. K. Postma, L. F. Coleman, and R. K. Hilliard, "Iodine Removal from Containment Atmospheres by Boric Acid Spray", Pacific Northwest Laboratories Report, BNP-100, July 1970.

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14. G. B. Wallis, "The Terminal Speed of Single Drops or Bubbles in an Infinite Medium," International Journal of Multiphase Flow, 1, pages 491-511 (1974).

15. E. C. Beahm, W. E. Shockley, C. F. Weber, S. J. Wisbey, and Y-M. Wang, "Chemistry and Transport of Iodine in Containment", U.S. Nuclear Regulatory Commission Report, NUREG/CR-4697, October 1986.

16. J. T. Bell, M. H. Lietzke, and D. A. Palmer, "Predicted Rates of Formation of Iodine Hydrolysis Species at pH Levels, Concentrations, and Temperatures Anticipated in LWR Accidents," NUREG/CR-2900, October 1982.

17. J. T. Bell, D. O. Campbell, M. H. Lietzke, D. A. Palmer, and L. M. Toth, "Aqueous Iodine Chemistry in LWR Accidents: Review and Assessment", NUREG/CR-2493, April 1982.

18. E. C. Beahm, W. E. Shockley, and O. L. Culberson, "Organic Iodide Formation Folling Nuclear Reactor Accidents", NUREG/CR-4327, December 1985.