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Document Control Desk
U.S. Nuclear Regulatory Commission
Washington, DC 20555

ATTENTION: T. R. QUAY

SUBJECT: HYDROGEN CONTROL MEETING ACTION ITEMS

Dear Mr. Quay:

During a meeting on May 20, 1997, Westinghouse personnel and NRC staff discussed the hydrogen control system in the AP600 and agreed to a number of action items. These items were documented in an NRC letter dated June 12, 1997. The responses to the items related to the effect of poisons, testing, safety classification and conformance with regulatory guidance for the PARS are attached. The responses to the items related to the igniters are also attached. Markups of the SSAR changes that are required are attached. These SSAR changes will be included in Revision 15 of the SSAR.

The action items from the May 20, 1997, meeting are included in the open item tracking system as items 5368 through 5389. The Westinghouse status of the items provided with this transmittal is tabulated below. An item is given the status Closed for those items that needed a response that is provided in this letter and does not require an SSAR revision.

Action Item #	OITS #	Status
I.A.1	5368	Confirm W
I.A.2	5369	Confirm W
I.B	5370	Closed
I.C.1	5371	Confirm W
I.C.2	5372	Confirm W
I.D.1	5373	Closed
I.D.2	5374	Confirm W
I.D.3	5375	Confirm W
I.E.2	5376	Confirm W

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Action Item #	OITS #	Status
I.E.3	5377	Confirm W
I.E.4	5378	Confirm W
I.F	5379	Closed
I.G.1	5380	Confirm W
I.G.2	5381	Confirm W
I.G.3	5382	Confirm W
I.H	5383	Confirm W
I.I	5384	Confirm W
II.A	5385	Confirm W
II.B	5386	Confirm W
II.C	5387	Confirm W
II.D	5388	Confirm W
II.E	5389	Closed

Please contact Donald A. Lindgren at (412) 374-4856 if you have any questions.

Brian A McIntyre

Brian A. McIntyre, Manager
Advanced Plant Safety and Licensing

jml

Attachment

cc: W. Huffman, NRC (w/Attachment)
N. Liparulo, (w/o Attachment)

May 20, 1997 Hydrogen Meeting Action Items

I.A.1 (5368) Westinghouse will document in the SSAR sensitivity cases to address adverse distribution of hydrogen and the ability of the design to cope with these distributions. (For example, Westinghouse will evaluate the performance of the PARs at less than bulk average conditions.)

Response

SSAR Figure 6.2.4-1 (Revision 13) includes a curve identified as "Worst Case PAR Depletion Rate". This curve represents the calculated hydrogen concentration within containment based on design basis assumptions for hydrogen generation including conservative assumptions on the contributions of radiolysis, corrosion, zirconium-water reaction and dissolved hydrogen within the reactor coolant prior to the event. The hydrogen concentration versus time is also based on a generic passive autocatalytic recombiner performance using a conservative depletion rate equation. The conservative depletion rate equation includes a pessimistic uncertainty from the measured test data from Reference 1. The differential between this curve and the 4% regulatory limit represents the maximum gradient that could be postulated to exist within containment between a postulated unmixed region and the global containment concentration and remain within the limits. In other words, if a volume was postulated within containment where hydrogen could buildup over time and remain unmixed, then a gradient of up to 2.6% could exist between this volume and containment concentration and still maintain local concentrations below the 4% limit.

I.A.2 (5369) Westinghouse will incorporate the substance of the February 7, 1997 letter (DCP/NRC0735) on aerosol mixing into SSAR Subsection 6.2.4. The discussion will be supplemented for treatment of downward flow, condensation in dome, and the scope will be changed to include hydrogen and aerosol mixing in the long term.

Response

Information on the distribution of hydrogen in containment is being added as Appendix 6A of the SSAR.

I.B. (5370) The staff is concerned about the effectiveness of the PARs for the area above the 135' elevation. In past designs containment sprays could be relied on to demonstrate a well-mixed environment. Westinghouse will reconsider the merits of more than two PARs in light of the staff's concern.

Response

The evaluation of the mixing inside containment following a design basis as documented in subsection 6.2.4.1.1 of the SSAR supports the conclusion that the natural convection driven by decay heat in the core and condensation and heat transfer through the containment shell promotes sufficient mixing so that one PAR will maintain the hydrogen concentration below the regulatory limit. The two PARs are located approximately 180 degrees apart near potential upflow regions to provide adequate containment coverage and margin.

I.C.1 (5371) Westinghouse will address why PAR coverage in the accumulator rooms and the CVS valve room area is not needed either through a discussion of mixing or an explanation as to why hydrogen will not accumulate in these rooms. An alternate approach is to add safety related PARs in these areas to address the staff's concerns.

Response

Hydrogen above global concentration can only be introduced into one of these compartments by flooding with reactor coolant and subsequent radiolysis. The configuration of the containment internal structure and compartment drain lines is such that if the break is within one of the compartments then that compartment will flood to the ceiling and no hydrogen can accumulate within that compartment. Additionally, the curb level for the CVS compartment has been changed to be lower than the other two compartments and therefore this compartment will preferentially flood. There is insufficient water volume in the containment to flood the accumulator/valve rooms after the CVS compartment has been flooded. The curb height specified in Section 3.4 will be changed in Revision 15 of the SSAR. For floods that do not completely flood the CVS compartment, a PAR incorporated into the CVS compartment will maintain the hydrogen concentration below the regulatory limit. Subsections 6.2.4.1.3 and 6.2.4.2.2, Table 6.2.4-2, Table 3.2-3, and Table 3.11-1 will be revised in Revision 15 of the SSAR to include the CVS PAR

I.C.2 (5372) Westinghouse will make the PAR unit in the vent of the IRWST safety-grade or provide a justification for it not being safety grade.

Response

The IRWST PAR will be upgraded to safety related. Subsections 6.2.4.1.3 and 6.2.4.2.2, Table 6.2.4-2, Tech Spec 3.6.10 and bases, Table 3.2-3, and Table 3.11-1 will be revised in Revision 15 of the SSAR to include the IRWST PAR.

I.D.1 (5373) Westinghouse will submit the EPRI report concerning fission product poisons or include excerpts of the report in the SSAR.

Response

Copies of the EPRI Report "Effects of Inhibitors and Poisons on the Performance of Passive Autocatalytic Recombiners (PARs) for Combustible Gas Control in ALWRs" was transmitted to the staff with letter DCP/NRC0900, dated June 6, 1997.

I.D.2 (5374) Westinghouse should add a COL item that requires the applicant to determine the performance of the selected unit including the effects of contaminants.

Response

Evaluating the performance of the PAR in the presence of chemical contaminant is within the scope of environmental qualification. Environmental qualification of equipment is addressed in Section 3.11 and Appendix 3D. Subsection 6.2.4.1.2 will be revised in Revision 15 of the SSAR to reference to Section 3.11 and Appendix 3D. Subsection 3D.5.5.16 will be revised in Revision 15 of the SSAR to address requirements for testing of the chemical environment of the PARS. The Combined License applicant must procure equipment that has been qualified or qualify equipment in accordance with the commitments of the environment qualification program as described in the SSAR.

I.D.3 (5375) Westinghouse will change the first paragraph on page 6.2-42 which concerns fission product poisons to be consistent with staff position letter sent to Westinghouse in an April 1, 1997 letter. Westinghouse will cross reference to Section 3.11.

Response

Subsections 6.2.4.2.2 and 3D.5.5.1.6 will be revised in Revision 15 of the SSAR to provide for environmental qualification of the PARs in conformance with the staff position.

I.E.2 (5376) Westinghouse will develop a means to convey to the Combined License applicant the importance of the following areas for surveillance testing, 1. temperature requirement, 2. time it takes to reach temperature, 3. where the temperature is measured, 4. input of hydrogen/oxygen mixture used in test, and 5. verify uniform thickness of wafer during the visual surveillance requirement. The test objectives should be clearly identified.

Response

Subsection 6.2.4.5.1 will be revised in Revision 15 of the SSAR to provide additional information on test objectives for PARs.

I.E.3 (5377) Westinghouse should consider beefing up SSAR section 3.9 note 9 to discuss the important area for PAR surveillance testing.

Response

Note 9 in Table 3.9-17 will be revised in Revision 15 of the SSAR to reference the information on testing in subsection 6.2.4.5 which contains the details of the PAR inservice testing requirements.

I.E.4 (5378) Westinghouse will cleanup PAR Technical Specification basis as it applies to single failure criteria.

Response

Subsection 6.2.4.1.3 will be revised in Revision 15 of the SSAR to clarify how single failure criteria are applied to the PARs

The Technical Specification Basis Section B3.6.10 has been revised to be consistent with the single failure criteria.

I.F (5379) Westinghouse will fix reference in SSAR 6.2.4 to Battelle Frankfurt test. The staff disagrees that the PAR testing conducted under the NIS QA program is appropriate for design certification. The SSAR needs to clarify that the Battelle Frankfurt testing was not conducted in accordance with Westinghouse's QA program, WCAP-12600, Revision 2 and has been provided as proof of principle. The COL applicant needs to demonstrate that the PAR procured is capable of the depletion rate referenced in the SSAR and that this demonstration is in accordance with their Appendix B QA program and 10CFR part 21.

Response

The testing used to support the proof of principle for the PAR has been done by independent, reputable organizations using internationally recognized quality assurance standards (ISO 9001). This testing is sufficient for design certification purposes.

The PARS are safety-related components and are included as such in Table 3.2-3. 10CFR Appendix B and 10 CFR Part 21 apply to procurement of all safety-related components. Subsection 6.2.4.2.2 will be revised in Revision 15 of the SSAR to also include a redundant statement that procurement of the PARs are in accordance with the quality assurance program of the Combined License applicant.

I.G.1 (5380) Westinghouse will add to section 6.2.4.1.5 that the design complies with 10CFR 50.44, GDC 41, 42 and 43, and Reg guide 1.7.

Response

A list of regulatory criteria and guidance will be added in Revision 15 of the SSAR to the design basis in subsection 6.2.4.1.

I.G.2 (5381) Reg guide 1.7. Westinghouse will fix chapter 1A of SSAR to update wording with C.3, C.4 and C.5 to show that they do not have an exception.

The discussion of Reg. guide 1.7 in Appendix 1A will be revised in Revision 15 of the SSAR to change the AP600 Position on C.3, C.4, and C.5 to Conforms from Exception

I.G.3. (5382) Westinghouse will identify component(s) that will be used to comply with Reg Guide 1.7, item C.4.

Response

A reference will be added subsection 6.2.4.1 in Revision 15 of the SSAR indicating that the containment recirculation system discussed in subsection 9.4.7 provides the capability for controlled containment purge. This capability is consistent with position C.4 of Regulatory Guide 1.7.

I.H (5383) Westinghouse will evaluate Reg Guide 1.82, Rev 2, to demonstrate that debris clogging of the PARs is not a problem.

Response

A list of regulatory criteria and guidance will be added to the design basis in subsection 6.2.4.1 in Revision 15 of the SSAR. This list includes Regulatory Guide 1.82. Also, a discussion of why the PARs are not susceptible to blockage will be included in subsection 6.2.4.1.3.

I.I. (5384) The SSAR needs to discuss protection of the PARs from missiles, jet impingement, or pipe ruptures.

Response

A list of regulatory criteria and guidance will be added to the design basis in subsection 6.2.4.1 in Revision 15 of the SSAR. This list includes General Design Criteria 3. Section 3.5 addresses missile protection. As outlined in subsection 3.5.1.2.1.4 there are no credible missile sources inside containment. Section 3.6 addresses protection from pipe ruptures and jet impingement. Subsection 6.2.4.1.3 will be revised to note that the PARs are located well above potential pipe ruptures.

II.A (5385) Westinghouse will provide justification for not having igniter in upper dome (staff is skeptical of success of this approach) or will place igniters in the dome area.

Response

Four igniters have been added to the hydrogen igniter subsystem design. Subsections 6.2.4.2.3, 6.2.4.5.2, and 16.5.1 and Tables 6.2.4-3, 6.2.4-6 and 6.2.4-7 will be revised in Revision 15 of the SSAR to reflect 64 igniters. Figure 6.2.4-12 will be added to illustrate the igniter location

II.B. (5386) Westinghouse will provide justification in SSAR as to why igniters are not needed in the reactor vessel cavity. This discussion will include a reference to the three vent paths which are: Reactor vessel seal ring, steam generator compartments, and vertical access compartment.

Response

Table 6.2.4-6 will be expanded in Revision 15 of the SSAR to discuss the implementation of the igniter location criteria for AP600. For each major compartment the basis for igniter location either within the compartment or in the flow path from that compartment is discussed including the reactor cavity.

II.C. (5387) Westinghouse will enhance the discussion for justification for igniters located in the CVS valve room.

Table 6.2.4-6 will be expanded in Revision 15 of the SSAR to discuss the implementation of the igniter location criteria for AP600. For each major compartment the basis for igniter location either within the compartment or in the flow path from that compartment is discussed including the CVS valve room.

II.D (5388) Westinghouse will add to 6.2.4.1(6) that the igniters comply with 50.34f(2)(ix), 50.34f(1)(xii), and SECY-93-087. (Westinghouse will evaluate if SECY-93-087 and 50.34f(2)(ix) are the same).

Response

A list of regulatory criteria and guidance will be added to the design basis in subsection 6.2.4.1 in Revision 15 of the SSAR. This list includes 10CFR50.34f and hydrogen control position in SECY-93-087.

II.E (5389) Westinghouse will add a discussion about the location of the igniters relative to missiles, jet impingement, or pipe ruptures.

Response

The igniters are nonsafety-related components and are not required to be protected from missiles, pipe ruptures and jet impingement. As discussed in Section 3.5 of the SSAR there are no credible missiles inside containment and there is only limited potential for pipe ruptures and jet impingement.

References:

1. Qualification of PARs for Combustible Gas Control in ALWR Containments", Electric Power Research Institute, April 1993.

WESTINGHOUSE LETTER DCP/NRC0975

SSAR ATTACHMENTS

Issue 121 Hydrogen Control for Large, Dry PWR Containments

Discussion:

Generic Safety Issue 121 concerns ongoing NRC experimental and analytical programs addressing the likelihood of safe shutdown equipment surviving a hydrogen burn. The staff also intends to explore the possibility and probable consequences of the formation of local detonable concentrations in large, dry PWRs. The concerns are prediction of conditions in realistic configurations, and containment and equipment survivability.

AP600 Response:

The AP600 includes provisions for hydrogen control for the unlikely severe accident cases in which large amounts of hydrogen could be generated because of degraded core events. Analyses were performed to examine the consequences of hydrogen burn and to evaluate the likelihood of deflagration to detonable transitions.

For severe accident cases, the containment hydrogen control system prevents hydrogen burn initiation at high hydrogen concentration levels. Hydrogen igniters promote burning when the lower flammability limit is reached and limits the containment hydrogen concentration to less than 10 volume percent during and following a degraded core or core melt.

Thus, for severe accident cases, the AP600 is designed to prevent the occurrence of hydrogen detonation, thereby preventing the possibility of the resultant large pressure spikes in containment, which is the source of concern for containment integrity and equipment survival. Details of the hydrogen ignition subsystem are provided in subsection 6.2.4.2.3. Placement of the hydrogen igniters is discussed in ~~Chapter 16 of the PRA evaluation report~~ subsection 6.2.4.

A hydrogen burn analysis shows that the AP600 hydrogen igniter system is effective in maintaining the hydrogen concentration throughout the containment close to the lower flammability limit, and that the peak pressure in the containment during and following hydrogen burn remains well below ASME service level C stress intensity limits. The hydrogen concentration is similar in all compartments analyzed, indicating that the hydrogen released mixes well in the AP600 containment. The analyses predict conditions in realistic configurations. Peak gas temperatures and pressures in each compartment for each case analyzed are provided, thus providing the hydrogen burn thermal environment that containment equipment will experience. Details are provided in Chapter 14 of the PRA report.

The challenge to the AP600 containment integrity from hydrogen deflagrations and detonations during core damage events is examined in the hydrogen deflagration and detonation analyses. This bounding evaluation assumes that an amount of hydrogen equivalent to 100-percent active cladding oxidation burns all at once in the AP600 containment, with no credit taken for the hydrogen igniters. The evaluation concludes that a hydrogen deflagration is unlikely to cause containment failure. Other analyses show that a

Criteria Section	Referenced Criteria	AP600 Position	Clarification/Summary Description of Exceptions
C.2		Conforms	
C.3	Regulatory Guide 1.29 Regulatory Guide 1.26	~~Exception~~ Conforms	~~The hydrogen recombiners are designed as safety-related components. The design, quality assurance, and redundancy requirements are appropriate to safety-related components.~~ The hydrogen recombiners are passive autocatalytic recombiners. They do not require and are not supplied with power.
C.4		~~Exception~~ Conforms	~~The filters in the containment purge are not seismic Category I. The purpose of the filters in the containment purge is to control normal operating releases. They are not provided for accident mitigation.~~
C.5		~~Exception~~ Conforms	~~The parameter values in Table 1 are used except for the source term assumptions used for radiolysis that are based on the use of TID-14844. Considering that the level of zirconium-water reaction that is used is consistent with effective core cooling (that is, there may be cladding failure but not major core degradation or core melt), the radiolysis source term for the AP600 is based on release of gap inventories.~~
C.6		Conforms	

Reg. Guide 1.8, Rev. 2, 4/87 - Qualification and Training of Personnel for Nuclear Power Plants

General		N/A	Not applicable to AP600 design certification. This is the Combined License applicant's responsibility. See Section 13.2 for the Combined License information item on training.

Reg. Guide 1.9, Rev. 2, 12/79 - Selection, Design, and Qualification of Diesel Generator Units Used as Standby (Onsite) Electric Power Systems at Nuclear Power Plants

General		N/A	Guidelines apply to Class 1E diesel-generators. They are not applicable to the AP600.
C.1-14		N/A	Guidelines apply to Class 1E diesel-generators. They are not applicable to the AP600.

Table 3.2-3 (Sheet 58 of 64)

AP600 CLASSIFICATION OF MECHANICAL AND FLUID SYSTEMS, COMPONENTS, AND EQUIPMENT

Tag Number	Description	AP600 Class	Seismic Category	Principal Construction Code	Comments
Health Physics and Hot Machine Shop HVAC System (Continued)					
n/a	Fans, Ductwork	L	NS	SMACNA	
Balance of system components are Class E or Class L					
Containment Hydrogen Control System (VLS)					Location: Containment
n/a	Hydrogen Igniters	D	NS	Manufacturer Std.	Provides Hydrogen Control Following Severe Accidents
VLS-MY-E01A	Catalytic Hydrogen Recombiner A	C	I	Manufacturer Std.	
VLS-MY-E01B	Catalytic Hydrogen Recombiner B	C	I	Manufacturer Std.	
VLS-MY-E02	IRWST Catalytic Hydrogen Recombiner	C	I	Manufacturer Std.	
VLS-MY-E03	CVS Compartment Catalytic Hydrogen Recombiner	C	I	Manufacturer Std.	
n/a	Fire Dampers	Note 3	NS	UL-555	
Balance of system components are Class E or Class L					
Radwaste Building Ventilation System (VRS)					Location: Radwaste Building
n/a	Shutoff, Isolation, and Balancing Dampers	L	NS	ANSI/AMCA-500	
n/a	Fire Damper	Note 3	NS	UL-555	
n/a	Air Handling Units w/ Filters	L	NS	UL 900	
n/a	Fans, Ductwork	L	NS	SMACNA	
Balance of system components are Class E or Class L					
Turbine Building Ventilation System (VTS)					Location: Turbine Building
n/a	Shutoff, Isolation, and Balancing Dampers	L	NS	ANSI/AMCA-500	
n/a	Fire Dampers	Note 3	NS	UL-555	
n/a	Air Handling Units w/ Filters	L	NS	Manufacturer Std.	
n/a	Fans, Ductwork	L	NS	Manufacturer Std.	
Balance of system components are Class L					

5. The flow capability of each IRWST injection line is demonstrated every 10 years. This demonstration is accomplished by conducting flow tests and inspections. A flow test is conducted to demonstrate the flow capability of the injection line from the IRWST through the IRWST injection check valves. Water flow from the IRWST through the IRWST injection check valve demonstrates the flow capability of this portion of the line. The test is terminated when the flow measurement is obtained. The portion of the line from the IRWST squib valve to the DVI line is demonstrated by an inspection of the inside of the line. The inspection will show that the lines are not obstructed. It is not necessary to operate the IRWST injection squib valves for this inspection.

6. The flow capability of each containment recirculation line is demonstrated every 10 years. This demonstration is accomplished by conducting an inspection. The line from the containment to the containment recirculation squib valve is inspected from the containment side. The line from the squib valve to the IRWST injection line is inspected from the IRWST side. The inspection will show that the lines are not obstructed. It is not necessary to operate the containment recirculation squib valves for this inspection.

7. The heat transfer capability of the passive residual heat exchanger is demonstrated every 10 years. This demonstration is accomplished by conducting a test during cold shutdown conditions. The test is conducted with the RCPs in operation and the RCS at a reduced temperature. Flow through the heat exchanger is initiated by opening one outlet isolation valve. The test is terminated when the flow and temperature measurements are obtained.

8. The MCR pressurization capability is demonstrated during each refueling cycle. The test is conducted with the normal HVAC lines connected to the MCR isolated using the dampers in VBS designated for this purpose in subsection 9.4.1. Pressurization of the MCR is initiated by opening one of the emergency MCR habitability air supply lines. The test is a limited duration test and is terminated when the MCR pressurization is measured, to ⅛ inch water gauge with respect to surrounding areas, with an airflow rate of 25 ±2 scfm.

9. The hydrogen recombination capability is demonstrated by performing a surveillance bench test of samples removed from each passive autocatalytic recombiner during each refueling outage. In addition, each passive autocatalytic recombiner device is visually inspected to verify that there is no obstruction ~~of~~ or blockage of the inlets or outlets. Subsection 6.2.4.5 provides identification of requirements and criteria for inservice testing of the PARs.

Table 3.11-1 (Sheet 43 of 44)

ENVIRONMENTALLY QUALIFIED ELECTRICAL AND MECHANICAL EQUIPMENT

Description	AP600 Tag No.	Envir. Zone (Note 2)	Function (Note 1)	Operating Time Required (Note 5)	Qualification Program (Note 6)
Core Makeup Tank A	PXS-MT-02A	1	ESF	1 yr	M *
Core Makeup Tank B	PXS-MT-02B	1	ESF	1 yr	M *
In-Containment Refueling Water Storage Tank	PXS-MT-03	1	ESF	1 yr	M *
Emergency Air Storage Tank 01A	VES-MT-01A	7	ESF	1 yr	M
Emergency Air Storage Tank 01B	VES-MT-01B	7	ESF	1 yr	M
Emergency Air Storage Tank 02A	VES-MT-02A	7	ESF	1 yr	M
Emergency Air Storage Tank 02B	VES-MT-02B	7	ESF	1 yr	M
Emergency Air Storage Tank 03A	VES-MT-03A	7	ESF	1 yr	M
Emergency Air Storage Tank 03B	VES-MT-03B	7	ESF	1 yr	M
Emergency Air Storage Tank 04A	VES-MT-04A	7	ESF	1 yr	M
Emergency Air Storage Tank 04B	VES-MT-04B	7	ESF	1 yr	M
Emergency Air Storage Tank 05A	VES-MT-05A	7	ESF	1 yr	M
Emergency Air Storage Tank 05B	VES-MT-05B	7	ESF	1 yr	M
Emergency Air Storage Tank 06A	VES-MT-06A	7	ESF	1 yr	M
Emergency Air Storage Tank 06B	VES-MT-06B	7	ESF	1 yr	M
Emergency Air Storage Tank 07A	VES-MT-07A	7	ESF	1 yr	M
Emergency Air Storage Tank 07B	VES-MT-07B	7	ESF	1 yr	M
Emergency Air Storage Tank 08A	VES-MT-08A	7	ESF	1 yr	M
Emergency Air Storage Tank 08B	VES-MT-08B	7	ESF	1 yr	M
Emergency Air Storage Tank 09A	VES-MT-09A	7	ESF	1 yr	M
Emergency Air Storage Tank 09B	VES-MT-09B	7	ESF	1 yr	M
Emergency Air Storage Tank 10A	VES-MT-10A	7	ESF	1 yr	M
Emergency Air Storage Tank 10B	VES-MT-10B	7	ESF	1 yr	M
Emergency Air Storage Tank 11A	VES-MT-11A	7	ESF	1 yr	M
Emergency Air Storage Tank 11B	VES-MT-11B	7	ESF	1 yr	M
Emergency Air Storage Tank 12A	VES-MT-12A	7	ESF	1 yr	M
Emergency Air Storage Tank 12B	VES-MT-12B	7	ESF	1 yr	M
Passive Autocatalytic Recombiner A	VLS MY E01A	1	ESF	1 yr	M *
Passive Autocatalytic Recombiner B	VLS MY E01B	1	ESF	1 yr	M *
IRWST Passive Autocatalytic Recombiner	VLS MY E02	1	ESF	1 yr	M*
CVS Compartment Passive Autocatalytic Recombiner	VLS MY E03	1	ESF	1 yr	M*
Main Feed Pump A Status	ECS ES 3 XXX	8	PAMS	2 wks	E +
Main Feed Pump B Status	ECS ES 3 XXX	8	PAMS	2 wks	E +
Remote Shutdown Workstation		2		Note 3	E

The passive autocatalytic recombiners will be qualified with a chemical environment representing an environment beyond design basis conditions or otherwise anticipated to be present following a loss-of-coolant accident. The catalyst poisons potentially present subsequent to a core melt event (through in-vessel releases) are considered for potential degradation of PAR performance. Subsection 6.2.4 discusses the rationale for the chemical environment providing both a basis and environment definition.

3D.5.5.1.7 Submergence

Performance of equipment in a submerged condition is verified by a test that replicates the actual conditions with appropriate margin.

3D.5.5.2 High-Energy Line Break Accidents Outside Containment

For the majority of equipment located outside containment, the normal operating environment remains unchanged by a high-energy line break accident. As a consequence, qualification for such events is covered by qualification for normal conditions.

A limited amount of equipment located outside containment, near high-energy lines, could be subject to local hostile environmental conditions because of a high-energy line break outside containment. In this case, the equipment is qualified for the conditions resulting from events affecting its location and for which it is required to operate. These conditions are shown in Figure 3D.5-9. Sheet 1 shows the combined design and test conditions for equipment that is required to perform throughout all postulated events where superheat is delayed past five minutes. Sheet 2 shows the combined design and test conditions for equipment that is only required to perform for the first five minutes into the event. The maximum pressure for any event outside containment is less that 6 psig.

3D.6 Qualification Methods

The recognized methods available for qualifying safety-related electrical equipment are established in IEEE 323. These are type testing, operating experience, analysis, on-going qualification, or a combination of these methods. The choice of qualification method for a particular item of equipment is based upon many factors. These factors include practicability, size and complexity of equipment, economics, and availability of previous qualification to earlier standards.

The qualification method employed for each equipment type included under the AP600 equipment qualification program is identified in the individual equipment qualification data packages whether by test (Attachment A, Section 2.0), experience (Attachment A, Section 3.0), analysis (Attachment A, Section 4.0), or by a combination of these methods. The AP600 equipment qualification program may employ on-going qualification through the use of maintenance and surveillance. Guidance for such an approach is not included in this appendix.

Two situations are postulated, a design basis case and a severe accident case. In the design basis case there is a limited reaction of less than 1 percent of fuel cladding zirconium with water to form hydrogen. For this case there is an initial release of hydrogen due to the reaction of fuel cladding with water and the release of hydrogen contained in the reactor coolant system. This initial hydrogen release to containment is not sufficient to approach the flammability limit of 4 volume percent. However, hydrogen continues to evolve to the containment due to radiolysis of water and the corrosion of materials in the containment. The flammability limit will eventually be reached unless mitigating action is taken. The function of the containment hydrogen control system is to prevent the hydrogen concentration from reaching the flammability limit.

In the severe accident case it is assumed that 100 percent of the fuel cladding reacts with water. Although hydrogen production due to radiolysis and corrosion occurs, the cladding reaction with water dominates the production of hydrogen for this case. The hydrogen generation from the zirconium-steam reaction could be sufficiently rapid that it may not be possible to prevent the hydrogen concentration in the containment from exceeding the lower flammability limit. The function of the containment hydrogen control system for this case is to promote hydrogen burning soon after the lower flammability limit is reached in the containment. Initiation of hydrogen burning at the lower level of hydrogen flammability prevents accidental hydrogen burn initiation at high hydrogen concentration levels and thus provides confidence that containment integrity can be maintained during hydrogen burns and that safety-related equipment can continue to operate during and after the burns.

The containment hydrogen control system serves the following functions:

- Hydrogen concentration monitoring
- Hydrogen control during and following a design basis loss of coolant accident (provided by passive autocatalytic recombiners [PARs])
- Hydrogen control during and following a degraded core or core melt scenarios (provided by hydrogen igniters).

6.2.4.1 Design Basis

A. The safety related portion of the hydrogen control system is protected from the effects of natural phenomena, such as earthquakes, tornadoes, hurricanes, floods, and external missiles (General Design Criterion 2).

B. The safety related portion of the hydrogen control system is designed to remain functional after a safe shutdown earthquake (SSE) and to perform its intended function following the postulated hazards of fire, internal missiles, or pipe breaks (General Design Criteria 3 and 4). Missile protection is discussed in section 3.5, pipe break protection in 3.6 and fire protection in 9.5.1 and appendix 9A.

C. The hydrogen control system is designed to provide containment atmosphere cleanup (hydrogen control) in accordance with General Design Criterion 41, 42 and 43.

D. The hydrogen control system is designed in accordance with the requirements of 10 CFR 50.44 and 10 CFR 50.34(f) and meets the NRC staff's position related to hydrogen control of SECY-93-087.

E. The hydrogen control system is designed in compliance with the recommendations of NUREG 0737 and 0660 as detailed in subsection 1.9.

F. The hydrogen control system is designed in accordance with the recommendations of Regulatory Guide 1.7 as discussed in appendix 1A. The containment recirculation system discussed in subsection 9.4.7 provides the controlled purge capability for the containment as specified in position C.4 of Regulatory Guide 1.7

G. The hydrogen control system is designed and fabricated to codes consistent with the quality group classification, described in Section 3.2. Conformance with Regulatory Guide 1.26, 1.29, and 1.32 is described in subsection 1.9.

H. The hydrogen control system complies with the intent of Regulatory Guide 1.82 "The Water Sources For Long-Term Recirculation Cooling Following A Loss-Of-Coolant Accident" as it could be applied to concerns for blockage of air flow paths.

6.2.4.1.1 Containment Mixing

Containment structures are arranged to promote mixing via natural circulation. The physical mechanisms of natural circulation mixing that occur in the AP600 are discussed in WCAP-14407 (Proprietary), WCAP-14408 (Nonproprietary) (Reference 20), and summarized as follows. Appendix 6A provides additional information on the distribution of hydrogen in post-accident containment atmosphere. For a postulated break low in the containment, buoyant flows develop through the lower compartments due to density head differences between the rising plume and the surrounding containment atmosphere, tending to drive mixing through lower compartments and into the region above the operating deck. There is also a degree of mixing within the region above the operating deck, which occurs due to the introduction of and the entrainment into the steam-rich plume as it rises from the operating deck openings. Thus, natural forces tend to mix the containment atmosphere.

Two general characteristics have been incorporated into the design of the AP600 to promote mixing and eliminate dead-end compartments. The compartments below deck are large open volumes with relatively large interconnections, which promote mixing throughout the below deck region. All compartments below deck are provided with openings through the top of the compartment to eliminate the potential for a dead pocket of high-hydrogen concentration. In addition, if forced containment air-circulation is operated during post-accident recovery, then nonsafety-related fan coolers contribute to circulation in containment.

In the event of a hydrogen release to the containment, passive autocatalytic recombiners act to recombine hydrogen and oxygen on a catalytic surface (see subsection 6.2.4.2.2). The enthalpy of reaction generates heat within a passive autocatalytic recombiner, which further drives containment mixing by natural circulation. Catalytic recombiners reduce hydrogen concentration at very low hydrogen concentrations (less than 1 percent) and very high steam concentrations, and may also promote convection to complement passive containment cooling system natural circulation currents to inhibit stratification of the containment atmosphere (Reference 17). The implementation of passive autocatalytic recombiners has a favorable impact on both containment mixing and hydrogen mitigation.

6.2.4.1.2 Survivability of System

The portion of the containment hydrogen control system required for the design basis loss of coolant accident is designed to withstand the dynamic effects associated with postulated accidents, the environment existing inside the containment following the postulated accident, and a safe shutdown earthquake.

The environmental qualification of the PAR's and hydrogen monitors are performed in accordance with the specifications of Section 3.11 using the methodology defined in Appendix 3D. Within Reference 27, the NRC has concluded that the chemical environment for environmental qualification should include potential poisons. Specifically, that the PAR's should be environmentally qualified to include the source term constituents which were conservatively assumed to yield the radioactivity dose rates for environmental qualification. The AP600 PAR's will be qualified pursuant to the guidance of Reference 27 and utilizing the poisons resulting from a core melt event through in-vessel releases as discussed in Reference 28. This approach is conservative since the level of potential poisons assumed is inconsistent with the functional purpose of the PAR in design basis hydrogen mitigation. The magnitude of poisons is based on the concentration consistent with a source term derived from a severe accident core melt scenario rather than the regulatory criteria for design basis accidents.

The containment hydrogen control equipment provided to mitigate severe accident conditions (igniter subsystem) is designed to function under the event environment including the effects of combustion of hydrogen in containment.

6.2.4.1.3 Single Failure Protection

The hydrogen monitoring function ~~and the hydrogen recombination subsystem are~~ is designed to accommodate a single failure. The hydrogen recombination subsystem consists of qualified passive devices which are not susceptible to single failures. However to provide margin and increased containment coverage two global containment PAR's are provided and credit for only a single unit is assumed in the hydrogen analysis. The location of the PAR's are such that the units are not susceptible to debris blockage as identified in Regulatory Guide 1.82. The global PAR's are at an approximate elevation of 164 feet and not immediately above the loop compartments. The IRWST PAR is located above the operating deck above the IRWST well away from any pipe failure locations that could produce design basis accidents. All units are above the maximum flooding elevation. Based on the locations of the PAR's they are not susceptible to debris blockage. The hydrogen ignition system, since it is provided only to address a low-probability severe accident, is designed to accommodate probable component and system failures.

6.2.4.1.4 Validity of Hydrogen Monitoring

The hydrogen monitoring function monitors hydrogen concentrations of various ~~diverse~~ locations within the containment.

6.2.4.1.5 Hydrogen Control for Design Basis Accident

The containment volume average hydrogen concentration is prevented from exceeding 4 volume percent. This limit eliminates the potential for flammable conditions.

6.2.4.1.6 Hydrogen Control for Severe Accident

The containment hydrogen concentration is limited by operation of the distributed hydrogen ignition subsystem. Ignition causes deflagration of hydrogen (burning of the hydrogen with flame front propagation at subsonic velocity) at hydrogen concentrations below between the flammability limit and 10 volume percent and thus prevents the occurrence of hydrogen detonation (burning of hydrogen with supersonic flame front propagation).

6.2.4.2 System Design

6.2.4.2.1 Hydrogen Concentration Monitoring Subsystem

The hydrogen concentration monitoring subsystem consists of two groups of eight hydrogen sensors each. The sensors are placed in various locations throughout the containment free volume including the upper dome and containment compartments.

The system contains a total of three sensors designated as Class 1E and thirteen sensors designated as non-Class 1E. The three Class 1E sensors are seismic Category 1 and serve to provide a post accident monitoring function for design basis accidents. See Section 7.5 for additional information. The sensors designated as non-Class 1E provide a defense in depth function of monitoring local hydrogen concentrations.

The 1E hydrogen sensors are powered by ~~either~~ a Class 1E power source and the ~~or~~ non-Class 1E hydrogen sensors are powered by a non-Class 1E power source. The Class 1E instrument channels are independent of the non-Class 1E instrument channels. Sensor parameters are provided in Table 6.2.4-1. Hydrogen concentration is continuously indicated in the main control room. Additionally, high hydrogen concentration alarms are provided in the main control room.

The sensors are designed to provide a rapid response detection of changes in the containment hydrogen concentration. The response time of the sensor is at least 90 percent in 10 seconds.

6.2.4.2.2 Hydrogen Recombination Subsystem

The hydrogen recombination subsystem is designed to accommodate the hydrogen production rate anticipated for a design-basis loss of coolant accident. The hydrogen recombination subsystem consists of two passive autocatalytic recombiners installed inside the containment above the operating deck at an approximate elevation of 162 feet and 13 feet inboard from the containment shell. The locations provide placement within a homogeneously mixed region of containment as supported by subsection 6.2.4.1.1 and Appendix 6A. The location is in a predominately upflow natural convection region. Additionally, the PARs are located azmuthally away from potential high upflow regions such as the direct plume above the loop compartment.

A third PAR is located at one of the vent paths from the IRWST and is utilized to limit the accumulation of hydrogen within the IRWST during normal and post-accident operation.

A fourth PAR is located in the chemical and volume control system compartment to limit the accumulation of hydrogen within the compartment as a result of radiolysis and corrosion within the compartment from a partially flooded condition following a design basis LOCA.

The passive autocatalytic recombiners are simple and passive in nature without moving parts and independent of the need for electrical power or any other support system. ~~The subsystem operates independent of the availability of power following an accident resulting in the generation of hydrogen.~~ The recombiners are safety-related equipment. They are seismic Category I and are qualified for the post-loss of coolant accident environment. The recombiners require no power supply and are self-actuated by the presence of the reactants (hydrogen and oxygen).

Normally, oxygen and hydrogen recombine by rapid burning only at elevated temperatures (greater than about 1100°F [600°C]). However, in the presence of catalytic materials such as the palladium group, this "catalytic burning" occurs even at temperatures below 32°F (0°C). Adsorption of the oxygen and hydrogen molecules occurs on the surface of the catalytic metal because of attractive forces of the atoms or molecules on the catalyst surface. Passive autocatalytic recombiner devices use palladium or platinum as a catalyst to combine molecular hydrogen with oxygen gases into water vapor. The catalytic process can be summarized by the following steps (Reference 15):

1. Diffusion of the reactants (oxygen and hydrogen) to the catalyst
2. Reaction of the catalyst (chemisorption)
3. Reaction of intermediates to give the product (water vapor)
4. Desorption of the product
5. Diffusion of the product away from the catalyst

The reactants must get to the catalyst before they can react and subsequently the product must move away from the catalyst before more reactants will be able to react.

The passive autocatalytic recombiner device consists of a stainless steel enclosure providing both the structure for the device and support for the catalyst material. The enclosure is open on the bottom and top and extends above the catalyst elevation to provide a chimney to yield additional lift to enhance the efficiency and ventilation capability of the device. The catalyst material is either constrained within screen cartridges or deposited on a metal plate substrate material and supported within the enclosure. The spaces between the cartridges or plates serve as ventilation channels for the throughflow. During operation, the air inside the recombiner is heated by the recombination process, causing it to rise by natural convection. As it rises, replacement air is drawn into the recombiner through the bottom of the passive autocatalytic recombiner and heated by the exothermic reaction, forming water vapor, and exhausted through the chimney where the hot gases mix with containment atmosphere. The device is a molecular diffusion filter and thus the open flow channels are not susceptible to fouling.

Passive autocatalytic recombiners begin the recombination of hydrogen and oxygen almost immediately upon exposure to these gases when the catalyst is not wetted. If the catalyst material is wet, then a short delay is experienced in passive autocatalytic recombiner startup (References 19 and 29). The delay is short with respect to the time that the PARs have to control hydrogen accumulation rates (days to weeks) following a design basis accident. The recombination process occurs at room or elevated temperature during the early period of accidents prior to the buildup of flammable gas concentrations. Passive autocatalytic recombiners are effective over a wide range of ambient temperatures, concentrations of reactants (rich and lean, oxygen/hydrogen less than 1 percent) and steam inerting (steam concentrations greater than 50 percent). Although the passive autocatalytic recombiner depletion rate reaches peak efficiency within a short period of time, the rate varies with hydrogen concentration and containment pressure, (Reference 19).

Reference 19 provides passive autocatalytic recombiner performance estimates appropriate (depletion rates) for a design basis accident, while a best-estimate depletion rate is appropriate for severe accident hydrogen control scenarios where realistic estimates of system performance are appropriate due to the low probability of occurrence. A conservative or lower bound estimate of depletion rate may be used for a design basis accident analysis. The conservative depletion rate accounts for effects such as instrumentation error, curve fitting, startup delay and a single failure. This rate (with one of the two containment passive autocatalytic recombiners available) is used for the analysis results presented in Figure 6.2.4-1, "Passive Autocatalytic Recombiner Sensitivity Study - Dry Conditions, Impact on Containment H_2 Concentrations."

The depletion rate assumed in the analysis is based on a generic passive autocatalytic recombiner application as described in Reference 19, and is expected to be representative of a number of vendor's recombiners. The calculated containment hydrogen concentration presented in Figures 6.2.4-1 and 6.2.4-2 is based on the assumptions and analysis discussed in subsection 6.2.4.3. The results demonstrate abundant margin for system performance. Further, the hydrogen concentration following an accident with only one of the two available passive autocatalytic recombiners operating within containment demonstrates significant margin to maintaining hydrogen concentrations below the recommendations of Regulatory

Guide 1.7, Control of Combustible Gas Concentrations in Containment Following a Loss-of-Coolant Accident.

The equations predicting the depletion rate are as follows:

- For H_2 concentrations less than 0.2 percent depletion rate (kg/hr) = 0.0
- For H_2 concentrations equal to or greater than 0.2 percent depletion rate (kg/hr) = $78{,}800 \times [0.029883 \times ([C\text{-}0.2]/100)^2 + (0.001009 \times [C\text{-}0.2]/100) \times P]/(T + 273)$

where C = volume average H_2 concentration at passive autocatalytic recombiner inlet
P = total pressure (bars)
T = gas temperature at passive autocatalytic recombiner inlet (°C)

The conditions under which the passive autocatalytic recombiners are assumed to operate for a design basis accident for defining the lower bound hydrogen depletion rate per Reference 19 are:

- Inlet gas temperatures ranging from 100 to 330°F
- Pressures ranging from 1 to 4 atmospheres
- Hydrogen concentrations up to 5 volume percent
- Steam concentrations ranging from near zero to 75 percent
- Condensing steam environment
- No significant levels of potential catalyst poisons

The basis for defining the hydrogen depletion rate is testing conducted by Battelle Frankfurt of both full scale and segment model NIS passive autocatalytic recombiner units. The results of the tests and their use in the definition of a hydrogen depletion rate equation appropriate for a design basis accident is provided in References 18 and 19. Subsequent test conducted by EPRI and EdF (Reference 29) support the conclusions of Battelle testing. Reference 19 assumed no significant levels of catalyst poisons (for example, iodine, carbon monoxide, cable fire combustion products and tellurium) would be present following a design basis event. This assumption is consistent with the regulatory limits imposed on clad damage levels of 10 CFR 50.46 and 50.44 for a loss of coolant accident. The existence of significant levels of poisons would normally mandates consideration of events and hydrogen generation rates for which other design attributes of the hydrogen control system are specifically provided. Events which generate high levels of iodine and tellurium, for example, are the result of gross fuel clad damage and cladding/water reactions.

However, in accordance with Reference 27, the PAR's will be environmentally qualified in the presence of catalyst poisons which would be present following a design basis event that results in a source term defined in NUREG 1465 for an event progressing through the stages of reactor coolant, gap and early in-vessel releases. Further, based on industry test data and catalyst poison literature, the hydrogen recombination subsystem performance for a DBA will be evaluated with the reduction in performance anticipated as a result of the effects of poisons and inhibitors as determined in Reference 28. The fractions of core inventory released through reactor coolant, gap and early in-vessel stages of core damage event are identified in NUREG 1465. Reference 28 considers the releases of NUREG 1465 and addresses the potential effects of poisons and inhibitors on the performance of the PAR's. The approach in Reference 28 is to compile existing information and data as a basis for establishing a generic bounding value of a deactivation reduction factor for design and qualification of PAR's. The approach combines qualitative information based on established chemical and physical principles with quantitative information from testing of catalysts systems subjected to a wide range of inhibitors and poisons. The sources of test data include (1) tests on PAR's conducted by two suppliers over the past several years, (2) tests on the same two types of PAR's conducted recently in France by EPRI/EdF/CEA and (3) tests on catalyst pellet-bed filters conducted in a laboratory about 25 years ago and additional testing described in Reference 28. The report concludes that "Even if the accident were to progress to beyond a DBA to substantial in-vessel damage, PAR recombination capacity would be reduced by no more than 25%..."

To illustrate the margin available and the tolerance to catalytic poisons and inhibitors, Figure 6.2.4-2 demonstrates the effects of the presence of elevated concentrations of poisons and inhibitors in containment. The curve demonstrates the effects of the conservative depletion rate discussed above in combination with a 25 percent penalty due to poisons and inhibitors. The curve remains below 1.5 percent hydrogen concentration. The margin of difference between the regulatory limit of 4 percent and the projected concentration may be considered to represents the maximum potential gradient between global hydrogen concentration and an isolated postulated hypothetical volume of containment atmosphere.

The environments in which safety-related components are designed and qualified to function are discussed in Section 3.11. The pressure, temperature, and chemical environment conditions for which components are designed to function have been based on analysis of the design basis event and the systems response. The radiation environments have, in contrast, been the result of a deterministic application of the accident source term. As specified in NUREG 1465, to determine the accident source term for regulatory purposes, the staff examined a range of severe accidents that have been analyzed for light water reactors. The environmental qualification guidance and practice is conservatively based on the effects of *radiation* due to a severe accident source term.

~~To illustrate the margin available and the tolerance to catalytic poisons, Figure 6.2.4-2 demonstrates the effects of the presence of elevated concentrations of poisons in containment. An estimate of the effect of iodine is documented in Reference 18 and is projected to be less than a 30 percent decrease in depletion. This value is also projected to envelope the potential impact of other potential poisons such as tellurium.~~

The passive autocatalytic recombiner testing and reporting of test data, conducted under the NIS quality assurance program has demonstrated proof of principle as~~, is~~ appropriate for design certification. An evaluation and summary of the quality assurance program for the Battelle tests is provided in Reference 21. Procurement will be in accordance with the COL applicants QA program.

A summary of component data for the hydrogen recombiners is provided in Table 6.2.4-2.

6.2.4.2.3 Hydrogen Ignition Subsystem

The hydrogen ignition subsystem is provided to address the possibility of an event that results in a rapid production of large amounts of hydrogen such that the rate of production exceeds the capacity of the recombiners. Consequently, the containment hydrogen concentration will exceed the flammability limits. This massive hydrogen production is postulated to occur as the result of a degraded core or core melt accident (severe accident scenario) in which up to 100 percent of the zirconium fuel cladding reacts with steam to produce hydrogen.

The hydrogen ignition subsystem consists of ~~60~~64 hydrogen igniters strategically distributed throughout the containment. Since the igniters are incorporated in the design to address a low-probability severe accident, the hydrogen ignition system is not Class 1E. Although not class 1E, the igniter coverage, distribution and power supply has been designed to minimize the potential loss of igniter protection globally for containment and locally for individual compartments. The igniters have been divided into two power groups. Power to each group will be normally provided by offsite power, however should offsite power be unavailable, then each of the power groups is powered by one of the onsite non-essential diesels and finally should the diesels fail to provide power then approximately 4 hours of igniter operation is supported by the non-Class 1E batteries for each group. Assignment of igniters to each group is based on providing coverage for each compartment or area by at least one igniter from each group.

The locations of the igniters are based on evaluation of hydrogen transport in the containment and the hydrogen combustion characteristics. Locations include compartmented areas in the containment and various locations throughout the free volume, including the upper dome.

For enclosed areas of the containment at least two igniters are installed. The separation between igniter locations is selected to prevent the velocity of a flame front initiated by one igniter from becoming significant before being extinguished by a similar flame front propagating from another igniter. The number of hydrogen igniters and their locations are selected considering the behavior of hydrogen in the containment during severe accidents. The likely hydrogen transport paths in the containment and hydrogen burn physics are the two important aspects influencing the choice of igniter location.

The primary objective of installing an igniter system is to promote hydrogen burning at a low concentration and, to the extent possible, to burn hydrogen more or less continuously so that the hydrogen concentration does not build up in the containment. To achieve this goal, igniters are placed in the major regions of the containment where hydrogen may be released, through which it may flow, or where it may accumulate. The criteria utilized in the evaluation and the application of the criteria to specific compartments is provided in Table 6.2.4-6. The location of igniters throughout containment is provided in Figures 6.2.4-5 through 6.2.4-11. The location of igniters is also summarized in Table 6.2.4-7 identifying subcompartment/regions and which igniters by power group provide protection. The locations

Production rate of hydrogen as a function of time is shown graphically in Figure 6.2.4-3 and the production of hydrogen is shown in Figure 6.2.4-4.

6.2.4.3.1.4 Initial Reactor Coolant Hydrogen Inventory

During normal operation of the plant, hydrogen is dissolved in the reactor coolant and is also contained in the pressurizer vapor space. Following a loss of coolant accident, this hydrogen is assumed to be immediately released to the containment atmosphere. Table 6.2.4-4 lists the assumptions used for determining the amount of hydrogen from this source. The total hydrogen released to the containment as a result of this source is 1171 standard cubic feet.

6.2.4.3.2 Hydrogen Mixing

The AP600 is designed to prevent the accumulation of hydrogen in compartments. If there is the possibility of accumulation in compartments, venting is provided to allow the hydrogen to escape to the larger containment volume. Mixing of the containment air mass is accomplished through natural processes as a result of the passive cooling of the containment (see subsection 6.2.2) that induces a recirculating air flow in the containment. The release rate for a design basis accident is sufficiently slow that mixing is effectively assured. Additional details are provided in subsection 6.2.4.1.1 and Appendix 6A.

6.2.4.3.3 Hydrogen Recombination

Assuming no hydrogen removal, the concentration of hydrogen in the containment atmosphere increases with time as shown in Figure 6.2.4-1. The curve shows that the flammability limit of 4 volume percent is not reached until after 28 days. Hydrogen recombination begins prior to reaching this limit. The passive autocatalytic recombiners are brought into service by the presence of the reactants. The available passive autocatalytic recombiner test data as discussed in Reference 19 supports passive autocatalytic recombiner startup within 7 hours of reaching 1 volume percent hydrogen concentration in containment. Subsequent to passive autocatalytic recombiner startup the conservative lower bound equation for depletion rates provided in Reference 19 has been used to predict containment concentrationsconsidering only the PARs between the 150 and 175 foot elevations. Figure 6.2.4-1 ~~also~~ shows the impact of operation of one of the two recombiners on containment hydrogen concentration. The hydrogen concentration never exceeds 1.5 percent which indicates ample margin in the hydrogen recombiner capacity. Figure 6.2.4-2 evaluates the containment hydrogen concentration using the same lower bound equation for a single PAR's depletion rate but with additional conservatism to account for catalyst poisons or evaluation of margin. The curve identified as "Worst Case PAR Depletion Rate with Catalyst Poisons" has been reduced as a result of the effects of poisons and inhibitors which could be released to containment following a core melt scenario progressing through reactor coolant, gap, and early in-vessel releases. In accordance with Reference 28 the lower bound depletion rate has been reduced by 25 percent to conservatively account for the effects of potential poisons and inhibitors.

A further demonstration of the passive autocatalytic recombiner's available capacity margin is provided by calculation of containment concentrations with artificially reduced depletion rates. Figure 6.2.4-2 provides the impact of one of two available passive autocatalytic recombiners operating at 20, 10 and 1 percent of the conservative lower bound capacity. The curves provide indication of the abundant hydrogen control margin. Also provided in Figure 6.2.4-2 are the results of a calculation assuming no recombination until the hydrogen concentration reaches 3.5 volume percent in containment. Although a zero depletion rate until concentration reaches a 3.5 percent threshold is excessively conservative, the results emphasize the abundant margin.

6.2.4.4 Design Evaluation (Severe Accident)

Although a severe accident involving major core degradation or core melt is not a design basis accident, the containment hydrogen control system contains design features to address this potential occurrence. The hydrogen monitoring subsystem has sufficient range to monitor concentrations up to 20 percent hydrogen. The hydrogen ignition subsystem is provided so that hydrogen is burned off in a controlled manner, preventing the possibility of deflagration with supersonic flame front propagation which could result in large pressure spikes in the containment.

The hydrogen released to the containment due to initial inventory of hydrogen in the coolant would be the same as for the design basis case (see subsection 6.2.4.3.1.4).

The hydrogen production due to corrosion of aluminum and zinc or to radiolysis of water is not of concern for evaluating the containment hydrogen control system for the severe accident since hydrogen production from these sources takes place at a relatively slow rate and over a long period of time.

It is assumed that 100 percent of the active fuel cladding zirconium reacts with steam. This reaction may take several hours to complete. The igniters initiate hydrogen burns at concentrations less than 10 percent by volume and prevent the containment hydrogen concentration from exceeding this limit. Further evaluation of hydrogen control by the igniters is presented in the AP600 Probabilistic Risk Assessment.

6.2.4.5 Tests and Inspections

6.2.4.5.1 Preoperational Inspection and Testing

Hydrogen Monitoring Subsystem

Pre-operational testing is performed either before or after installation but prior to plant startup to verify performance.

Hydrogen Recombination Subsystem

Pre-operational testing is performed following vendor production testing and installation but prior to plant startup to verify PAR performance. The PAR's are verified to provide a hydrogen depletion rate of greater than or equal to the minimum depletion rate identified in Table 6.2.4-2. It is also verified that two PAR's are installed within containment at an elevation of between 150 and 175 feet with the PAR centerline at least 10 feet from the containment shell. It is also verified that a PAR is located in the exhaust of an IRWST vent and within the chemical and volume control system compartment.

A sample of the PAR cartridges or plates are selected and removed from each passive autocatalytic recombiner and surveillance bench tests are performed on the removed specimens to confirm continued satisfactory performance. The specimen is placed in a performance test apparatus and exposed to a known standard air/hydrogen sample. The test instrumentation will be designed to assess PAR performance and the time to reach a threshold recombination start ~~is~~ used to measure degradation in catalytic action. The overall PAR performance verification will be based on vendor testing recommendations and may include among other means recombiner internal or exhaust temperature measurement or exhaust sample concentrations measurement. Should internal temperature measurement be utilized as the measured recombination parameter, location of the sensor must be consistent for all samples and with vendor test recommendations to assure consistency between tests. The recombiner start verification will be based on a time dependent measurement of the recombination rate parameter or other instrumentation verifying the recombination start. The vendor manufacturing acceptance data or accepted industry standards will be utilized as acceptance data provided it represents performance in excess of the required rate specified in Table 6.2.4-2

Hydrogen Ignition Subsystem

Pre-operational testing and inspection is performed after installation of the hydrogen ignition system and prior to plant startup to verify operability of the hydrogen igniters. It is verified that 64~~0~~ igniter assemblies are installed at the locations defined by Figures 6.2.4-5 through 6.2.4-11. Operability of the igniters is confirmed by verification of the surface temperature in excess of the value specified in Table 6.2.4-3. This temperature is sufficient to ensure ignition of hydrogen concentrations above the flammability limit.

6.2.4.5.2 In-service Testing

Hydrogen Monitoring Subsystem

The system is normally ~~in~~ service. Periodic testing and calibration are performed to provide ongoing confirmation that the hydrogen monitoring function can be reliably performed.

26. "AP600 Accident Analyses-Evaluation Models," WCAP-14601, Revision 1 (Proprietary).

27. Thomas T. Marten, "AP600 Use of Passive Autocatalytic Recombiners (PARs) for Design Basis Hydrogen Control" to Mr. Nicholas Liparulo, April 1, 1997.

28. EPRI Report, "The Effects of Inhibitors and Poisons on the Performance of Passive Autocatalytic Recombiners for Combustible Gas Control in ALWRs," May 22, 1997.

29. EPRI Report TR-107517, Volumes 1, 2, and 3, "Generic Model Tests of Passive Autocatalytic Recombiners (PARs) for Combustible Gas Control in Nuclear Power Plants," June 1997.

Table 6.2.4-2

COMPONENT DATA - HYDROGEN RECOMBINER (NOMINAL)

Number	~~2~~
Full Size PAR	2
Partial size PAR	2
Inlet hydrogen concentration range for design basis events (volume percent)	0 - 4
Average efficiency (percent)	85
Depletion rate	Reference 19
Minimum acceptable depletion rate ~~(@120°F and atmospheric pressure)~~	
Full Size PAR	1 scfm
Partial Size PAR	0.25 scfm

* Determined at prevailing conditions of 120°F, 3.5 volume percent of hydrogen and atmospheric pressure.

Table 6.2.4-3

COMPONENT DATA - HYDROGEN IGNITER (NOMINAL)

Number	64
Surface Temperature (°F)	1600 to 1700

Table 6.2.4-6 (Sheet 1 of 3)

IGNITER LOCATION

Criteria

- A sufficient number of igniters are placed in the major transport paths (including dominant natural circulation pathways) of hydrogen so that hydrogen can be burned continuously close to the release point. This prevents hydrogen from preferentially accumulating in a certain region of the containment.
- Igniters (minimum of 2) are located in major regions or compartments where hydrogen may be released, through which it may flow, or where it may accumulate.
- It is preferable to ignite a hydrogen-air mixture at the bottom so that upward flame propagation can be promoted at lean hydrogen concentrations. Igniters within each subcompartment are located in the vicinity of, and above, the highest potential release location within the subcompartment.
- In compartments with relatively small openings in the ceiling, the potential may exist for the hydrogen-air mixture to rise and to collect near the ceiling. Therefore, one or more igniters are placed near the ceiling of such compartments. Igniter coverage is provided within the upper 10 percent of the vertical height subcompartments or 10 feet from the ceiling whichever is less. In cases where the highest potential release point is low in the compartment, both this and the previous criteria are considered.
- To the extent possible, igniters are placed away from walls and other large surfaces so that a flame front created by ignition at the bottom of a compartment can travel unimpeded up to the top.
- A sufficient number of igniters are installed in long, narrow compartments (corridors) so that the flame fronts created by the igniters need to travel only a limited distance before they merge. This limits the potential for significant flame acceleration.
- Igniter coverge are provided to contol combustion in areas where oxygen rich air may enter into an inerted region with combustible hydrogen levels during an accident scenario.
- Igniters are located above the flood level, if possible. Those which may be flooded have redundant fuses to protect the power supply.
- In locations where the potential hydrogen release location can be defined, i.e. above the IRWST spargers, at IRWST vents, etc igniter coverage is provided as close to the source as feasible.
- Provisions for installation, maintenance, and testing is be considered.

Table 6.2.4-6 (Sheet 2 of 3)

IGNITER LOCATION

Implementation

- *Reactor cavity* – Hydrogen releases within the reactor cavity will flow either through the vertical access tunnel, through the opening around the RCS hot and cold legs into the loop compartments or if the refueling cavity seal ring fails then potentially through the refueling cavity. The potential flow paths have at least four igniters with at least two powered by each of two power groups. No igniters have been located within the reactor cavity since this region would always be flooded, adequate igniter coverage is available in hydrogen pathways from the reactor cavity and any maintenance or inspection would result in elevated personnel exposure.

- *Loop Compartments* – Hydrogen releases from the hot or cold legs or from the reactor cavity would flow up through the loop compartment to the dome region. Igniter coverage provided within the loop compartment consists of a total of four igniters at two different elevations covering the perimeter of the compartment and with two igniters powered by one power group and two by the second power group. Additional coverage is provided above the loop compartments at elevation 162' with four igniters above each loop compartment and powered by different power groups.

- *Pressurizer Compartment* – Hydrogen releases within the pressurizer compartment would flow up through the compartment toward the dome region. Igniter coverage is provided within the compartment consists of a total of four igniters at two different elevations covering the perimeter of the compartment with two igniters powered by one power group and two by the second power group. Additional coverage is provided above the pressurizer compartment at elevation 162' with two igniters above powered by different power groups.

- *Tunnel Connection Loop Compartments* – The tunnel between the loop compartments and extending downward into the reactor coolant drain tank cavity is provided with four igniters for hydrogen control. Releases within the reactor cavity or from the loop compartment may flow through this vertical access tunnel. Igniter coverage is provided over the width of the tunnel at three separate elevations and are powered by different power groups.

- *Refueling Cavity* – Hydrogen releases from the reactor cavity or from the potentially from the reactor coolant loops may flow up past the refueling cavity seal ring and through the refueling cavity to the dome region. Igniter coverage provided within the refueling consists of a total of four igniters at two different elevations covering the perimeter of the compartment with two igniters powered by one power group and two by the second power group. Additional coverage is provided above the refueling cavity at elevation 162' with four igniters powered by different power groups.

- *Southeast Valve and Accumulator Rooms* – Hydrogen releases within the southeast valve or accumulator rooms will rise with the mass and energy releases to near the ceiling and exit either through the stairwell on the west wall or through piping penetration holes in the ceiling. The hydrogen control protection is provided by two igniters, one located near the ceiling of each of the adjoining rooms. The igniters are powered by different power groups and provide backup control for each other.

Table 6.2.4-6 (Sheet 3 of 3)

IGNITER LOCATION

- *East Valve, Northeast Accumulator, and Northeast Valve Room* – Hydrogen releases within the east valve, northeast accumulator or valve rooms will rise with the mass and energy releases to near the ceiling and exit either through the enlarged vent area surrounding the discharge piping from the core makeup tank located at the 107" 2"" elevation and through other piping penetration holes in the ceiling. The hydrogen control protection is provided by three igniters, one located near the ceiling of each of the adjoining rooms. The igniters are powered by different power groups and provide backup control for each other.

- *North CVS Equipment Room* – Hydrogen releases within the CVS equipment room will rise from the piping or equipment located on the CVS module to near the ceiling, pass over the outer barrier wall and flow up through the stairwell or ceiling grating. Hydrogen control is provided by two igniters located near the ceiling of the equipment room between the equipment module and the major relief paths from the compartment. The igniters are powered by different power groups.

- *IRWST* – Hydrogen releases into the IRWST are controlled by the distribution of igniters internal to the IRWST and within the vents from and into the IRWST. Two igniters on different power groups are located within the IRWST below the tank roof of the IRWST and above the spargers. In the event of hydrogen releases via the spargers, the igniters directly above the release points will provide the most immediate point of recombination. Should the environment within the IRWST be inerted or otherwise not be ignited by the assemblies above the sparger, the hydrogen will be ignited as it exhausts from the IRWST at any of four of the vents fitted with igniter assemblies. Two of the four igniters are powered by one power group and two by the second power group. Finally, in the event that the IRWST is hydrogen rich and air is drawn into the IRWST the mixture will become flammable. In order to provide this recombination, the two inlet vents on the other side of the IRWST from the sparger and primary exhaust vents are fitted an igniter each.

- *Lower Compartment Area* – Hydrogen releases within the lower compartment will rise with the mass and energy releases to near the ceiling and exit either through the north stairwell or along the circumferential gap between the operating deck and the containment shell. The hydrogen control protection is provided by eleven igniters spread over the potential release areas and located either just above the mezzanine deck elevation or near the ceiling. This approach provides wide coverage over the entire compartment area at two separate elevations. The igniters are split between the two separate power groups.

- *Upper Compartment* – Hydrogen control is provided at three separate levels within the upper compartment. At the 162 foot elevation, 10 igniters are distributed over the area primarily above the major release flow paths including the loop compartments, refueling cavity, pressurizer compartment and above the stairwell from the lower compartment area. The igniters are split between the two power groups. At 210 foot elevation, an igniter is provided in each quadrant at the mid region of the upper compartment with two igniter on each of the two power groups. At the upper region elevation 235 four additional igniters are located to initiate recombination of hydrogen not ignited at either the source or along its flow path. The four igniters are split between the two power groups.

Table 6.2.4-7

SUBCOMPARTMENT/AREA IGNITER COVERAGE

Subcompartment	Igniter Coverage (Elevation)[1] Power Group 1	 Power Group 2
Reactor Cavity	1(El 91') 3 (El 95') 13, 5, 55 (El 120') 58 (El 132') 8, 12 (El 139')	4 (El 95') 2 (El 99') 11, 7, 56 (El 120') 57 (El 132') 6, 14 (El 139')
Loop Compartment 01	13 (El 120') 12 (El 139')	11 (El 120') 14 (El 139')
Loop Compartment 02	5 (El 120') 8 (El 139')	7 (El 120') 6 (El 139')
Pressurizer Compartment	49 (El 154') 60 (El 135')	50 (El 154') 59 (El 135')
Tunnel connecting Loop Compartments	1 (El 91') 3 (El 95') 31 (El 120')	4 (El 95') 2 (El 99') 30 (El 120')
Southeast Valve Room	21 (El 105')	20 (El 105')
Southeast Accumulator Room	21 (El 105')	20 (El 105')
East Valve Room	18 (El 105')	19 (El 105')
Northeast Accumulator Room	18 (El 105')	17, 19 (El 105')
Northeast Valve Room	18 (El 105')	17 (El 105')
North CVS Equipment Room	34 (El 105')	33 (El 105')
Lower Compartment Area (CMT and Valve area)	22 (El 133') 27, 28, 29, 31, 32 (El 120')	23, 24, 25 (El 133') 26, 30 (El 120')
IRWST Compartment	35, 37 (El 135')	36, 38 (El 135')
IRWST Interior	9 (El 133')	10 (El 133')
IRWST Inlet	16 (El 133')	15 (El 133')
Refueling Cavity	55 (El 120') 58 (El 132')	56 (El 120') 57 (El 132')
Upper Compartment		
Lower Region	39, 42, 44, 43, 47 (El 162')	40, 41, 45, 46, 48 (El 162')
Mid Region	51, 54 (El 210')	52, 53 (El 210')
Upper Region	61, 63 (El 235')	62, 64 (El 235')

<u>Note:</u>
1. Elevations are approximate.

APPENDIX 6A

HYDROGEN AND FISSION PRODUCT DISTRIBUTION IN THE AP600 POST-DESIGN BASIS ACCIDENT CONTAINMENT ATMOSPHERE

The AP600 design-basis analyses for hydrogen control (subsection 6.2.4.3) and natural aerosol removal coefficient (Appendix 15B) assume that the fission products and hydrogen released to the containment following a postulated design basis loss of coolant accident (LOCA) are homogeneously distributed in the containment atmosphere within the open compartments that participate in natural circulation. The purpose of this discussion is to justify the homogeneous assumption for hydrogen control (recombiner placement) and aerosol natural deposition calculations.

The following evaluation includes:

- Identification of the accident sequence assumptions and boundary conditions in the reactor coolant system and containment prior to the fission product and hydrogen releases
- Identification of the limiting steam and fission product release location from the reactor coolant system to the containment
- Identification of the design basis hydrogen source locations in the containment
- Discussion of containment natural circulation in quasi-steady conditions
- Discussion of AP600 passive containment cooling system (PCS) large-scale test (LST) insights that support the well-mixed assumption

6A.1 Design Basis Sequence Assumptions

The design-basis fission product source term (subsection 15.6.5.3.1) and hydrogen source term (subsection 6.2.4.3) are superimposed onto a thermal-hydraulic conditions of the design-basis accident sequence for the evaluation of fission product deposition and hydrogen recombination. The following assumptions define the design basis conditions. The AP600 design-basis sequence consists of a LOCA which drains the reactor coolant system (RCS) and core makeup tanks (CMTs) sufficiently to activate the automatic depressurization system (ADS). Both trains of all four stages of automatic depressurization system open sequentially. During the depressurization, the core makeup tanks and accumulators inject into the reactor vessel downcomer. The final reactor coolant system pressure is essentially equal to the containment pressure which allows gravity injection of the IRWST water. Steam is produced in the vessel at the rate dictated by decay heat minus the heat in the volatile fission products which have been released from the core. The passive containment cooling system water flow is initiated based on high containment pressure from the blowdown or the automatic depressurization system prior to the release of fission products.

Fission product release occurs from a fully depressurized reactor coolant system. The aerosols are carried into the containment in a buoyancy-driven steam flow. The earliest time of fission product release from core degradation is conservatively shown to be approximately 50 minutes after accident initiation (subsection 15.6.5.3.1), well past the time of the blowdown or automatic depressurization system. Hydrogen is released over the long-term as a result of the radiolysis of water and corrosion of aluminum and zinc. The containment condition during and following the release is quasi-steady-state. Internal heat sinks are assumed to be essentially thermally-saturated and no longer effective, and the condensation rate of steam on the containment dome and shell is equivalent to the decay heat steaming rate.

6A.1.1 Break Size and Fission Product Release Location in Containment

This section discusses each of the postulated fission product release locations from the reactor coolant system, the containment location for each, the size limitations and the phenomena associated with the break locations. It is shown that it is appropriate to assume that the steam and fission products are released from the reactor coolant system hot leg to the containment above the maximum water flood-up elevation in the steam generator compartment gas space.

6A.1.1.1 Releases From Depressurization System Lines

Any design-basis LOCA which can be postulated to produce a large core activity release to containment will actuate the four stages of the automatic depressurization system. The stage 1, 2 and 3 automatic depressurization system lines, which relieve from the top of the pressurizer (see Figure 6A-1), deliver flow to the containment through the in-containment refueling water storage tank (IRWST). This is not considered to be a major fission product release pathway because the IRWST is a cold, effectively closed system with no leakage pathway to the environment. The IRWST is nearly full of water during the depressurization blowdown which would trap any postulated fission products released to the IRWST. At the time the water is drained below the spargers, the reactor coolant system is depressurized with stage 4 automatic depressurization system open, and the IRWST vents, which are closed with flappers, are not expected be significantly opened by the small buoyancy-driven flows. Aerosols released from stages 1, 2 and 3, either before or after the draining of the IRWST, would essentially be trapped in the water or in the IRWST compartment. Therefore, this pathway is conservatively neglected as a release pathway from the reactor coolant system to maximize the activity entering the containment atmosphere.

Stage 4 automatic depressurization system lines relieve reactor coolant system coolant, steam, and fission products from the hot legs (see Figure 6A-1) to the steam generator compartments above the maximum water flood-up level. The stage 4 lines consist of four 10-inch schedule 160 lines. Two lines are connected to each of the two hot legs. Each of these trains relieves at the 112-foot elevation to a steam generator compartment.

Of the postulated release locations in the reactor coolant system, openings in the hot-side piping, such as the stage 4 automatic depressurization system, provide the lowest resistance pathway for fission product releases to the containment because of the large flow area, high temperatures, short resident time and low surface area for aerosol deposition in the reactor coolant system. To reach openings in the cold side piping when stage 4 automatic depressurization system valves are open, the reactor coolant system low-pressure natural circulation flow must pass through the steam generator tubes (see Figure 6A-1). At the superheated steam temperature of the gas which accompanies the fission product flow, significant heat transfer would take place in the steam generator tubes which are cooled on the secondary side by water. Aerosol deposition to the tubes would remove fission products from the release before the flow reached the containment. Therefore, releases from cold-side breaks are less severe than hot side breaks with the stage 4 automatic depressurization system open.

6A.1.1.2 Releases From Coolant Loop Breaks

Breaks in the reactor coolant system loop piping (hot legs or cold legs) relieve primary coolant, steam and fission products to the steam generator compartments. Assuming double-ended guillotine breaks, the hot-leg break has a diameter of 31 inches (78.7 cm), the cold-leg break has a diameter of 22 inches (55.9 cm). Breaks in the hot leg piping are more limiting than breaks in the cold leg with respect to the fission product releases to the containment because of the larger break area, higher temperatures, shorter resident time and lower surface area for aerosol deposition in the reactor coolant system. Therefore, of the coolant loop breaks, hot leg breaks to the steam generator compartment provide the more conservative magnitude of fission product release to the containment. Because of the similar fission product flow path, release magnitude and release location, the hot leg breaks can be lumped with the stage 4 automatic depressurization system releases.

6A.1.1.3 Direct Vessel Injection Line Breaks

A break in one of the two direct vessel injection lines can relieve steam and fission products outside the steam generator compartments to one of the two dead-ended accumulator compartments below the core makeup tank Room. The piping is 8-inch diameter schedule 160 piping, but an orifice at the reactor vessel wall limits the break size to a 4-inch diameter. The nozzle connects to the reactor vessel downcomer (see Figure 6A-1), so all direct vessel injection line breaks relieve from the cold-side of the reactor coolant system. The accumulator compartments have significant heat sink surfaces (equipment, grating, support structures and compartment walls) for aerosol deposition to trap fission products within the dead-ended compartment. Given the small break size, cold-side location of the break, the compartment retention capacity, and the large relief flow area associated with the open stage 4 automatic depressurization system valves, very little fission product release is expected from the direct vessel injection line. The steam release to an accumulator compartment is negligible with respect to that from the stage 4 automatic depressurization system.

6A.1.1.4 Core Makeup Tank Balance Line Breaks

Breaks in the core makeup tank balance lines can relieve steam and fission products to the core makeup tank room. The balance line piping is 8-inch diameter schedule 160 piping. The balance line nozzle is attached to a cold leg (see Figure 6A-1). Given the small break size, cold-side location of the break, the compartment retention capacity, and the large relief flow area associated with the open stage 4 automatic depressurization system valves, very little fission product release is expected from the balance line. The steam, hydrogen and fission product releases to the core makeup tank room is negligible with respect to the release from the stage 4 automatic depressurization system.

6A.1.1.5 Chemical and Volume Control System Line Breaks

A break in the chemical and volume control system (CVS) line relieves to the dead-ended chemical and volume control system compartment below the core makeup tank room. The chemical and volume control system piping is 3-inch diameter schedule 160 piping. The inlet of the chemical and volume control system draws from the cold leg and the outlet discharges to the reactor coolant pump suction, both on the cold-side of the reactor coolant system (see Figure 6A-1). Given the small break size, cold-side location of the break, the compartment retention capacity, and the large relief flow area associated with the open stage 4 automatic depressurization system valves, very little fission product release is expected from the chemical and volume control system piping. The steam release to the chemical and volume control system compartment is negligible with respect to that from the stage 4 automatic depressurization system.

6A.1.1.6 Fission Product Release Location Conclusion

The fission product releases are expected to discharge mainly from the stage 4 automatic depressurization system lines, which relieve from the hot legs to the steam generator compartments. Stage 4 automatic depressurization system is open in all design-basis LOCA sequences that can be postulated to produce large core activity releases to the containment. For a coolant loop break, the release would also go to the steam generator compartments along with the releases from the stage 4 automatic depressurization system lines. Fission products released to other postulated containment locations are negligible by comparison because the releases are from the cold-side of the reactor coolant system through comparatively long and narrow piping pathways. Therefore, the bounding release pathway is a hot-side break into the steam generator compartments with fission product and steam releases through the break and stage 4 automatic depressurization system.

6A.1.2 Design-Basis Hydrogen Source Locations

The hydrogen source for long-term, design-basis hydrogen release is from water pools in the containment. There are two potential locations for substantial water pools in the AP600 containment, the floodable region of the containment (that includes the reactor cavity, the lower steam generator compartment, the tunnel between the steam generator compartments and the core makeup tank room to the 108' 2" elevation), and the compartments below the core makeup tank room floor (that includes the two accumulator compartments and the chemical and volume control system compartment).

In a design-basis accident, the floodable region of the containment may be submerged up to approximately the 108' elevation. The accumulator compartments are curbed to the 108' 2" elevation to prevent water from overflowing into them. The chemical and volume control system compartment is curbed at a lower elevation to provide a reservoir to assure that the accumulator compartments cannot be flooded from overflow. Water may overflow into the chemical and volume control system compartment, but not over the curbs into the accumulator compartments. If an reactor coolant system break occurs in an accumulator compartment, the compartment will be completely filled with water and overflow into the core makeup tank room, the chemical and volume control system compartment and the floodable region. The cavity, reactor coolant drain tank room and the tunnel are submerged. The accumulator compartments are either both not flooded or one (with the reactor coolant system break) is completely submerged and the other is not flooded. The IRWST always has a water pool surface. Therefore, the water pool surface, which is the source location of the long-term design basis hydrogen release, can be located in the steam generator compartments, the core makeup tank room, the chemical and volume control system compartment and the IRWST.

Boundary Conditions for Evaluating Circulation and Stratification in Design Basis Hydrogen and Source Term Analyses

Based on the design-basis sequence, the following assumed boundary conditions apply in the containment:

- Steam is released from the reactor coolant system into both steam generator compartments through stage 4 automatic depressurization system, low in the containment (elevation 112 ft), at the rate of decay heat,
- The fission products are released as discussed in subsection 15.6.5.3.1, along with the steam flow, over a period of 1.8 hours,
- The reactor coolant system is depressurized prior to the fission product release which begins at 50 minutes, so the flow entering containment from the reactor coolant system is buoyancy driven,
- The containment conditions are quasi-steady-state and the internal heat sinks are essentially thermally-saturated, so the condensation rate on the containment is assumed to be equal to the steaming rate,
- The containment is flooded to the 108' elevation,
- Hydrogen is released to the containment from water pools in the core makeup tank room, chemical and volume control system compartment and steam generator compartments at a rate described in section 6.2.4.3.

6A.2 Containment Natural Circulation and Mixing

This section describes the natural circulation flow path and the entrainment processes in the containment atmosphere. Figure 6A-2 graphically depicts the containment natural circulation flow paths and the entrainment processes.

The steam plume, rising from a point low in the containment, and the condensation on the containment surface and wall entrainment rates provide the driving forces for natural circulation in the containment. Based on the sequence timing, the containment conditions at the time of the fission product and hydrogen releases are quasi-steady-state. Therefore, it is assumed:

$Q_{st} \approx$ constant
$Q_{cond} = Q_{st}$

where:
Q_{st} = steam volumetric flowrate
Q_{cond} = condensation volumetric flowrate.

Steam and fission products are released low in the containment through stage 4 automatic depressurization system at the 112-foot elevation as hot, buoyant plumes from the low pressure primary system into the steam generator compartments. Entrainment into the rising plume drives circulation of surrounding atmosphere into the bottom of the steam generator compartment through the openings to the core makeup tank room. The fission products are released from the reactor coolant system with the steam plumes. The plumes rise through the steam generator compartments, mix with the flow entrained from below and are released into the upper compartment at the top of the steam generator doghouses (148-foot elevation). The plumes rise unconstrained for over 100 feet in the containment. As the plumes rise, the surrounding upper compartment gas mixture is entrained. The steam, fission products and any non-condensable gases (e.g. hydrogen and air) in the plumes are mixed with a large volume of entrained atmosphere in the rising plume.

An estimate of the volume entrained into the plume above the operating deck is made conservatively neglecting entrainment into the lower steam generator compartment, and assuming the plumes from the two steam generator compartments behave as one:

$Q_{ent} = 0.15 * B^{1/3} * Z^{5/3}$ (Reference 1)

where:
Q_{ent} = volumetric flowrate of entrained gas in the rising plume above the operating deck
Z = height of rising plume
$B = g*Q_{ST}*(\rho_{amb} - \rho_{st})/\rho_{amb}$
g = gravitational acceleration

The fission product releases occur at approximately 1 hour when the best estimate (no uncertainty) 1979 ANS decay heat rate is 1.4%. At one hour, the volatile fission products which are released from the core contribute 30% of the decay heat, so the decay heat fraction is 1.0% and 19 MW of steam is generated in the reactor vessel. At a containment pressure of approximately 50 psia, the source flow is approximately 165 ft^3/sec and $\Delta\rho/\rho$ is approximately 1/4. Thus, $B^{1/3}$ = 11 ft$^{4/3}$/sec. For a release into the upper compartment where Z = 100 ft, Q_{ent} = 3500 ft^3/sec and Q_{ent}/Q_{st} = 21.

At 24 hours, best estimate (no uncertainty) 1979 ANS decay heat is 0.6%, and the volatile fission products released from the core contribute 15% of the decay heat. The heat generated in the vessel, generating steam is 9.7 MW, the containment pressure is 34 psia and $\Delta\rho/\rho$ = 0.32. So the source flow is approximately 121 ft^3/sec, $B^{1/3}$ = 10.7 $ft^{4/3}$/sec, Q_{ent} = 3400 ft^3/sec and Q_{ent}/Q_{st} = 28. Therefore, for the AP600 height above the operating deck, a conservative entrainment ratio for times greater than 1 hour after accident initiation is:

$$Q_{ent}/Q_{st} > 20$$

The application of water to the external surface of the containment shell maintains the containment shell at a cool temperature. The condensation of steam on the containment shell creates a heavy, air-rich downward flowing gas boundary layer on the wall. Fission products are carried along in the wall layer flow. As it flows downward along the wall, the wall layer also entrains surrounding mixture. Thus, the circulation flow rate in the above-deck volume generates significant circulation flow.

A review of literature on circulation within enclosures (appendix 9.C of Reference 2) shows that as long as there is cooling on the inner surface of the containment shell, there are no regions of stratification in the containment including under the containment dome. There are significant recirculation flows in the stratified regions between the plume and the wall layer. Thus concentration gradients are small and there are no stagnant regions above the operating deck.

The circulation time constant due to entrainment above the operating deck for the AP600 can be estimated by $V/(20*Q_{st})$, where V is the containment volume above the operating deck, and the steam generator compartments and core makeup tank room above the 108' elevation, 1.62×10^6 ft^3. Therefore, the circulation time constant at 1 hour is approximately 490 seconds. At 24 hours it is 670 seconds. The time constant is estimated to be conservatively large as it does not include entrainment into the downward flowing wall layer. At 1 hour, during the fission product release, the time constant of 490 seconds is very short compared to the 1.3 hour fission product release duration. In the long term, the plume entrainment rate of 3400 ft^3/sec is much greater than the long-term hydrogen release rate which is on the order of 0.1 ft^3/sec (see Figure 6.2.4-3). The time constant at 24 hours is more than 1000 times shorter than the hydrogen release time constant. Therefore, the fission products and hydrogen can be assumed to be homogeneous within the gas volume as soon as they are released. There is no stagnant region in the upper compartment as the entire volume participates in the rising plume, entrainment flow and wall layer. Stratification exists in the form of a relatively shallow, continuous vertical steam gradient as discussed in section 3.0.

Over the time period of interest, no mechanisms exist .o separate the non-condensable gases (air and hydrogen) once they are mixed in the rising plumes. The molecular weight difference is so overwhelmed by natural circulation it does not lead to gravitational separation. The terminal gravitational settling rate of hydrogen in air at 1 atm and 25°C is less than 10^{-6} cm/sec (Reference 4). Over the height of the upper compartment, 100 ft, the average separation length is 50 ft (1524 cm) so the time for gravitational separation of the hydrogen and air is 1.5×10^9 seconds. By comparing the separation time to the time constant for the plume entrainment circulation (670 seconds) it is determined that the separation rate is orders of magnitude less effective than the convective mixing forces. Thus gravity effects do not lead to separation of hydrogen from the non-condensable mixture.

As the downward boundary layer flow reaches the operating deck (135-foot elevation), it has been cooled and somewhat depleted of steam. The air, hydrogen and fission products remain well-mixed in the flow. Vents in the operating deck (135' elevation, see Figure 6A-2) along the wall allow the denser gases to "drain" down into the core makeup tank room and circulate through the doorways which empty to the steam generator compartments. Little condensation is expected below the operating deck in the quasi-steady-state condition as the metal heat sinks are essentially thermally-saturated. The condensation on heat sinks below the operating deck is small compared to that on the steel shell. The core makeup tank room communicates with the steam generator compartments such that air flow will freely pass to the steam generator compartments. In the steam generator compartment, the circulation flow is entrained by the initial steam source, and the circuit begins again.

The accumulator and chemical and volume control system compartments and the reactor cavity, including the reactor coolant drain tank room, do not participate in the large-scale natural circulation flow as they are dead-ended or filled with water. The IRWST compartment is essentially sealed at the vents by flappers after blowdown. The accumulator and chemical and volume control system compartments, IRWST, reactor cavity and reactor coolant drain tank compartments are not considered in the calculation of the aerosol deposition. For the hydrogen control analysis, the chemical and volume control system and IRWST compartments are included as confined volumes that may have water pools that provide a source of hydrogen. The other compartments are either completely water-filled or do not contain a significant pool of water for hydrogen generation.

6A.3 Insights From the Passive Containment Cooling System Large Scale Test and AP600 Stratification Studies

The AP600 Passive containment cooling system Large Scale Test (LST) provides insight into the circulation and stratification behavior in the AP600 containment. The following results are consistent with international test data from various scales (Reference 2, appendix 9.C). Since the large scale test did not include a flow path into the simulated steam generator compartment, the degree of mixing of injected light non-condensable gases with the existing air throughout the test vessel is conservatively underestimated. This is because the extra flow path would allow density-driven circulation through the path into the compartment, introducing an additional mixing mechanism which exists in AP600.

In the large scale test rising plume, large amounts of surrounding air-steam mixture were entrained with the released gases. Estimates of entrainment above the deck in large scale test show that about one times the break volumetric flow is entrained. In several large scale test tests, 217.1, 218.1, 219.1, and 221.1, in which helium (a hydrogen simulant) was released in an amount equal to 10-20 volume percent, non-condensable gas concentrations were measured (Reference 3). The helium fraction was reduced from 100% at the release point to 50% of the non-condensable gas in the dome during the initial period of injection. For design basis hydrogen releases, the hydrogen concentration as a fraction of the non-condensable gas in the dome would be much less due to the increased height for entrainment.

The existence of circulation under the dome in the large scale test can be seen based on the reduction of helium non-condensable fraction over time after the helium release stops. The mixing of helium above the deck establishes homogeneous concentrations in only a few minutes in the large scale test. Note that it was seen to take hours for the circulation to mix the injected helium with the non-condensable gases in the compartment below the deck, however, this was due to a lack of a flow path in the simulated steam generator compartments. Because of the additional height for entrainment in the AP600, circulation is about 10 times greater than in the large scale test based on plume entrainment alone. Wall layer entrainment and circulation through the steam generator compartment would further increase the circulation in AP600. This result indicates that in the AP600 circulation distributes the injected non-condensable gases with the air throughout the containment quickly compared to the rate of release.

The effect of external cooling on non-condensable gas distributions was studied in large scale test 219.1 which started out with a dry external shell, injected helium, and then initiated the external water cooling. Non-condensable gas data showed that the application of external cooling acts to accelerate the mixing of non-condensable gases, which is probably due to the higher wall layer entrainment rate from the higher condensation rate on the cooler shell.

As discussed above, the fluid dynamics of entrainment into a buoyant plume and wall boundary layers generate large amounts of circulation within the above deck region. Thus, the region is not a static, layered stratification, and there are no stagnant pockets of gases that do not participate in the circulation. The physics do, however, lead to a standing vertical steam density gradient in the circulating stratified region, which will tend to be slightly richer in steam at the top due to the lower density of the injected steam.

Based on the above, at quasi-steady conditions, the decay heat steaming and heat and mass transfer to the steel shell create natural circulation in the containment that mixes the fission products and hydrogen quickly throughout the circulating volume. Circulation time constants indicate that it is reasonable to assume non-condensable gases and fission products can be assumed to be homogeneous in the volumes participating in the circulation. The rising plume and the cooling of the shell create a vertical steam density gradient and a vertical temperature gradient in the upper compartment circulating stratified region. The density and temperature gradients result from a balance between the forces that drive the natural circulation. In the evaluation, no credit is taken for cold plumes falling from the containment dome which cause further circulation above the operating deck.

Based on the above, condensation and sensible heat transfer occur over the entire steel shell, albeit at different rates over the height of the shell. As shown in Appendix 15B, thermophoresis and diffusiophoresis are directly related to the heat and mass transfer. Fission products are present at all sites of steam condensation and sensible heat transfer in the containment. In Appendix 15B, the processes are modeled by assuming homogeneous aerosol mass distribution throughout the circulating volume and averaging the steam condensation and sensible heat transfer over the entire upper shell. This treatment provides a valid estimate of the aerosol deposition rates.

6A.4 Conclusions

Based on first principal arguments and insight from testing at various scales, the following conclusions are made with respect to mixing in the AP600 containment during quasi-steady conditions:

- As long as there is cooling on the inner surface of the containment shell, downward wall flow will prevent stagnation under the dome,

- No unmixed pockets develop as the doorways extend to the floor and vents are in the ceiling. For the rooms participating in the natural circulation flow, the entire volume participates in the circulation,

- The rising plume, condensation of steam on the containment shell, and downward flowing wall layer create vertical steam density and temperature gradients above the operating deck

- Fission products and hydrogen are quickly and uniformly mixed, relative to the duration of the release, in the containment volumes participating in the natural circulation

- For the purpose of calculating long-term aerosol deposition and hydrogen depletion, it is reasonable to assume that aerosols and non-condensable gases are homogeneous throughout the major compartments participating in the containment natural circulation: the steam generator compartments, upper compartment and core makeup tank room.

6A.5 References

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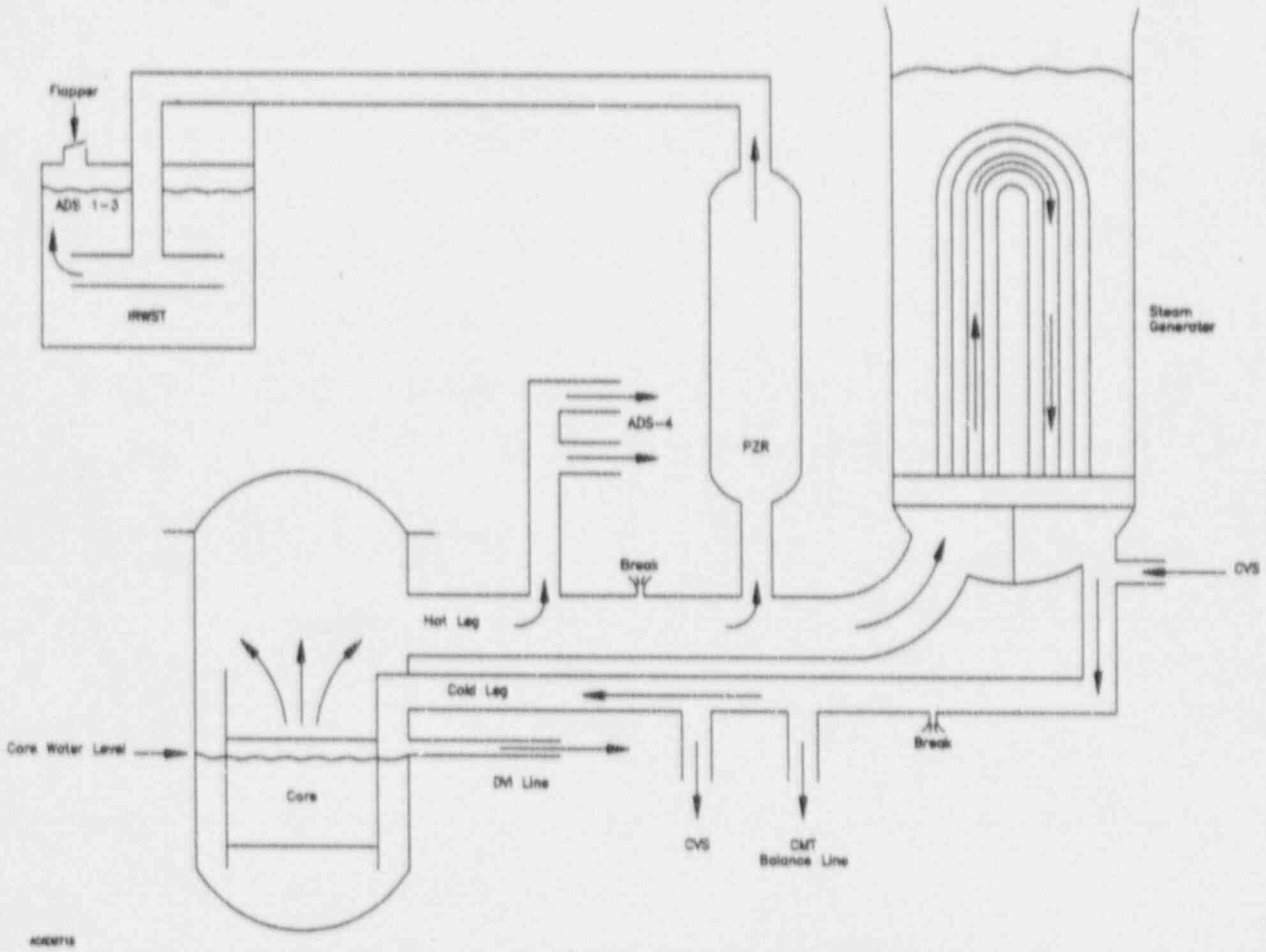

Figure 1 – RCS Release Locations

Figure 6A-1

RCS Release Locations

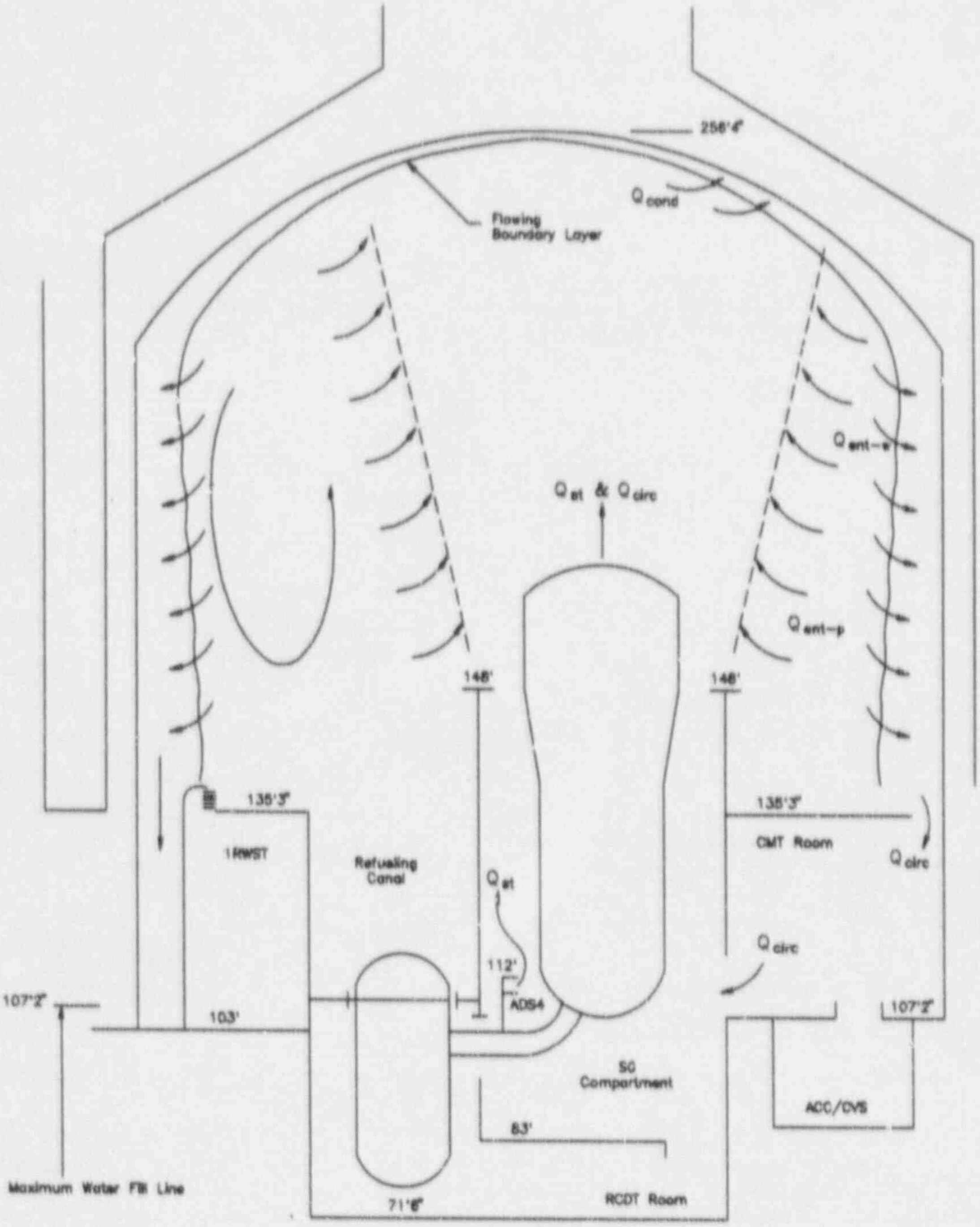

Figure 2 – Containment Natural Circulation

Figure 6A-2

Containment Natural Circulation