

BWR OWNERS' GROUP

James M. Kenny, Chairman
Tel: (610)774-5362
Fax: (610)774-6575

c/o PPL • Two North Ninth Street • Mail Code GENA6-1 • Allentown, PA, 18101-1179

NRC Project 691

BWROG-01036
June 22, 2001

US Nuclear Regulatory Commission
Mr. Robert Pulsifer
One White Flint North (Mail Stop 13D1)
11555 Rockville Pike
Rockville, MD 20852-2738

**SUBJECT: BWR OWNERS' GROUP LICENSING TOPICAL REPORT
NEDO-33003 "REGULATORY RELAXATION FOR THE H₂/O₂ MONITORS AND
COMBUSTIBLE GAS CONTROL SYSTEM" DATED JULY 2001**

**Attachment: NEDO-33003 "Regulatory Relaxation for the H₂/O₂ Monitors and Combustible Gas
Control System" dated February 2001**

The BWR Owners' Group (BWROG) has completed an evaluation with respect to the current requirements and potential regulatory relaxations for BWR H₂/O₂ Monitors and Combustible Gas Control Systems (CGCS). Post-LOCA H₂ and O₂ monitoring and control is required to support Emergency Operating Procedures and the associated core damage assessments. Containment atmosphere hydrogen (H₂) and oxygen (O₂) monitors are currently required to be safety grade in accordance with RG 1.7 and RG 1.97. While it has been shown that the containment gas atmosphere can potentially reach flammable concentrations a few days after an accident is initiated, evaluations show that a reduction in the safety classification of the H₂ and O₂ monitoring systems results in no loss in functionality or safety margin. The BWROG has concluded that the problems associated with H₂ and O₂ monitoring systems' reliability, reduced availability and high costs outweigh any benefit gained by utilizing safety grade sensors and other system components as opposed to more readily available and reliable non-safety grade components.

The BWR Owners' Group (BWROG) has performed bounding comprehensive analyses to determine whether combustible gas mixtures can occur in BWR containments. For design basis events (assuming ECCS meets single failure criterion), which have low iodine releases into the reactor coolant, a combustible gas mixture cannot occur. However, for the iodine concentrations assumed in severe accident scenarios (ECCS failures beyond its design basis), combustible gas mixtures can occur several days after the initiating event. This is due to increased radiolysis of water under high iodine concentrations. Thus, for beyond design basis events, recombiners and containment purge systems could be beneficial to mitigate the possibility of a large, uncontrolled late radioactive material release. However, a severe accident scenario is required for iodine concentrations to reach the necessary levels, and the probability of such an occurrence is small. For low probability severe accidents, the regulations do not specify that combustible gas control equipment be safety grade.

D044

The BWROG has also considered the effect of re-classifying combustible gas monitoring and control equipment from a safety risk perspective. PRA analyses for Mark I and II containments take credit for inerting, and thus, containment failure due to hydrogen is not found to be significant. For Mark III containments, detonatable concentrations of hydrogen are prevented by the igniters with the associated containment mixing systems, and thus, hydrogen recombiners serve no useful purpose. Unfortunately, existing PRAs do not address time periods several days after severe accidents where combustible gas monitoring and control systems are of interest due to the buildup of radiolytically generated gases, and thus, quantitative risk assessments have not been made. The risk insights indicate that the existence or non-existence of combustible gas monitoring systems would have no effect on large early release frequencies (LERF). There is no effect on core damage frequency (CDF), because hydrogen generation is a consequence (not a cause) of core damage.

The BWROG concludes that combustible gas monitoring and control systems are only beneficial for BWRs with inerted containments to mitigate a potential large, late radionuclide release from a beyond design basis accident (DBA) for ECCS. This late release could potentially occur several days after event initiation. Because equipment required to mitigate severe accidents is normally not required to be safety grade, the BWROG requests that the following regulatory relaxations be implemented:

- For all BWR containments, commercial grade H₂ and O₂ monitoring systems are acceptable;
- For Mark III containments, the requirement for O₂ monitoring should be eliminated;
- Hydrogen recombiner safety-related classification requirements should be eliminated;
- For Mark III containments, remove the hydrogen recombiners and rely exclusively on igniters for long-term hydrogen control;
- Retain H₂ vent and purge systems (Containment Air Dilution Systems) but eliminate safety-related classification requirements; and
- Eliminate the associated Technical Specification requirements for the above changes.

The BWROG requests that this Licensing Topical Report be reviewed in anticipation of use of the Consolidated Line Item Improvement Process (CLIP) similar to the submittals described in the Federal Register on August 11, 2000 (Volume 65, number 156). After the NRC reviews and approves this Licensing Topical Report and prepares a model safety evaluation (SE) and associated significant hazards consideration (SHC) assessment, applicable changes will be incorporated into the Standard Technical Specifications in a manner that supports subsequent license amendment applications. Participating BWR owners to which these NRC-developed models apply will then request amendments confirming the applicability of the SE and the NSHC determination to their reactors. These amendments will also provide the requested plant-specific

verifications and commitments. This approach minimizes the resource demand on both the licensee and the NRC for developing individualized justifications and for conducting regulatory reviews, respectively.

We understand that the NRC may be hesitant on approving BWR plant specific license change requests on these subjects because the NRC is proceeding on rulemaking to risk inform 10CFR50.44. It is expected that the results of the NRC risk informing work will provide the relaxations that are being requested by the BWROG in this Licensing Topical Report. However, since several BWRs face large system refurbishment and replacement costs in the near future, the BWROG requests that the NRC allow the requested BWR licensing relaxations during the rulemaking period.

This letter has been endorsed by a substantial number of the members of the BWR Owners' Group; however, it should not be interpreted as a commitment of any individual member to a specific course of action. Each member must formally endorse the BWROG position in order for that position to become the member's position.

The BWR Owners' Group is looking forward to your timely review of this Licensing Topical Report. If you desire to discuss this information in more detail, please contact the General Electric Project Manager, TA Green at (408) 925-1308 or the undersigned.

Very truly yours,



James M. Kenny, Chairman
BWR Owners' Group

Tel: (610) 774-5362

Fax: (610) 774-6575

E-mail: jmkenny@pplweb.com

cc: BWROG Primary Representatives
BWROG Executive Oversight Committee
BWROG Post Accident Sampling Station Subcommittee
NRC Public Document Room
A Heymer, NEI
TG Hurst, GE
TA Green, GE
RA Head, GE



GE Nuclear Energy

*General Electric Company
175 Curtner Avenue, San Jose, CA 95125*

NEDO-33003
DRF T49-00045-00
Class I
July 2001

BWR Owners' Group
Licensing Topical Report

**Regulatory Relaxations for the H₂/O₂ Monitors
and
Combustible Gas Control Systems**

**IMPORTANT NOTICE REGARDING THE
CONTENTS OF THIS REPORT**

Please Read Carefully

DISCLAIMER

The only undertakings of the General Electric Company (GE) respecting information in this document are contained in the contract between the company receiving this document and GE. Nothing contained in this document shall be construed as changing the applicable contract. The use of this information by anyone other than a customer authorized by GE to have this document, or for any purpose other than that, for which it is intended, is not authorized. With respect to any unauthorized use, GE makes no representation or warranty, and assumes no liability as to the completeness, accuracy or usefulness of the information contained in this document, or that its use may not infringe privately owned rights.

TABLE OF CONTENTS

	<u>Page</u>
1 EXECUTIVE SUMMARY	1-1
2 INTRODUCTION	2-1
3 REGULATORY REQUIREMENTS	3-1
3.1 HYDROGEN AND OXYGEN MONITORS.....	3-1
3.2 COMBUSTIBLE GAS CONTROL SYSTEMS	3-1
4 JUSTIFICATION FOR ELIMINATION AND/OR RE-CLASSIFICATION OF COMBUSTIBLE GAS CONTROL SYSTEMS AND H₂/O₂ MONITORS.....	4-1
4.1 COMBUSTIBLE GAS CONTROL SYSTEMS	4-1
4.1.1 <i>Mark III Hydrogen Recombiner Systems</i>	4-1
4.2 EVALUATION OF HYDROGEN AND OXYGEN MONITORS	4-2
4.2.1 <i>Function Evaluations</i>	4-2
4.2.2 <i>Practicality Evaluation</i>	4-3
4.3 NRC SECY-00-0198 RECOMMENDATIONS	4-4
5 ANNUAL COST BURDEN.....	5-1
5.1 CONTAINMENT AIR DILUTION SYSTEM	5-1
5.2 HYDROGEN RECOMBINERS	5-1
5.3 NRC STAFF'S COST ESTIMATE	5-2
5.4 H ₂ AND O ₂ MONITOR COST ESTIMATES	5-2
6 CONCLUSIONS/RECOMMENDATIONS	6-1
6.1 RECOMMENDATIONS.....	6-1
APPENDIX A EVALUATION OF CONTAINMENT HYDROGEN AND OXYGEN CONCENTRATIONS	A-1

ACRONYMS AND ABBREVIATIONS

ALARA	As Low As Reasonably Achievable
AOO	Anticipated Operational Occurrence
BWR	Boiling Water Reactor
BWROG	Boiling Water Reactor Owners' Group
BWRVIP	Boiling Water Reactor Vessel and Internals Program
CFR	Code of Federal Regulations
DBA	Design basis accident
DNB	Departure from Nucleate Boiling
EPRI	Electric Power Research Institute
GDC	General Design Criterion/Criteria
H ₂	Hydrogen gas
O ₂	Oxygen gas
LERF	Large Early Release Frequency
LOCA	Loss of Coolant Accident
LTR	Licensing Topical Report
NRC	Nuclear Regulatory Commission
NSSS	Nuclear Steam Supply System
PASS	Post Accident Sampling System
PRA	Probabilistic Risk Assessment
RCPB	Reactor Coolant Pressure Boundary
RPV	Reactor Pressure Vessel
RPS	Reactor Protection System
SAR	Safety Analysis Report
SER	Safety Evaluation Report
SFC	Single Failure Criterion
TRM	Technical Requirements Manual
TS	Technical Specifications
TSFT	Technical Specification Task Force (Nuclear Energy Institute)

1 EXECUTIVE SUMMARY

Containment atmosphere hydrogen (H₂) and oxygen (O₂) monitors are currently required to be safety grade. Because the BWR containment gas atmosphere can potentially reach flammable concentrations a few days after an accident is initiated the BWROG acknowledges that post-LOCA H₂ / O₂ gas concentrations are required to support Emergency Operating Procedures. However, evaluations show that the elimination of hydrogen monitoring (for inerted containments) or a reduction in the safety classification of the H₂ and O₂ monitoring systems as compared to more readily available and reliable non-safety grade components, results in no loss in functionality or safety margin. This reports shows that the costs associated with maintaining safety grade H₂ and O₂ monitoring systems and combustible gas control systems far exceed any safety benefit gained.

The BWR Owners' Group (BWROG) has performed a comprehensive analysis to determine whether combustible gas mixtures can occur in BWR containments (see Appendix A). For design basis events which have low iodine releases into the reactor coolant, a combustible gas mixture cannot occur. The analysis shows that combustible gas mixtures are only possible for the extremely improbable beyond design basis accidents and even then can only occur several days after the initiating event. However, the probability of a beyond design basis accident scenario is extremely small ($< 10^{-5}/\text{yr}$), and as such, do not warrant special treatment considerations for those systems designed solely to mitigate improbable events.

The BWROG considered the effect of re-classifying combustible gas monitoring and control equipment from a safety risk perspective. PRA analyses for Mark I and II containments take credit for inerting, and thus, containment failure due to hydrogen is not found to be significant. For Mark III containments, detonatable concentrations of hydrogen are prevented by the hydrogen igniters along with the associated containment mixing systems, and thus, PRA analyses for Mark III containments show that containment failure due to hydrogen is not significant. PRAs are not required to consider effects several days after accidents since ample time is available to take other protective actions for the public through Emergency Preparedness plans. Therefore, risk insights indicate that even without taking credit for combustible gas monitoring systems, there is no effect on large early release frequencies (LERF). Likewise, there is no effect on core damage frequency (CDF), because hydrogen generation is a consequence (not a cause) of core damage.

The BWROG concludes that combustible gas monitoring and control systems are not required for design basis accidents for all BWR containments. These systems could be needed for BWRs with inerted containments only to mitigate the highly unlikely, beyond design basis accident, and even then not until several days after event initiation. Therefore, the high cost of maintaining special treatment provisions for these systems is not warranted for the safety benefit provided.

The BWROG concludes that the following regulatory actions are appropriate based on this Licensing Topical Report:

- For all BWR containments, commercial grade H₂ and O₂ monitoring systems are acceptable;
- For Mark III containments, the requirement for O₂ monitoring should be eliminated;
- H₂ recombiner safety-related classification requirements should be eliminated;
- For Mark III containments, remove the H₂ recombiners and rely exclusively on igniters for long-term hydrogen control;
- Retain H₂ vent and purge systems (containment air dilution systems) but eliminate safety-related classification requirements;
- Consistent with their removal or change in safety classification, the Containment H₂ and O₂ Analyzer requirements should be removed from the Post Accident Monitoring Technical Specification (Table 3.3.3.1-1 in NUREG-1433 and NUREG-1434);
- For Mark I and II containments, consistent with the change in safety classification, the Primary Containment Hydrogen Recombiner Technical Specification (TS 3.6.3.1 in NUREG-1433) should be deleted;
- For Mark I and II containments, consistent with the change in safety classification, the Primary Containment Oxygen Concentration Technical Specification (TS 3.6.3.3 in NUREG-1433) should be deleted; and
- For Mark III containments, consistent with the removal of the H₂ recombiners, the Primary Containment Hydrogen Recombiner Technical Specification (TS 3.6.3.1 in NUREG-1434) should be deleted.

Note: Actual plant-specific TS location numbers may vary from those listed above.

NRC approval of this Licensing Topical Report will form the basis for the TSTF to make these changes.

2 INTRODUCTION

This generic Licensing Topical Report (LTR) addresses two safety grade BWR systems where the costs to provide maintenance and periodic testing are believed to be excessive with respect to the safety benefits. These systems are the containment atmosphere H₂ and O₂ monitoring and the combustible gas control systems. This report provides a review of the regulatory requirements for these systems, summarizes current plant operating experience, evaluates system performance from a design basis perspective, and evaluates system operating and maintenance costs. It also provides the basis for relaxing current burdensome regulatory requirements.

BWRs currently employ redundant safety-grade Containment Atmosphere Monitoring (CAM) systems to monitor the levels of H₂ or O₂ in the primary containment to help ensure that the post-LOCA containment atmosphere does not become flammable prior to taking corrective action. The BWROG has determined that these monitors only provide useful information after very low probability beyond design bases accidents and for core damage assessment. The costs of maintaining these systems as safety grade equipment far outweigh any safety benefits as compared to non-safety grade equipment.

Depending on the type of containment design employed (Mark I, II, or III), BWRs currently use a combination of containment inerting, containment hydrogen recombiners, hydrogen igniters, containment atmosphere purge systems, containment mixing systems, and containment atmosphere dilution systems to control post-LOCA H₂ and O₂ concentrations. The BWROG has reviewed the assumptions used for calculating containment H₂ and O₂ concentrations for a design basis accident to assess whether combustible gas mixtures will occur as a function of post-LOCA radiolytic gas production. It is shown that combustible gas mixtures can occur only when very low probability beyond-design-basis accident iodine release assumptions are employed. Thus, the requirements for safety grade systems to mitigate these highly unlikely accidents are not beneficial from a safety perspective. The controlling regulation with respect to combustible gas control systems (10 CFR 50.44) does not require these systems to be safety grade. It is also concluded that commercial grade systems will provide adequate performance and reliability for these very low probability events.

The NRC is currently in the process of risk-informing 10 CFR 50.44. In a February 1, 2000 draft report, "Risk-Informing 10 CFR 50.44 – Standards for Combustible Gas Control System in Light-Water-Cooled Power Reactors," the NRC suggests that under a risk-informed approach that recombiners, purge systems, re-pressurization systems, etc., belong to the long-term accident management and mitigation category. It was stated that these systems do not offer a defense against large early release frequencies (LERF) type sequences, but do have a role in (long-term) survivability of the containment atmosphere following core damage events. Potential options proposed by the NRC for risk-informing this equipment include:

- Eliminating the requirement to measure the hydrogen (H₂) gas concentration inside all containment types; or to measure oxygen (O₂) gas concentrations in Mark III

containments, or (as a minimum) commercial grade instrumentation should be allowed;

- For Mark III containments, remove internal recombiners and rely exclusively on igniters for long-term H₂ detonation prevention;
- For Mark I and II containments, recombiners would be retained (where currently installed) but the safety grade classification requirement would be eliminated; and
- Retain H₂ vent and purge systems (containment air dilution systems) but eliminate safety classification requirements.

On September 13, 2000, the ACRS reviewed the NRC staff's specific recommendations for revising the 10 CFR 50.44 regulations, and supported the staff's assessment on the risk-significance. The ACRS stated that the NRC work will provide the basis for development of a risk-informed regulation that can provide both a safety benefit and a reduction in unnecessary burden for licensees.

On September 14, 2000, the NRC staff's recommendations (provided in Section 4.3) for revising the 10 CFR 50.44 regulations was published in SECY-00-0198, and on January 19, 2001, the commission approved the staff's recommendations in SECY-00-0198, and stated that "the staff should proceed expeditiously with rule making on the risk-informed alternative version of 10 CFR 50.44."

These NRC and ACRS evaluations are consistent with those performed by the BWROG, and the proposed options to eliminate O₂ monitoring and control equipment and/or re-classify H₂/O₂ monitoring and control equipment to non-safety is consistent with the BWROG recommendations.

3 REGULATORY REQUIREMENTS

The 10 CFR 50.44 fuel cladding metal-water reaction is based on an assumed “result of degradation, but not the total failure, of emergency core cooling functioning.” However, 10 CFR 50.46 is the design basis for light-water nuclear power reactor ECCS performance. 10 CFR 50.44(h) states “As used in this section: (1) Degradation, but not total failure, of emergency core cooling functions means that the performance of the emergency core cooling system is postulated, for the purposes of design of the combustible gas control system, not to meet the acceptance criteria in § 50.46.” Therefore, 10 CFR 50.44 is only applicable to beyond (10 CFR 50.2) design bases events, which are the severe accident scenarios.

The controlling regulations (10 CFR 50.44 and App. A GDC 41, 42 and 43) do not specify that H₂ monitors, O₂ monitors and combustible gas control equipment be safety grade. The interpretations that these items be safety grade are based on Regulatory Guides 1.7 and 1.97.

3.1 Hydrogen and Oxygen Monitors

10 CFR 50.44, “Standards for combustible gas control systems in light-water-cooled power reactors,” requires that each boiling or pressurized light-water reactor be provided with the capability for measuring the H₂ concentration in the containment atmosphere. Regulatory Guide 1.97, “Instrumentation for Light-Water-Cooled Nuclear Power Plants to Assess Plant and Environs Conditions During and Following an Accident” specifies that these instruments should be safety grade.

3.2 Combustible Gas Control Systems

10 CFR 50.44 defines the regulatory requirements for post-LOCA containment atmosphere flammability control. The rule requires the applicant or licensee to show that during the time period immediately following a postulated LOCA, but prior to effective operation of the combustible gas control system either: 1) an uncontrolled hydrogen-oxygen recombination would not take place in the containment, or 2) the plant could withstand the consequences of uncontrolled hydrogen-oxygen recombination without loss of safety function. If neither of these conditions can be shown, the rule requires that the containment be provided with an inerted atmosphere in order to provide protection against hydrogen burning and explosion during this time period. Regulatory Guide 1.7, “Control of Combustible Gas Concentrations in Containment Following a LOCA,” provides guidance for implementation of 10 CFR 50.44 and specifies that combustible gas control systems meet the same requirements as an engineered safety feature.

4 JUSTIFICATION FOR ELIMINATION AND/OR RE-CLASSIFICATION OF COMBUSTIBLE GAS CONTROL SYSTEMS AND H₂O₂ MONITORS

4.1 Combustible Gas Control Systems

The regulations normally do not require equipment, used to mitigate beyond design basis events, to be safety grade. Except for containment isolation devices, this position should apply to the combustible gas control system components.

Deterministic evaluations of the functional need for combustible gas control systems in Mark I & II containments and Mark III containments are provided in Appendix A. These evaluations demonstrate that for realistic design basis accident scenarios, hydrogen recombiners and other means of combustible gas control are not needed. The evaluations demonstrate that combustible gas control systems could be needed only for beyond design basis accidents at BWRs that have inerted containments.

Given the extremely low probability of beyond design basis accidents (regardless of containment design), requiring the combustible gas control systems to be safety grade does not significantly improve plant safety. Declaring an item safety grade usually has three major effects: 1) the item is seismically qualified, 2) if inside containment it is qualified for a harsh environment, and 3) 10 CFR 50, App. B quality assurance is applicable.

Because the RCPB components within containment are seismically qualified, they are not assumed to fail as a result of a seismic event. The operating equipment of the combustible gas control systems are not part of the RCPB, are not needed or used to mitigate a seismic event, and are not used to achieve and maintain safe shutdown. Thus, combustible gas control components are not required by 10 CFR 100 to be seismically qualified.

Regardless of safety classification, per normal purchasing practices, all items are purchased or evaluated for their functional requirements and applicable environmental conditions (temperature, humidity, pressure and radiation) prior to their installation. Therefore, allowing commercial combustible gas control system components would not significantly affect quality, and thus, plant safety.

4.1.1 Mark III Hydrogen Recombiner Systems

Mark III plants were originally designed with only hydrogen recombiners to control the hydrogen generated for design bases events. After 1978, the Mark III plants were backfitted with hydrogen igniters in their drywells and containments to control the H₂ generated for severe accidents. The igniters are usually redundant, diesel-backed, class 1E systems. The igniter systems capabilities are based on H₂ releases resulting from the metal-water reaction of up to and including 75% of the fuel cladding. Based on AEC Safety Guide 7, the hydrogen recombiner systems were originally designed for H₂ releases resulting from the metal-water reaction of 5% of the fuel cladding. The igniter systems capabilities are, therefore, significantly greater than the capabilities of the recombiner systems. The BWROG has concluded that because igniters

installed in Mark III plants maintain H₂ gas below the combustible concentration at which a significant pressure increase could occur, the recombiners are superfluous and can be deleted without significantly affecting safety.

As shown in Section 4.3, this position is consistent with the fourth NRC staff recommendation in SECY-00-0198.

4.2 Evaluation of Hydrogen and Oxygen Monitors

10 CFR 50.44 does not specify the safety classification of the H₂ or O₂ monitors. However, based on Regulatory Guide 1.97, they are classified as important to safety. Generic exceptions to this requirement in Regulatory Guide 1.97 are justified for the H₂ and O₂ monitors in all containments.

4.2.1 Function Evaluations

Hydrogen monitors are not needed to initiate combustible gas control systems, and thus, H₂ monitors can not mitigate a threat to the containment. As shown in Section 4.3, this position is consistent with the second NRC staff recommendation in SECY-00-0198.

Mark I and II containments are inerted by nitrogen during normal operation. Combustible gas control in Mark I and II containments is solely based on the control of the O₂ concentration (in volume %) within these containments. All operator actions to prevent H₂ combustion are based on maintaining the O₂ concentration below a prescribed limit. Therefore, an operator having knowledge of the H₂ concentration does not aid the operator nor affect any safety function. Because the H₂ monitors in Mark I and II containments are used only to assess the extent of core damage following a severe accident, these monitors should be re-classified as Regulatory Guide 1.97 Category 3 instruments (not important to safety), and be allowed to be commercial grade.

Mark III containments are not inerted, and use H₂ igniters to control the H₂ concentration by burning the H₂ below concentrations where significant pressure increases can occur. Combustible gas control in Mark III containments is solely based on the control of the H₂ concentration. All operator actions to prevent H₂ combustion are solely based on maintaining the H₂ concentration below a prescribed limit. Therefore, an operator having knowledge of the O₂ concentration does not aid the operator nor affect any safety function, and thus, is irrelevant. Therefore, the O₂ monitors in Mark III containments should not be required or, at least, be re-classified as Regulatory Guide 1.97 Category 3 instruments (not important to safety) and allowed to be commercial grade.

4.2.1.1 Comparison of H₂ and O₂ Monitoring Technologies

The existing safety related H₂ and O₂ monitors use older technologies which are less reliable than newer commercial grade monitors. Modern (readily available) commercial grade technologies were compared with the older technologies, which currently exist at many plants.

This comparison demonstrates that the newer commercial grade sensors function better and are easier to maintain (i.e., increased availability) than the older safety grade sensors. The cost to qualify these newer sensors to be safety grade cannot be justified because the associated increase in plant safety would not be significant. The typical disadvantages of older technologies and advantages of newer technologies are listed below.

Typical disadvantages of the older (safety-related) H₂ and O₂ sensor technologies are:

- Pressure sensitive;
- High drift (leading to out of tolerance "as-found" conditions);
- Damaged by moisture;
- Require multiple points for calibration (takes a long time);
- Long "settling time" for sensors after calibration;
- Support/obsolescence issues; and
- Poor or aging sampling systems aggravating all of the above.

Typical advantages of modern commercial grade H₂ and O₂ sensor technologies are:

- Pressure compensated;
- Temperature compensated;
- Lower drift (<1% of reading between services);
- Sensors can be used directly in liquid or in gas (i.e., not susceptible to moisture damage);
- Lower maintenance;
- Single point calibration;
- Minimal settling time (minutes instead of hours) after calibration/verification;
- Systems supported (i.e., readily available and common spare parts, etc.); and
- Turnkey sampling systems are available.

Therefore, allowing plants to use commercial grade H₂ and O₂ sensor systems would improve equipment availability, while reducing maintenance costs.

4.2.2 Practicality Evaluation

Based on the functions of H₂ and O₂ monitors and the advantages of newer commercial grade technologies, the requirement for these monitors to be safety grade does not increase safety. Declaring an item safety grade usually has three major effects: 1) the item is seismically qualified, 2) if inside containment it is qualified for a harsh environment, and 3) 10 CFR 50, App. B quality assurance is applicable. The H₂ and O₂ monitors are not needed or used to mitigate the consequences of a seismic event and do not perform/ensure any safety-related

function, and thus, are not required by 10 CFR 100 to be seismically qualified. The H₂ and O₂ monitors are located outside containment, and thus, are not subjected to a harsh environment. Regardless of safety classification, per normal purchasing practices, all items are purchased or evaluated for their functional requirements and applicable environmental conditions (temperature, humidity, pressure and radiation) prior to their installation. Therefore, allowing commercial grade H₂ and O₂ monitors would not significantly affect plant safety.

4.3 NRC SECY-00-0198 Recommendations

SECY-00-0198 provides a status report on the NRC staff's study of possible risk-informed changes to the technical requirements of 10 CFR Part 50, to provide the staff's recommendations for risk-informed changes to 10 CFR 50.44 that will both enhance safety and reduce unnecessary burden. SECY-00-0198 states "Based upon current risk information and research results, the staff believes that little to no risk significance or benefit is associated with some of the combustible gas control requirements of this regulation, potentially resulting in unnecessary burden. In addition, the staff also believes that the current requirements do not address some risk-significant concerns from accident scenarios. Therefore, the staff recommends changes to the requirements that represent both a safety enhancement (some of which may have an associated additional burden) and a reduction in unnecessary burden."

The SECY-00-0198 recommendations (reprinted below) are basically consistent with the BWROG positions discussed herein:

1. Specify in the regulation a specific combustible gas source term using best available calculational methods for a severe accident that includes in-vessel (and ex-vessel) hydrogen and carbon monoxide generation in such a way that the alternative regulation addresses the likely sources of combustible gases. These sources would only address challenges to the containment that could potentially result in a large radionuclide release within 24 hours after the onset of core damage. This is consistent with the approach taken in the staff's review of the Advanced Light Water Reactors (ABWR, System 80+ and AP-600). This recommendation would involve a short-term (~3 months) effort by the staff to perform the calculations and to specify the source term in the regulation that is based on these calculations.
2. Eliminate the requirement to measure H₂ concentration in containment. Hydrogen monitoring is not needed to initiate or activate the combustible gas control systems for each type of containment, hence H₂ monitors have a limited significance in mitigating the threat to containment in the early stages of a core-melt accident. Hydrogen monitoring for emergency response purposes is addressed separately from 10 CFR 50.44.
3. Retain the requirement to insure a mixed atmosphere. The intent of this requirement is to maintain those plant design features (e.g., open

- compartments) that promote atmospheric mixing and is considered an important defense-in-depth element (i.e., meeting the intent of GDC 50).
4. Eliminate the requirement to control combustible gas concentration resulting from a postulated LOCA. This type of accident is not risk significant and the means to control combustible gas concentration (e.g., recombiners) does not provide any benefit for the risk-significant accidents or, if a vent-purge method is used, can result in unnecessary releases of radioactive material to the atmosphere. Long-term combustible gas control is addressed in Item 9 below.
 5. Retain the requirement to inert Mark I and Mark II containments. Removal of this requirement would result in the integrity of these containments being highly vulnerable to gas combustion.
 6. Retain the requirement for high point vents in the reactor coolant system (RCS). Combustible gases in the RCS can inhibit flow of coolant to the core, therefore, the capability to vent the RCS provides a safety benefit in its ability to terminate core damage.
 7. Modify the requirement for the hydrogen control system for Mark III and ice condenser containments to control combustible gas during risk-significant core-melt accidents (e.g., station blackout). Since the control system uses igniters that are alternating current (ac) dependent, under station blackout conditions, these containments may remain vulnerable to gas combustion. Alternately, if station blackout could be shown by the licensee to be of low enough frequency, with due consideration of uncertainties and defense-in-depth, then the sequence would not be risk significant and the licensee would have complied with the requirement via the current igniter system. Such an approach represents a performance-based aspect of this recommendation.
 8. Include a performance-based second alternative within this regulation that would allow a licensee to use risk information and plant-specific analysis on the generation and control of combustible gases to demonstrate that the plant would meet specified performance criteria (e.g., maintain containment integrity for at least 24 hours for all risk-significant events). This may be especially attractive to future plants.
 9. Recommend that long-term (more than 24 hours) control of combustible gas be included as part of the licensee's Severe Accident Management Guidelines (SAMG) since combustible gases still pose a challenge to containment integrity in the long term with the possibility of a large, late radionuclide release.

On January 19, 2001, the commission approved the staff's recommendations in SECY-00-0198, and stated that "the staff should proceed expeditiously with rule making on the risk-informed alternative version of 10 CFR 50.44."

5 ANNUAL COST BURDEN

The BWROG surveyed the participating utilities to estimate the cost burden of maintaining BWR Containment Air Dilution (CAD) Systems, H₂ Recombiners, and H₂/O₂ Monitoring Systems. These costs can vary significantly due to system differences and the number of obsolescence problems experienced. The information provided in the following subsections should be considered representative for a typical BWR. Multiple estimates are provided, including the NRC staff's estimate from SECY-00-0198. The potential cost of replacement power due to a forced shutdown due to lack of spare parts is not included, however, a one day forced shutdown could easily eclipse the total annual cost of operation listed below. These cost estimates consistently demonstrate that implementing the requested hydrogen control related recommendations would result in significant annual cost burden reductions.

5.1 Containment Air Dilution System

The typical cost to maintain a BWR Containment Air Dilution System is approximately \$200K annually. The major costs include:

- Vendor support \$15K
- Maintenance planning and scheduling \$25K
- System and design engineering \$80K
- Component replacements and system repairs \$75K

The cost of obsolescence continues to increase, and this helps to explain the relatively high cost of maintenance on this system. The BWROG has estimated that 25 to 50% of these costs could be eliminated if the CAD System (except for containment isolation valves) is reclassified to non-safety. This would result in annual savings of \$50K to \$100K.

5.2 Hydrogen Recombiners

The cost to operate and maintain a typical post-LOCA hydrogen recombiner system is approximately \$36K per year per reactor as follows:

- Surveillance \$11K
- Maintenance \$3K
- Design Modifications \$12K
- Plant simulator, training, and other support \$10K

In addition, there is a threat of lost power generation if the recombiner system is out of service. There is a 30-day LCO for 1 recombiner train out of service and a 7-day LCO for both recombiners out of service. Plant operations are at risk due to the ever-increasing component obsolescence problems for which the flow controllers are of specific concern. For example, one recombiner flow control loop was upgraded to a digital controller. This caused a domino effect

of additional training, design, spare inventory, etc. Typical BWR recombiner systems have approximately 135 components identified in the plant safety-related component list. With the trend towards fewer safety-related suppliers, the alternative design changes for equivalent components or commercial grade dedication typically have significant budget impacts.

Major modifications to these systems over the last few years have included replacement of the above mentioned flow controller, replacement of a motor operator, and disabling of a recirculation valve.

The surveillance requirements for this safety-related system are substantial. A system functional test is usually required every 18 months. This includes a visual inspection of the recombiner vessel, and the heater circuits are checked for continuity and resistance to ground. In addition, the containment isolation valves for the suction side and return side require Type C local leak rate testing. Because the system piping and equipment is considered the outboard isolation, an air pressure test of the entire system is performed. In addition, fourteen system valves are in the MOV program. Testing and inspection activities can include an inspection every 18 months to ensure the stem and operator lubrication is acceptable, an electrical PM every 36 months, and VOTES testing every 54 to 60 months.

The BWROG has estimated that annual cost saving of at least \$25K could be expected if the hydrogen recombiners are reclassified as non-safety. This takes into consideration the projected increased costs due to equipment obsolescence issues.

For Mark III containments, 100% of the actual hydrogen recombiners related costs could be eliminated.

5.3 NRC Staff's Cost Estimate

SECY-00-0198 includes the burden reduction estimate associated with NRC's recommendations (provided in Section 4.3) on risk-informed changes to 10 CFR 50.44. SECY-00-0198 states "the staff recommends that safety enhancements that have the potential to pass the backfit test be assessed for mandatory application through the generic issue program. The staff estimates that unnecessary burden reduction associated with this alternative is approximately \$200K per unit per year." As shown above, this is consistent with the BWROG estimates.

5.4 H₂ and O₂ Monitor Cost Estimates

BWROG surveys show typical H₂/O₂ monitors maintenance, testing and calibration costs from \$80,000 to \$150,000 per year. These costs are projected to be reduced by approximately 50%, if non-safety systems are employed. In addition, the surveys confirm that H₂/O₂ monitoring system replacement cost savings would be \$400,000 to \$900,000 per plant, if non-safety grade monitoring systems are installed.

6 CONCLUSIONS/RECOMMENDATIONS

BWR combustible gas control systems are needed only for highly improbable beyond design basis severe accident events for which the regulations normally do not require safety grade equipment. Except for containment isolation valves, it is justified that commercial grade combustible gas monitoring and control systems can be used without a significant decrease in safety. For Mark III containment plants, the igniters are needed to maintain H₂ gas below the combustible concentration at which significant pressure increase could occur, and thus, the hydrogen recombiner systems should not be required.

The function of the H₂ and O₂ monitors is to help operators in making decisions on the use of combustible gas control systems, and to assess extent of core damage after unlikely beyond design basis accidents. From a functional point of view, the H₂ monitors in all containments perform no safety function and do not aid in the prevention of a post-accident H₂ combustion. Since the H₂ monitors are used only to assess the extent of core damage following a severe accident, these monitors should be re-classified as Regulatory Guide 1.97 Category 3 instruments (not important to safety) and allowed to be commercial grade. The O₂ monitors in Mark III containments perform neither a safety function nor a severe accident assessment function. From a realistic point of view (regardless of containment design), requiring the H₂ and O₂ monitors to be safety grade does not enhance their quality nor capabilities. Therefore, the costs of maintaining the H₂ and O₂ monitors as safety grade are not justified.

The BWROG has also considered the effect of re-classifying combustible gas monitoring and control equipment from a safety risk perspective. The PRA analyses for Mark I and II containments take credit for inerting, and thus, the probability of containment failure due to H₂ combustion is found not to be significant. For Mark III containments, igniters maintain the H₂ concentration to below the combustible concentration where a significant pressure increase is possible, and thus, the hydrogen recombiners serve no useful purpose.

Plant-specific PRAs do not address time periods several days after a severe accident, when the buildup of hydrogen from radiolysis occurs and where combustible gas monitoring and control systems are of interest. Thus, quantitative risk assessments cannot be made. However, consistent with SECY-00-0198, risk insights indicate that the existence or non-existence of combustible gas monitoring systems would have no effect on large early release frequencies (LERF). There is no affect on core damage frequency (CDF), because hydrogen generation is a consequence (not a cause) of core damage.

6.1 Recommendations

Based on the analysis described above, the following regulatory relaxations are justified:

1. For all BWR containments, commercial grade H₂ and O₂ monitoring are acceptable;
2. For Mark III containments, the requirement for O₂ monitoring should be eliminated;
3. Hydrogen recombiner safety-related classification requirements should be eliminated;
4. For Mark III containments, remove H₂ recombiners and rely exclusively on igniters for long-term hydrogen control;
5. Retain H₂ vent and purge systems (containment air dilution systems) but eliminate safety-related classification requirements;
6. Consistent with their removal and/or change in safety classification, the Containment H₂ and O₂ Analyzer requirements should be removed from the Post Accident Monitoring Technical Specification (Table 3.3.3.1-1 in NUREG-1433 and NUREG-1434);
7. For Mark I and II containments, consistent with the change in safety classification, the Primary Containment Hydrogen Recombiner Technical Specification (TS 3.6.3.1 in NUREG-1433) should be deleted;
8. For Mark I and II containments, consistent with the change in safety classification, the Primary Containment Oxygen Concentration Technical Specification (TS 3.6.3.3 in NUREG-1433) should be deleted; and
9. For Mark III containments, consistent with the removal of the H₂ recombiners, the Primary Containment Hydrogen Recombiner Technical Specification (TS 3.6.3.1 in NUREG-1434) should be deleted.

Approval of this Licensing Topical Report will form the basis for future TSTFs to make these changes.

Appendix A

Appendix A

EVALUATION OF CONTAINMENT HYDROGEN AND OXYGEN CONCENTRATIONS

The following evaluation is expected to bound existing utility analyses for radiolytic hydrogen and oxygen production to determine potential flammability of the post-LOCA severe accident containment atmospheres for Mark I, II, and III designs during the first 100 days following the severe accident event. These bounding analyses are based on BWRs with the highest thermal power to containment free volume ratio assuming a 20% power uprate.

A.1 Hydrogen and Oxygen Generation Rates

Regulatory Guide 1.7 assumptions define the post-LOCA radiolytic hydrogen and oxygen generation rates (or chemical yields called G-values) as 0.5 molecule/100 eV for H₂ and 0.25 molecule/100 eV for O₂. Under current guidelines, these values are conservatively assumed to apply for boiling conditions that occur early in the severe accident scenario when the products of radiolysis are stripped from the primary coolant by boiling, as well as later in the severe accident scenario when boiling stops and the radiolytic gases are in equilibrium with the containment environment. A number of studies have been performed that show the radiolytic gas generation rates are significantly lower during non-boiling conditions (References A1, A2). In addition, it is well known that the presence of iodine in the primary coolant increases radiolysis due to interactions with radiolytically produced free radicals (References A3, A4).

Recent models developed by the NRC and others define the effect of iodine impurities and containment H₂ concentration on G-values for H₂ and O₂. The NRC model (Reference A3) uses simplifying assumptions to approximate the effect of the complex free radical reactions on the G-values. A more detailed model (PARGE), developed by Toshiba (Reference A4), uses thirty-five liquid phase chemical reactions to estimate the effect of iodine and containment H₂ concentrations on the G-values. Results of both models are shown in Figure A-1, where the G-value for H₂ or G(H₂) is plotted as a function of liquid phase iodine to hydrogen molar ratio. [G(O₂) is one half of G(H₂).]

Using the Figure A-1 data, relationships were developed for the NRC and PARGE models using Henry's law constant (200°F and 1 atm) to calculate G(H₂) as a function of volume percent H₂ in the containment and as a function of the fraction of core iodine inventory released during the accident. These relationships are then used with Regulatory Guide 1.7 assumptions and NUREG-0800, Section 6.2.5, Appendix A methodology to evaluate containment H₂ and O₂ concentrations with upper and lower bounding values for fraction of core iodine released during the event. The resulting calculated G-values, which vary from 0.43 to 0.01 molecule/100 eV of H₂, are used only during the non-boiling phase of the severe accident scenario. For the boiling phase, a G(H₂) value of 0.43 is used.

A.2 Accident Source Term for Core Iodine Release

For limiting BWR LOCA analysis during which the emergency core cooling systems function in accordance with the design basis no fuel failures are expected to occur; and, therefore, none of the iodine inventory would be released from the fuel rods. The Hatch-2 FSAR shows that the "nominal" limiting LOCA peak cladding temperature is 1133 degrees F and the upper bound peak cladding temperature is less than 1600 degrees F. Even under the upper bound conditions no fuel failures would be expected.

To bound the lower value of $G(H_2)$ using the above relationships, we have conservatively assumed that 1.5% of the core iodine inventory is released into the reactor coolant. This value is based on the following qualitative estimates that have been provided by GE Global Nuclear Fuels (GNF). This discussion conservatively estimates the expected fuel gap release fraction where long-term fuel cooling is maintained as specified in NUREG-1465 (Reference A5).

During irradiation of LWR fuel rods, solid and gaseous fission products are produced in the fuel pellets. The predominant gaseous fission products are isotopes of Xe and Kr. During normal operation some fraction of the gaseous fission products are released to the pellet-clad gap. On the basis of measurements of Xe and Kr inventories after irradiation, a fission gas release model has been developed. Application of this model to currently operating GNF fuel designs indicates that on a best estimate basis ~10-12% of Xe and Kr inventories are released from the pellets and are in the rod void volume (which includes the pellet-cladding gap and the plenum) as gaseous isotopes. Since I isotopes are precursors to Xe isotopes, it is reasonable to assume that the release fraction of I isotopes is similar to that for Xe and Kr, which would imply that during normal operation ~10-12% of I generated would be in the rod void volume. However, unlike Xe and Kr, the I isotopes readily combine with other fission products while still in the pellet or with the cladding after release to the rod void volume. On the basis of fission product yields and formation of I compounds, it is estimated that 10% of the I released from the pellet, or 1 to 1.2% of the I generated, is present in the rod void volume during normal operation.

On the basis of the discussion above, the inventory of gaseous I released to the coolant as a result of a DBA LOCA is estimated as follows. First, it is assumed that only gas in the rod void volume is available for release to the coolant (i.e., that the LOCA impact on pellet temperatures during the event is such that no additional release of gaseous fission products from the pellets to the void volume occurs during the event). Then even if all rods fail, less than 1.0-1.2% of I total inventory will be released to the coolant. Less than 0.25-0.30% of total I inventory would be released to the coolant assuming that 25% of the rods fail.

It is also assumed that during the LOCA event additional release of gaseous fission products from the pellets to the gap occurs due to increases in the average fuel temperature such that the best estimate I inventory doubles. This increases the above estimates by a factor of two. Therefore, if 25% of rods fail during the DBA LOCA, then less than 0.50-0.60% of total I inventory is released to the coolant. If 50% of the rods failed then 1.0-1.2% of total I inventory would be released to the coolant.

A value of 30% core iodine release is used for the upper bound, which is based on the NUREG-1465 fuel gap release plus the early in-vessel release. The 30% iodine release fraction is considered for a LOCA, as documented in NUREG-1465 and Draft Regulatory Guide DG-1081 (Reference 6). DG-1081 defines an acceptable accident source term as one that addresses “events that involve substantial meltdown of the core with the subsequent release of appreciable quantities of fission products.” A design basis LOCA does not result in a “substantial meltdown.” Therefore, the 30% iodine release fraction is only applicable to a (beyond-design-basis) severe accident (LOCA) scenario. Appendix A of DG-1081, in defining the assumptions for evaluating the radiological consequences of a LOCA, includes both the fuel gap and early in-vessel iodine releases.

A.3 Evaluation for Mark I & II Containment Designs

A bounding BWR plant design was chosen on the basis of a comparison of thermal power to containment volume ratios. Key parameters used in the analysis are summarized in Table A-1.

For Mark I & II containments that are inerted with nitrogen and control to the Regulatory Guide 1.7 flammability limit of 5% oxygen, it is assumed that no metal-water reaction occurs. This is a conservative assumption because any hydrogen produced from metal-water reaction serves as a diluent and delays the approach to the oxygen flammability limit.

Result of the analysis is shown in Figure A-2 using the NRC radiolysis model and the lower bounding value of 1.5% core iodine release. For the bounding BWR plant, O₂ approaches the Regulatory Guide 1.7 maximum value of 5% at approximately 32 days following the LOCA. Therefore, with hydrogen generation rates based on a low release fraction of core iodine, BWRs with Mark I or II containments are capable of meeting the Regulatory Guide 1.7 O₂ and H₂ limits without the need for recombiners or other means of combustible gas control. This result is based on an initial containment O₂ concentration of 2.6%. This initial O₂ concentration is expected to be typical even though the Technical Specification requirement is normally less than 4%. It is noted that some BWR plants routinely inert to less than 1% oxygen. If the initial containment O₂ concentration was somewhat higher the time to reach the Regulatory Guide 1.7 maximum value of 5% would be shortened. For example, if the initial containment O₂ concentration was 3% then O₂ would approach the Regulatory Guide 1.7 maximum value of 5% at approximately 10 days following the LOCA for the bounding BWR. If the initial O₂ concentration was 3.5% then O₂ would approach the Regulatory Guide 1.7 maximum value of 5% at approximately 6 days following the LOCA for the bounding BWR.

Results of the analysis using the NRC radiolysis model with the upper bounding value of 30% core iodine release show that the O₂ concentration exceeds the Regulatory Guide 1.7 maximum value of 5% at approximately 3.6 days following the LOCA (Figure A-3). Based on these results, it is concluded that combustible gas control systems could be beneficial for Mark I and II containment designs for a severe accident.

A.4 Evaluation for Mark III Containment Design

Assumptions used to evaluate Mark III containment designs are summarized in Table A-2. Again, a bounding plant design was selected based on core thermal power to containment free volume ratios. Using the lower bounding value of 1.5% core iodine release and the NRC radiolysis model, the containment H₂ concentration at 100 days following the LOCA is only 1.7%, well below the Regulatory Guide 1.7 limit of 4% (Figure A-4). This result is based on operation of the containment purge system to maintain mixing between the drywell and containment building following the initial blowdown. Thus, Regulatory Guide 1.7 limits are met without the use of recombiners and/or ignitors for all plants with Mark III containments.

Results of the analysis using the NRC radiolysis model with the upper bounding value of 30% core iodine release show that the H₂ concentration would exceed the Regulatory Guide 1.7 maximum value of 4% approximately 38 days following a severe accident LOCA (Figure A-5). Based on these results, it is concluded that combustible gas control systems are only beneficial for Mark III containment designs for accidents that result in significant metal-water reactions at the time of accident initiation.

A.5 Conservatism Used in the Analysis

Although the above analysis uses realistic values for combustible gas yields from radiolysis, a number of conservatisms are present. The evaluated H₂ and O₂ concentrations in the containment are therefore conservative. These conservatisms are described below:

1. Fraction of Gamma Energy Adsorbed in Coolant - The assumed fraction of gamma decay energy absorbed in the coolant was the Regulatory Guide 1.7 value of 10% for the duration of the transient under both boiling and non-boiling conditions. This value is conservative, particularly for boiling water that contains a significant void fraction. Jenks and Griess have reported that only about 2% of the fast neutron and 0.5% of the gamma energy are absorbed in boiling water (Reference A7). Results of GE analyses have indicated a value of 4.8% for the gamma absorption fraction in BWR primary coolant (Reference A8). For non-boiling water, results of calculations performed by GE indicate that the gamma absorption fraction is somewhat less than 10%.
2. Decay Heat Generation Rate - The decay heat generation rate used in the analysis is described in NUREG-0800, Section 6.2.5. The reactor decay heat profiles specified by the ANS 5.1 Standard (Reference A9) for two-year reactor operation have been fitted by several finite exponential series expressions. Between 400 and 4×10^7 seconds, the equations over predict the standard curve by 20%. The equations under predict the standard curve for the first 400 seconds. However, because the oxygen generation due to radiolysis is a concern only in the long term, the use of this decay heat model is conservative by approximately 20%.
3. Length of Boiling Period - The 12-hour time period assumed for primary coolant boiling is based on a limiting event consisting not of an accident but of an AOO isolation transient with only low-pressure core cooling systems available. The expected accident scenario should result in a primary coolant saturation period of only 2-3 hours.

4. Containment Leak Rate - The primary containment leak rate used in the analysis is conservatively assumed to be zero. Based on containment leak rate testing performed at BWRs, the actual leak rate is expected to 0.25-0.5% per day.
5. Radiolysis Model - The analysis uses the NRC radiolysis model. Relative to the more rigorous PARGE model, the NRC model results in G-values 10-20% higher.
6. Metal-water reaction – For inerted Mark I & II containments, it was assumed that no metal-water reaction occurs. Thus, the initial release of hydrogen is not available to provide dilution of containment oxygen, the controlling parameter in these designs. For Mark III designs, where hydrogen concentration is the limiting parameter, metal-water reaction in accordance with Regulatory Guide 1.7 was assumed.

A.6 Summary and Conclusions

Using the above deterministic approach, it is concluded that for realistic design basis accident scenarios where small quantities of iodine are released from the core at the onset of the accident, radiolysis will not result in combustible gas concentrations in the containment above the Regulatory Guide 1.7 concentration limits. For inerted Mark I and II containment designs with realistic initial O₂ concentrations, the Regulatory Guide 1.7 O₂ concentration limit is exceeded approximately 32 days following the LOCA. For Mark III containments, the Regulatory Guide 1.7 H₂ concentration limit is exceeded 38 days following the LOCA.

For Mark I and II containment designs, BWR combustible gas control systems may be beneficial only for severe accident scenarios based on an evaluation of radiolysis G-values. This determination of post-LOCA radiolysis using a complex modeling approach is based on a 30% release of core iodine, consisting of the 5% fuel gap and 25% early in-vessel releases as derived from NUREG-1465 and DG-1081.

For Mark III containment designs, BWR combustible gas control systems would not be required based on an evaluation of radiolysis G-values. Therefore, combustible gas control systems are only beneficial for Mark III containment designs for accidents that result in significant metal-water reactions at the time of accident initiation.

A.7 References

- A1. S. Gordon and J. Hart, "Radiation Decomposition of Water under Static and Bubbling Conditions," Argonne National Laboratory, Proceedings of the Second United Nations International Conference on the Peaceful Uses of Atomic Energy, Volume 29, September 1958.
- A2. D. Siegwarth and M. Siegler, "KRB Radiolysis Test," GE Nuclear Energy, NEDE 13148, Class II, November 1970.
- A3. K. Parczewski and V. Benaroya, "Generation of Hydrogen and Oxygen by Radiolytic Decomposition of Water in Some BWRs," U.S Nuclear Regulatory Commission, Joint ASME/ANS Nuclear Engineering Conference, Portland, Oregon, August 1984.
- A4. Watanabe, et. al., "Evaluation of Radiolytic Gas Generation under Post-Accident Conditions in BWRs," Nippon Atomic Industry Group and Toshiba Corporation, IAEA-SM-281/01P, International Symposium on Source Term Evaluation for Accident Conditions, November 1985.
- A5. L. Soffer, et. al., "Accident Source Terms for Light-Water Nuclear Power Plants," NUREG-1465, U.S. Nuclear Regulatory Commission, February 1995.
- A6. U.S. Nuclear Regulatory Commission, "Alternative Radiological Source Terms for Evaluating Design Basis Accidents at Nuclear Power Reactors," Draft Regulatory Guide DG-1081, December 1999.
- A7. G. Jenks and J. Griess, "Water Chemistry in Pressurized and Boiling Water Power Reactors", Oak Ridge National Laboratory, ORNL-4173, November 1967.
- A8. General Electric Co., "Nuclear Basis for ECCS (Appendix K) Calculations," NEDO-23729, November 1977.
- A9. American Nuclear Society, "Decay Heat Power in Light Water Reactors," ANSI/ANS 5.1, 1979.

Table A-1

Key Assumptions Used in Analysis for Mark I & II Designs

Parameter	Value
Rated thermal power, MW _t	4031 ¹
Drywell free volume, ft ³	163,700
Wetwell free volume, ft ³	134,800
Drywell initial relative humidity, %	20
Wetwell initial relative humidity, %	100
Drywell initial temperature, °F	145
Wetwell initial temperature, °F	95
Drywell initial pressure, psig	0.75
Wetwell initial pressure, psig	0.075
Boiling G(H ₂), molecule/100eV	0.43
Non-boiling G(H ₂), molecule/100eV	0.01-0.43
Primary coolant boiling period, hours	12
Core lower bound iodine release, %	1.5
Core upper bound iodine release, %	30
Containment initial O ₂ , %	2.6

Note:

1. Value includes 2% margin per Regulatory Guide 1.49 and the assumption of 20% power uprate.

Table A-2

Key Assumptions Used in Analysis for Mark III Designs

Parameter	Value
Rated thermal power, MW _t	3910 ¹
Drywell free volume, ft ³	270,016
Wetwell free volume, ft ³	1,303,888
Drywell initial relative humidity, %	20
Wetwell initial relative humidity, %	100
Drywell initial temperature, °F	145
Wetwell initial temperature, °F	95
Drywell initial pressure, psig	0.75
Wetwell initial pressure, psig	0.75
Boiling G(H ₂), molecule/100eV	0.43
Non-boiling G(H ₂), molecule/100eV	0.01-0.43
Primary coolant boiling period, hours	12
Core lower bound iodine release, %	1.5
Core upper bound iodine release, %	30
Containment initial O ₂ , %	20.9
Zirconium cladding weight, pounds	79,823

Note:

1. Value includes 2% margin per Regulatory Guide 1.49 and the assumption of 20% power uprate.

Figure A-1

Effect of Liquid Phase Iodine and Hydrogen Concentration on Hydrogen Yield

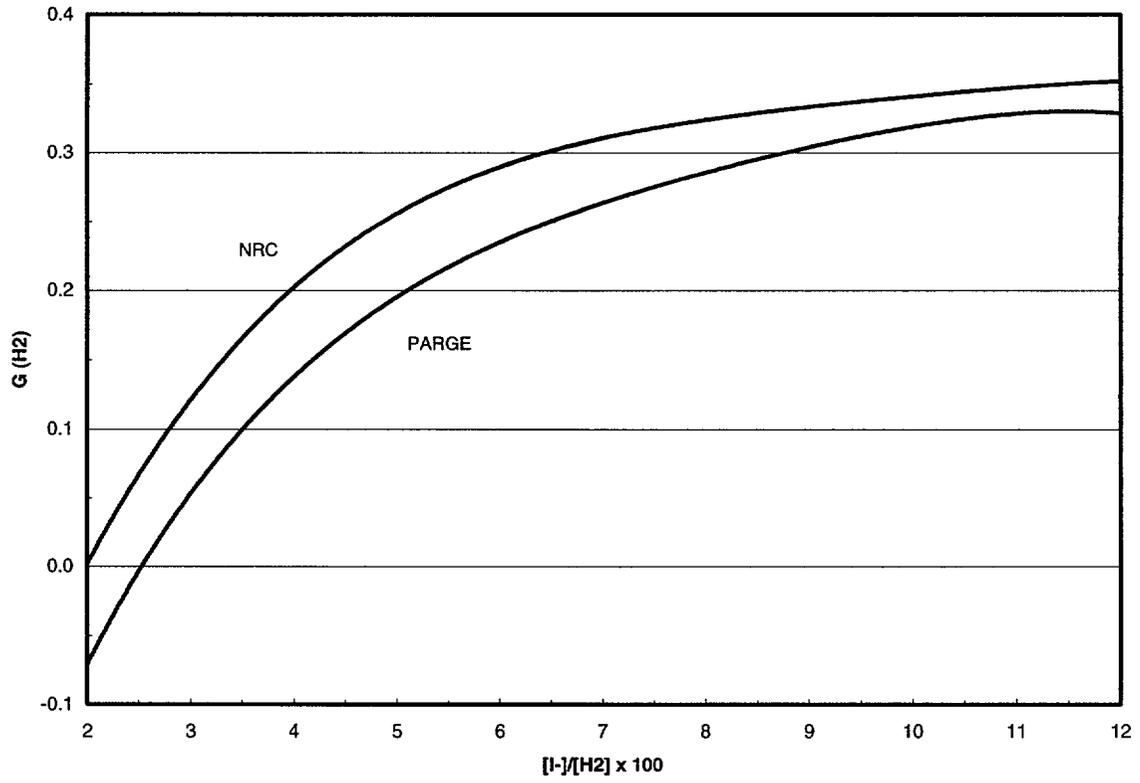


Figure A-2

Mark I or II Drywell Atmosphere with 1.5% Core Iodine

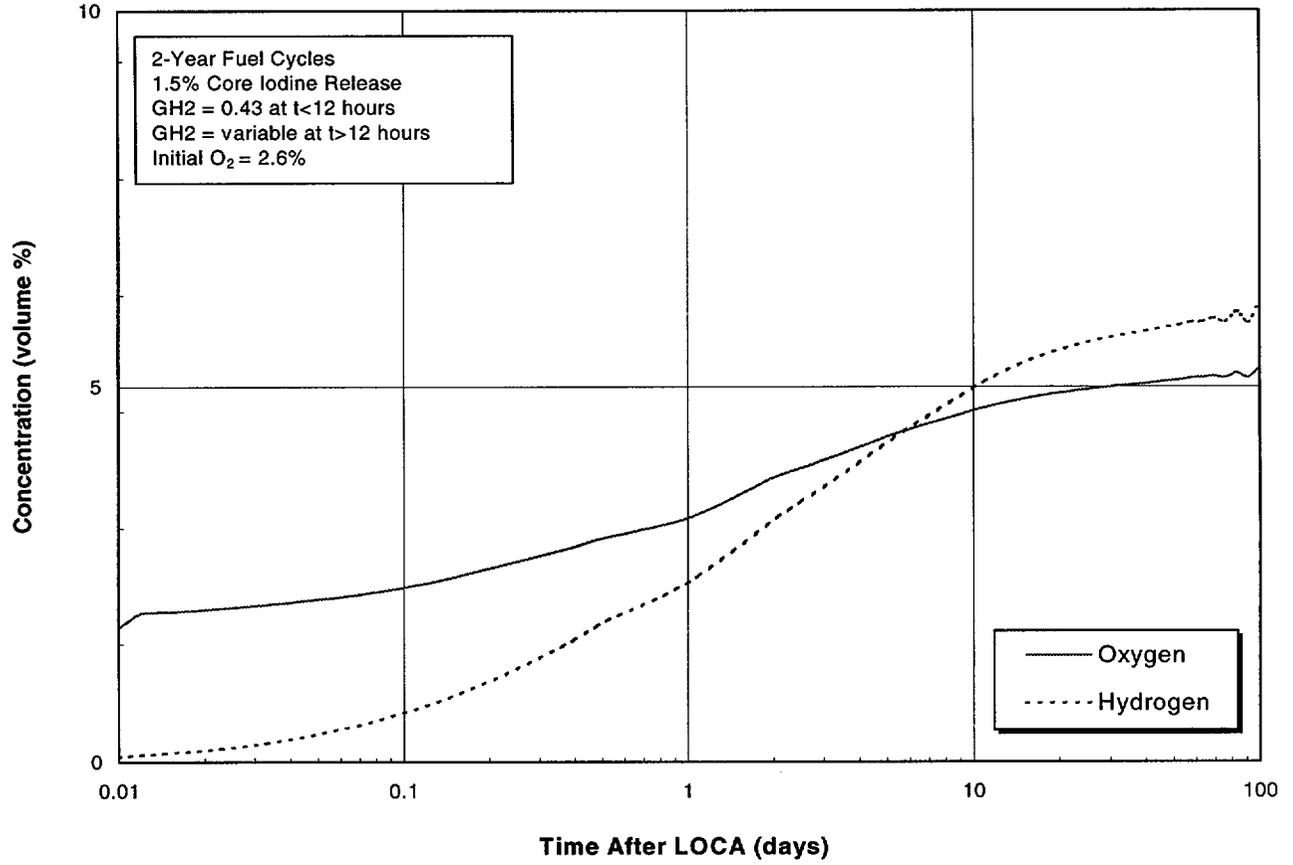


Figure A-3

Mark I or II Drywell Atmosphere with 30% Core Iodine

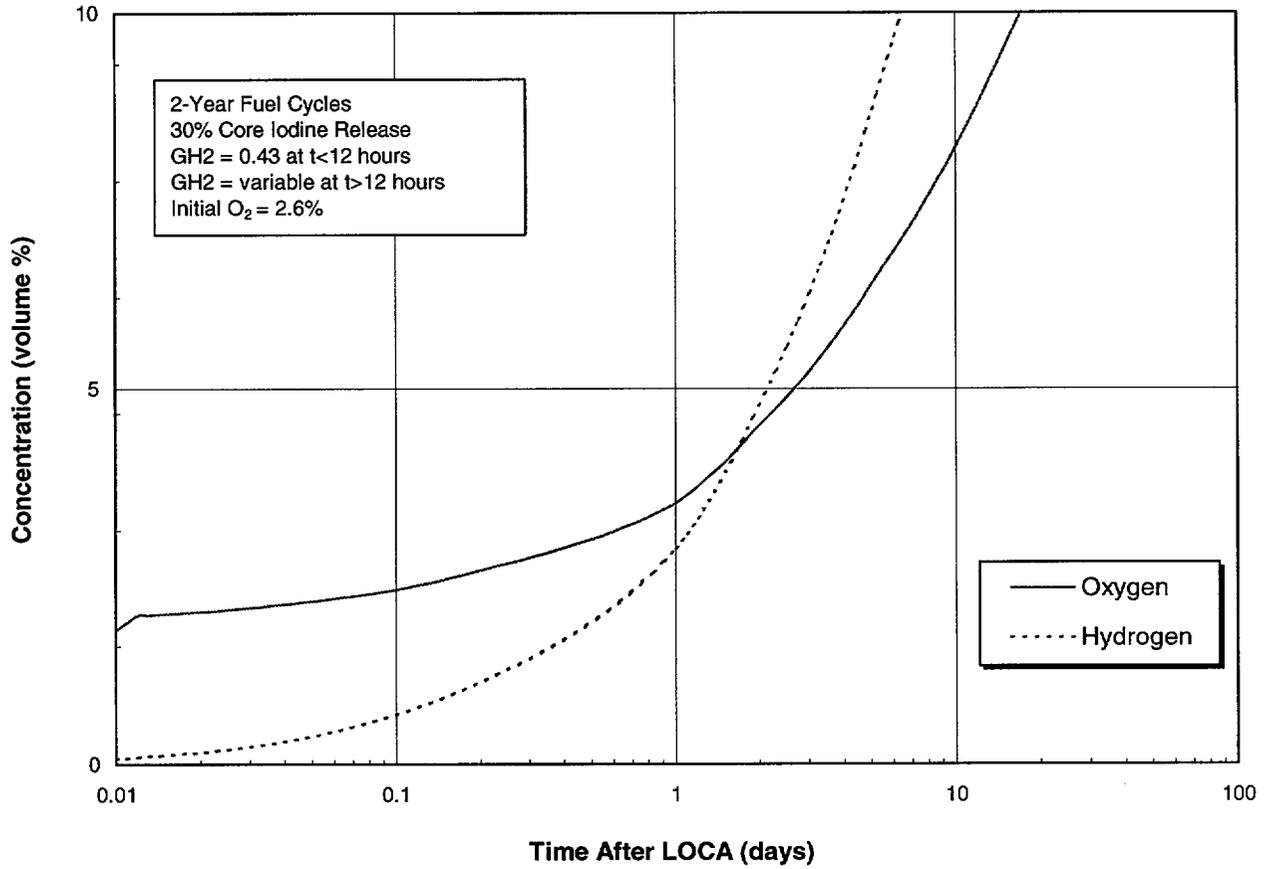


Figure A-4

Mark III Containment Hydrogen with 1.5% Core Iodine

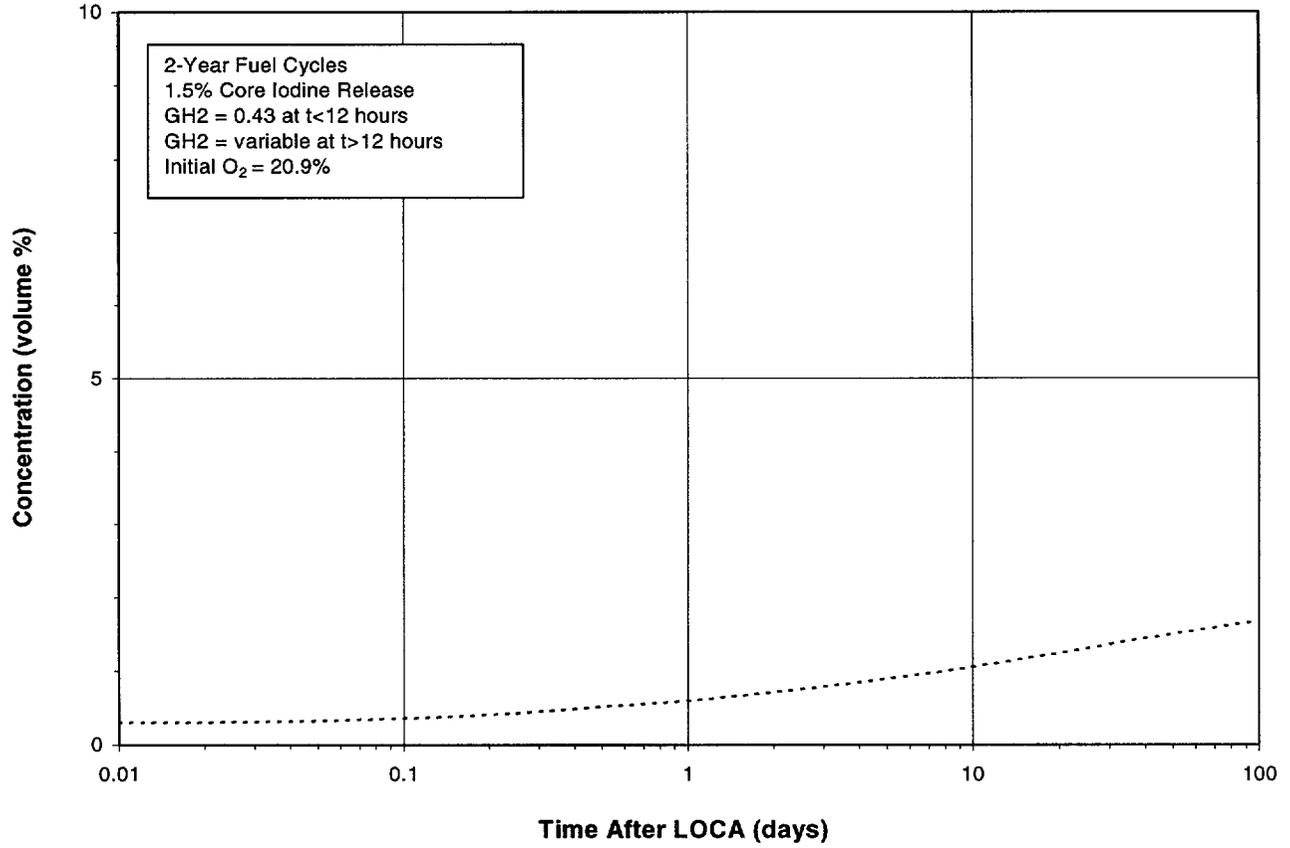


Figure A-5

Mark III Containment Hydrogen with 30% Core Iodine

