Attachment 2

FEASIBILITY STUDY FOR A RISK-INFORMED ALTERNATIVE TO 10 CFR 50.44 "Standards for Combustible Gas Control System in Light-water-cooled Power Reactors"

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1. INTRODUCTION

1.1 Background

In SECY-98-300 [1], the NRC staff presented the following three options for modifying the regulations in 10 CFR Part 50 to make them risk-informed:

1. Continue ongoing rulemaking activities and risk-informed approaches making no changes to the current Part 50
2. Change the special treatment rules in Part 50 to modify their scope to be risk-informed, and
3. Make changes to specific requirements in the body of the regulations, including the general design criteria (GDC).

In a June 8, 1999, Staff Requirements Memorandum (SRM), the Commission:

- Approved proceeding with the current rulemakings in Option 1
- Approved implementing Option 2, and
- Approved proceeding with a study of Option 3

SECY-99-264 [2] provides the NRC staff's plan for the study phase of its work to risk inform the technical requirements of 10 CFR 50 (i.e., Option 3 of SECY-98-300). The plan consists of two phases:

- an initial feasibility study (Phase 1) where recommendations to the Commission on proposed changes will be made, and
- an implementation phase (Phase 2) where changes resulting from Phase 1 approved by the Commission will be made.

Phase 1 consists of three tasks:

Task 1: Identification of candidate changes to requirements and design basis accidents.

- This task provides a first screening of the technical requirements in 10 CFR Part 50, implementing documents, and design basis accidents (DBAs). This screening uses criteria [2] to identify the best candidates for change. The criteria are used to identify requirements and DBAs which appear to have a frequency, risk, or conservatism which is either inordinately high or low.

Task 2: Prioritization of candidate changes to requirements and design basis accidents

- Prioritization criteria used in this task include rough estimates of the values and impacts of the candidate change (including values in safety benefit and burden reduction, and impacts in costs to the NRC and the licensee to make the change); and the practicality of the candidate change.

Task 3: Identification of recommended changes to requirements

- This task will establish the scope and feasibility of implementing the candidate changes identified in the previous tasks.

The changes identified and evaluated in the above tasks can include adding provisions to 10 CFR Part 50 allowing for risk-informed alternatives to the present requirements, revising specific

requirements to reflect risk-informed considerations, or deleting unnecessary or ineffective regulations.

However, in addition to the above tasks, SECY-99-264 states that the process for risk-informing will be tested on an expedited basis using at least two examples. In an attachment to SECY-99-264, 10 CFR 50.44 is identified as a candidate for prompt revision based on work done to date and the feedback received from stakeholders.

SECY-00-0086 [3] provides the first status report on risk-informing the technical requirements of 10 CFR PART 50. In SECY-00-0086 the staff describes a number of activities that have been accomplished since the beginning of the study:

- Developed an initial framework for risk-informing 10 CFR Part 50
- Met with stakeholders (both internal and external) to obtain their input on this study.
- Performed a trial implementation (i.e., 10 CFR 50.44) to test the procedures described in SECY-99-264.

The staff developed an initial framework (Attachment 1 to Reference [3]) to more clearly define and guide the work to be performed under the three tasks of Phase 1. The framework employs an approach that builds upon the defense in-depth philosophy and the concept of safety margins. The initial framework published for comment in February 2000 represents work in progress and it is anticipated that it will change as comments are received, it is further evaluated, and the trial implementation proceeds.

The staff has held a number of public meetings with stakeholders to solicit feedback on the risk-informing process. Lines of communication have been established with industry organizations. The staff has also had several discussions with the ACRS on this topic. The staff plans to continue to interact frequently with stakeholders during the risk-informing process.

As noted above, 10 CFR 50.44 “Standards for combustible gas control system in light-water-cooled reactors” was selected for the first trial implementation of the procedures in SECY-99-264. 10 CFR 50.44 was promulgated to provide a means for the control of hydrogen gas that could be evolved following a design basis loss-of-coolant accident (LOCA) and thereby reduce the risks of a hydrogen combustion that could threaten the integrity of the containment. Further requirements were added to 10 CFR 50.44 after the TMI-2 accident to reduce the risk of hydrogen combustion from degraded core accidents in the smaller volume containments. In Phase 1 the current requirements in 10 CFR 50.44 are evaluated and potential options are identified for changes to make the regulation risk-informed. This report describes the trial implementation of risk-informing 10 CFR 50.44.

1.2 Objectives

As part of the trial implementation, 10 CFR 50.44 was selected as a “test case” for piloting the process of risk-informing 10 CFR Part 50. This study therefore has the following objective:

- To demonstrate the feasibility of the risk-informing process by applying the procedures described in SECY-99-264 [2] together with the guidance in the framework document (Attachment 1 to Reference [3]) in order to risk-inform 10 CFR 50.44. The process should therefore be able to:
  - Identify and describe potential risk informed options.
  - Evaluate the options with the objective of identifying potential alternatives to the current requirements in 10 CFR 50.44.

– Provide the basis for recommendations to the Commission which, if approved, would lead to initiation of rulemaking.

1.3 Scope, Limitations and General Comments

The work to determine the feasibility of risk-informed changes to the technical requirements of 10 CFR 50.44 was carried out in the following manner:

- The focus of this test case is on risk-informing 10 CFR 50.44, which deals only with the threat to containment integrity from the combustion of combustible gases generated during an accident in which significant core damage occurs. There is no intention of developing an alternative containment rule that would be capable of mitigating all potential ways of failing containment (direct containment heating, direct contact of the core debris with the containment boundary, pressure due to steam and non condensible gas generation, etc.) during all severe accidents. Thus compliance with a risk-informed 10 CFR 50.44 will only ensure that the combustion threat is mitigated.

- The intention is to provide a better balance to the 10 CFR 50.44 technical requirements among needed defense-in-depth and safety margins as well as risk. This improved balance will be achieved by systematic considerations of the requirements and may involve relaxing requirements in some areas in combination with increasing requirements in other areas.

- The study will focus on potential changes to the technical requirements associated with 10 CFR 50.44. Since the basis for these requirements may be contained in the regulations themselves or in supporting regulatory guides, standard review plan sections, branch technical positions, or other documents, all such documents are reviewed and, as necessary, considered for change.

- The study identified a requirement that, while important to safety, was found not to be directly related to the concern being addressed by 10 CFR 50.44. The requirement was retained (even though it is not directly related to the concern) rather than moving it to a more relevant rule. This was done to avoid the additional effort that would be associated with deleting the requirement and moving it to another rule.

- This test case followed the process described in SECY-99-264 [2] and the framework document (Attachment 1 to Reference [3]), and thus has the following components, which are discussed in more detail in the references:

  – The set of safety principles established in Regulatory Guide 1.174 [4] will be applied to possible changes to requirements studied in this phase.

  – The criteria applied in this case study for risk categorization will build upon and be consistent with those being used in the Option 2 work as described in SECY-99-256 [5]. It will also build upon and be coordinated with the risk-informed plant oversight process.

  – The criteria established in this study with respect to needed quality of a licensee probabilistic risk assessment (PRA) will be consistent with those proposed in SECY-99-256 and RG 1.174.

– The principal focus of this work is on the current set of licensed reactors. However, potential regulatory changes that impact both current and future plants will receive higher priority than those only affecting current reactors.

1.4 Organization of Report

Chapter 2 of this report describes at a high level how the objective of risk-informing the regulations in Part 50 will be accomplished and how success will be measured. The approach follows the proposed framework for the risk-informing process described in Attachment 1 to Reference [3]. This and subsequent chapters in the report describe how this approach is applied to the requirements in 10 CFR 50.44.

A detailed examination of 10 CFR 50.44 was performed and is described in Chapter 3. Initially the analytical and physical requirements actually imposed by 10 CFR 50.44 are identified and described. Any relationship of 10 CFR 50.44 to other regulations and implementing documents is then identified. This information is needed because changes to 10 CFR 50.44 could potentially impact some of the related regulations or the implementing documents. It is also necessary to understand how the requirements in 10 CFR 50.44 are actually implemented both from the industry and the regulators perspective. This chapter is therefore intended to provide a clear picture of the requirements in 10 CFR 50.44 (and the supporting documentation) and indicate how they are implemented.

In Chapter 4 the concern (i.e., the threat to containment integrity from combustion) associated with 10 CFR 50.44 is described. The risk significance of combustion for the various containment designs and the associated needs for control of combustible gases are determined and also discussed. The purpose of this chapter is to identify the needed attributes for a risk-informed 10 CFR 50.44. This information taken together with the information in Chapter 4 is used to identify risk-informed options in Chapter 5.

Two approaches are used in Chapter 5 to develop potential risk-informed options for 10 CFR 50.44. One approach develops options based on the existing requirements in 10 CFR 50.44. The other approach addresses the concern (to be dealt with by 10 CFR 50.44) by systematically applying the strategies developed in the framework (Attachment 1 to Reference [3]) for risk-informed changes to 10 CFR Part 50. Both approaches have the same overall objective which is to develop risk-informed options dealing with the identified concern.

Finally, in Chapter 6, the implications of the alternative are evaluated and a preliminary assessment is presented in the report.

1.5 References

1. USNRC, “Options for Risk-Informed Revisions to 10 CFR PART 50 - “Domestic Licensing of Production and Utilization Facilities,” SECY-98-300, December 23, 1998.

2. USNRC, “Proposed Staff Plan for Risk-Informing Technical Requirements in 10 CFR PART 50,” SECY-99-264, November 8,1999.

3. USNRC, “Status Report on Risk-Informing the Technical Requirements of 10 CFR Part 50 (Option 3),” SECY-00-0086, April 12, 2000.

4. USNRC, “An Approach for Using Probabilistic Risk Assessments in Risk-Informed Decisions on Plant-Specific Changes to the Licensing Basis,” Regulatory Guide 1.174, July 1998.

5. USNRC, “Rulemaking Plan for Risk-Informing Special Treatment Requirements,” SECY-99-256, October 29, 1999.

2. APPROACH

This section describes at a high level how the objective of identifying risk-informed changes to the technical requirements of 10 CFR Part 50 will be accomplished and success measured. This section summarizes a framework (Attachment 1 to Reference [1]) developed by the staff to more clearly define and guide the process for identifying risk-informed changes. A representation of this framework is presented in Figure 2.1.

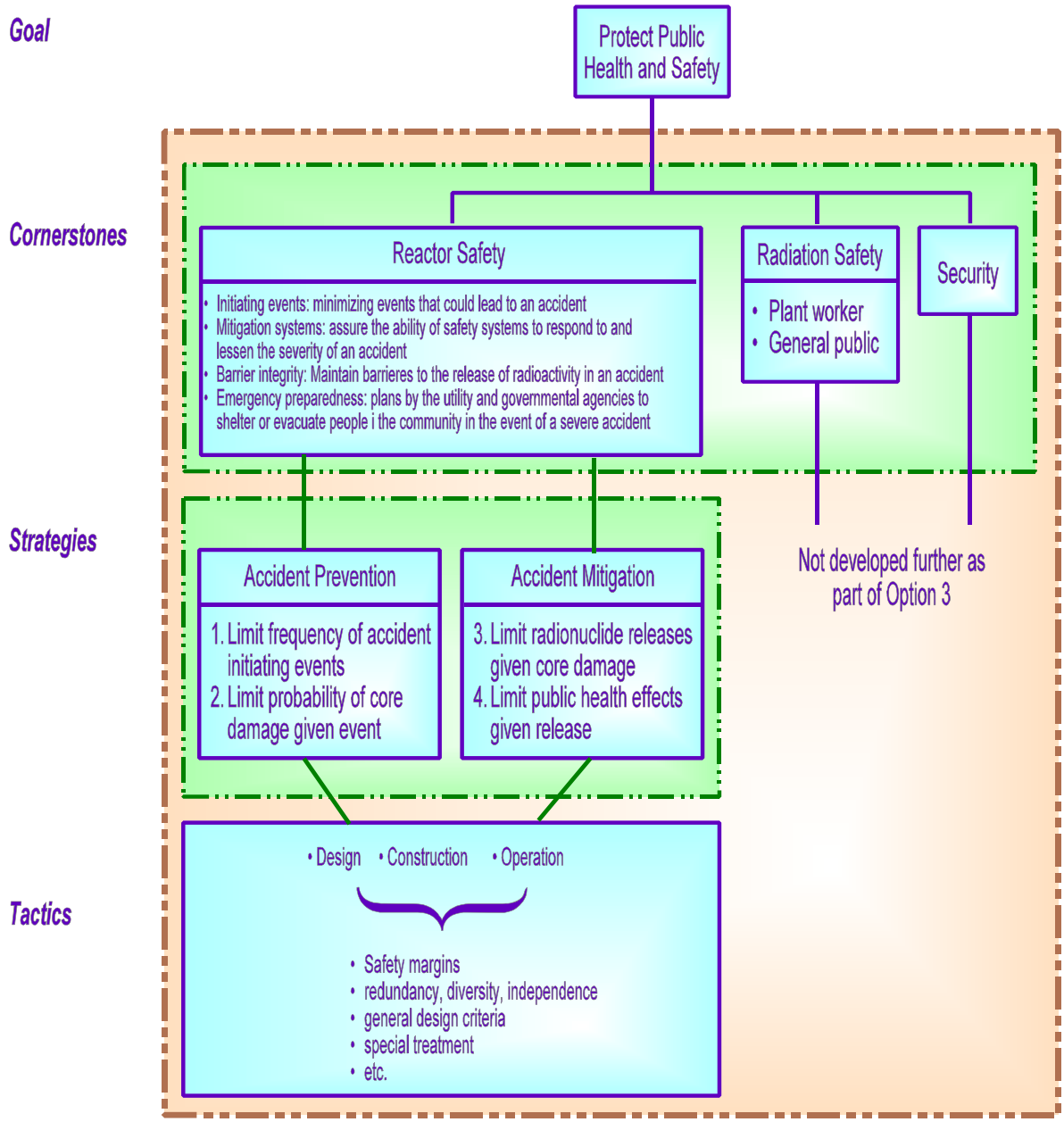

Figure 2.1 Risk-Informed Defense-in-Depth Framework

The structure and elements of the above framework are consistent with established regulatory philosophy and have as a high level goal the protection of the public health and safety. A balanced high-level defense-in-depth approach (based on prevention and mitigation) is included in the framework to help achieve this goal. The approach is summarized in the following working definition:

Defense-in-depth is the approach taken to protect the public by applying the following strategies in a risk-informed manner:

(1) limit the frequency of accident initiating events (initiators)

(2) limit the probability of core damage given accident initiation

(3) limit radionuclide releases during core damage accidents

(4) limit public health effects due to core damage accident

The strategies are applied considering the following defense-in-depth elements:

- *reasonable balance is provided among the strategies*
- *over-reliance on programmatic activities to compensate for weaknesses in plant design is avoided*
- *independence of barriers is not degraded*
- *safety function success probabilities commensurate with accident frequencies, consequences, and uncertainties are achieved via appropriate*
  - *redundancy, independence, and diversity,*
  - *defenses against common cause failure mechanisms,*
  - *defenses against human errors, and*
  - *safety margins*
- *the defense-in-depth objectives of the current General Design Criteria (GDCs) in Appendix A to 10 CFR Part 50 are maintained*

Various tactics are used to support the high-level strategies, and existing regulatory requirements deal with implementation of such tactics. The above framework is extended to include quantitative guidelines for risk-informing existing technical requirements. The intent is to develop risk-informed regulations, which retain deterministic characteristics, in such a way that compliance provides reasonable assurance of protection of the public health and safety. The quantitative guidelines for the different strategies are provided in Figure 2.2. These values are consistent with the quantitative health objectives (QHOs), and the subsidiary objectives in current use. The quantitative guidelines in Figure 2.2 are used in the implementation process to determine potential risk-informed options for each of the above strategies for a given regulatory requirement.

	Accident Prevention		Accident Mitigation	
	Core Damage Frequency $\leq 10^{-4}$/year		Conditional Large Early Release Probability $\leq 10^{-1}$ (Note 5)	
	Limit frequency of accident initiating events	Limit probability of core damage given event	Limit radionuclide releases given core damage	Limit public health effects given release
	Initiator Frequency	Conditional core damage probability	Conditional large early release probability	Conditional individual fatality probability
Frequent initiators	≥ 1/year	$\leq 10^{-4}$	$\leq 10^{-1}$	Note 3
Infrequent initiators	$\leq 10^{-2}$/year	$\leq 10^{-2}$	$\leq 10^{-1}$	Note 3
Rare initiators	$\leq 10^{-5}$/year	Note 4	Note 4	Note 3

Notes:
1. **The product across each row gives a large early release frequency of $<10^{-5}$/year.**
2. **It is preferable that no single type of initiator cause a large fraction of any frequency guideline.**
3. **No quantitative guideline is proposed for the fourth strategy, the LERF guideline is used as a surrogate.**
4. **For rare initiators, emphasis is placed on Strategy 1, limit initiator frequency.**
5. **Measures to mitigate late large releases are also appropriate. A conditional probability of a late large release (up to 24 hours after the onset of core damage) of $\leq 10^{-1}$ is proposed.**

Figure 2.2 Quantitative Guidelines for Risk-Informing Regulations

The definition of LERF in the above figure is the same as in Regulatory Guide 1.174. LERF is the frequency of those accidents leading to significant, unmitigated releases from containment in a time frame prior to effective evacuation of the close-in population such that there is a potential for early health effects. Such accidents generally include unscrubbed releases associated with early containment failure at or shortly after vessel breach, containment bypass events, and loss of containment isolation. This definition is consistent with accident analyses used in the safety goal screening criteria discussed in the Commission's regulatory analysis guidelines.

Not every containment bypass or early failure would result in a large release. To be risk-significant containment leakage must far exceed the design basis containment leak rate. Containment failure modes that result in scrubbed releases or leak paths that are isolated before the onset of significant core damage generally do not lead to large releases.

For some plants, large releases could occur hours after reactor vessel bottom head failure. An example would be a release due to containment overpressurization or high temperature while core-concrete interactions are proceeding in the absence of an overlying water pool. Containment heat removal systems may be inoperable in this scenario, and natural processes would take hours after the completion of core-concrete interactions to remove radionuclides from the containment atmosphere.

Effective evacuation can mitigate the threat of acute health effects offsite given such a delayed large release. However, there are accidents in which external events may preclude or hinder evacuation efforts. Plant workers would also need to be protected from any delayed large release. A quantitative guideline was therefore included in Figure 2.2 to reflect the need for defense-in-depth against the threats posed by such delayed releases. Specifically, the conditional probability of a large late release should be 10^{-1} or less. Late in this context extends to approximately 24 hours after the onset of core damage.

In implementing the framework (with its quantitative guidelines), three major steps are followed as depicted in Figure 2.3: (1) the selection of the regulation to be risk-informed, (2) the development of the risk-informed alternative, and (3) the evaluation of the risk-informed alternative.

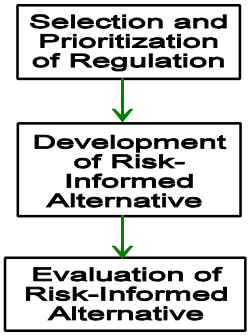

Figure 2.3 Process for Risk-Informing Regulations

The entire process dictated by this approach is likely to be highly interactive as more experience is gained in the development and evaluation of risk-informed options.

2.1 Selection of Regulation

The first major element in the process is the selection of the regulation that needs to be risk-informed. The selection process consists of five major components as shown in Figure 2.4.

A coarse screening of the regulations in Part 50 is initially performed to determine whether the regulation has an impact on prevention or mitigation of core-damage accidents, because these present the most risk to the public and risk information is most prevalent for such accidents. Only those regulations that have potential relevance to safe plant design, operation, or maintenance are candidates for risk-informing. A regulation may become a candidate for elimination if it does not impact any of the strategies or has an insignificant impact on the quantitative guidelines embedded in the three strategies delineated in Figure 2.2. As the second step in Figure 2.4 indicates, as part of this coarse screening an attempt is also made to identify risk-significant safety issues not implicitly addressed in the current regulations. Another screening is then performed, as the third step, to identify those regulations that do not warrant risk-informing and can be eliminated from further consideration; i.e., there is no need for safety improvement, there is no excess conservatism or margin in the regulation, and there is no unnecessary burden created by excessive conservatism. Fourth, an evaluation of the regulations is performed to identify any ties, overlaps or redundancies among regulations to determine if any should be “linked/grouped” as a “single” risk-informed regulation. Finally, the remaining set of regulations is prioritized.

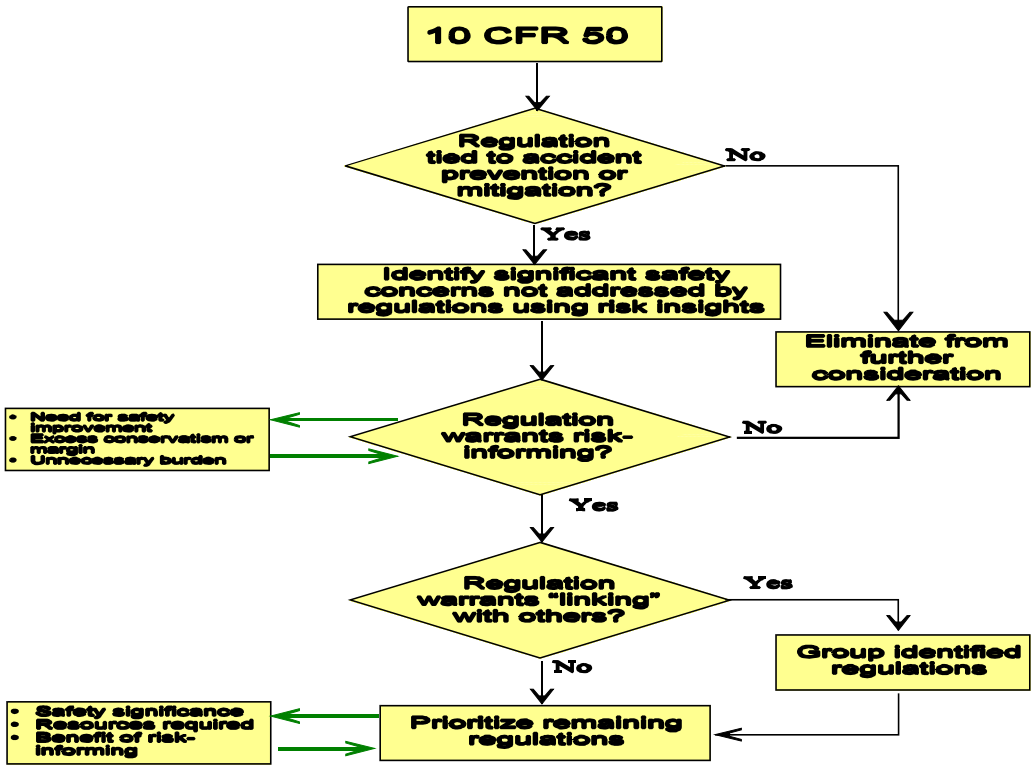

Figure 2.4 Process for selection and prioritization of regulations to be risk-informed

The prioritization considers three factors:

- the safety significance of the regulation
- the potential resources required to risk-inform (considering complexity, information requirements, need for a demonstration plant, time, manpower, etc.), and
- the benefit of making risk-informed changes to the regulation (e.g., the potential for reducing unnecessary burden).

2.2 Development of Risk-Informed Changes

The second major element in the process is to develop the changes to the technical requirements for the high-priority regulations identified in the first element of the process. Two approaches are followed for developing risk-informed changes to a regulation. Both approaches begin with an examination of the concern or concerns that necessitated the regulation, and both approaches have the same overall objective, which is to develop risk-informed requirements for dealing with the identified concern. However, one approach starts from the current set of technical requirements of the regulation and attempts to develop risk-informed changes by analyzing the technical requirements. The second approach takes a fresh start by applying the four high-level defense-in-depth strategies; in effect, ignoring the existing technical requirements of the regulation.

There are two principal reasons for following two approaches to developing a risk-informed alternative to a regulation. The first reason is for completeness. Following both of the above approaches gives greater confidence that all reasonable risk-informed options have been identified. The second reason is to identify a risk-informed alternative that is the most optimal by looking at

the concern from an alternative perspective, that is, without being constrained, or unduly influenced, by the existing requirements.

Potential changes identified by either of these two approaches are developed based on the following six considerations:

- risk insights from plant specific PRAs
- industry experience
- consistency with the quantitative guidelines identified in the framework document
- reasonable cost burden
- proven technology
- suitability for performance-based compliance monitoring

The potential changes derived from both approaches are evaluated to arrive at the risk-informed alternative.

2.2.1 Revising Current Requirements Approach

The approach based on revising the existing technical requirements is shown in Figure 2-5. Each of the six steps in this approach is described below.

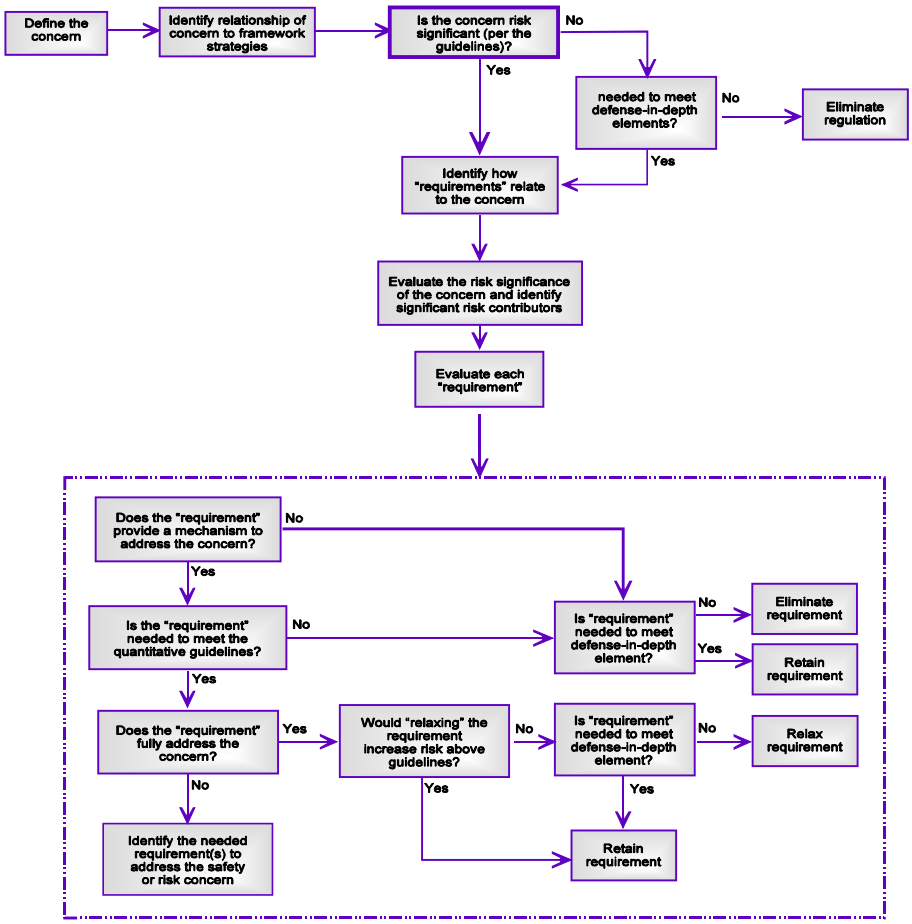

Figure 2.5 Current Requirements Approach to Develop Risk-Informed Options

(1) Define the concern:

As mentioned previously, development of risk-informed changes to the technical requirements of a regulation begins with an examination of the concern or concerns that necessitated the regulation. Only after the concern is clearly understood, can a determination be made as to how risk-significant the concern is, and how effectively the concern is addressed by the existing requirements. The concern should be expressed in terms of its risk significance (e.g., which risk-significant accidents are impacted, and how significant is this impact).

(2) Identify relationship of concern to framework strategies:

In Section 2.1 of this report, the four defense-in-depth strategies to be considered in making risk-informed changes to the regulations were identified. Two of these strategies are preventive (limit frequency of accident initiators and limit probability of core damage given an initiator), and two of the strategies are mitigative (limit radionuclide releases given core damage and limit public health effects given release). The next step in developing risk-informed changes is to identify which of the four strategies are impacted by the concern.

(3) Is the concern risk significant (per the guidelines)?

The risk significance of the concern is assessed against the quantitative guidelines in Figure 2-2. Based on information derived from PRAs, an assessment of the quantitative significance of the concern is made with respect to the quantitative guidelines presented in Figure 2-2 for various types of plants (as defined by their nuclear steam supply systems or containment designs). If the risk significance of the concern results in values significantly below the quantitative guidelines, then the regulation (in its entirety) may become a candidate for elimination. Such regulations must be evaluated to determine (1) if the low risk is because of the technical requirements imposed by the regulation, and if not, then (2) whether the technical requirements are needed to meet any of the defense-in-depth elements. If it is determined that they are not needed to meet the guidelines nor are they needed to maintain defense-in-depth, then the regulation itself becomes a candidate for elimination.

(4) Identify how "requirements" relate to the concern:

Each technical requirement contained in the existing regulation is identified and described in detail in terms of the affected systems, structures, components and procedures (if any) for the various types of plants and the criteria used for assessing compliance with the requirements. A review is then made to determine the relationship of each requirement to other regulations and implementing documents, such as regulatory guides, standard review plan, branch technical positions, generic letters, etc. The purpose of this review is to obtain a detailed understanding of the implications of revising any particular requirement in terms of its impact across the body of the regulations and implementing documents.

Subsequent to the above review, the basis and method of implementation of the requirements by industry are identified and described. A determination is made as to whether the requirement has been implemented by the licensees on the basis of the regulation alone, on the basis of an associated regulatory guide or other implementing document, or on some other basis.

Lastly, each requirement identified at the beginning of this step is evaluated in the context of how effectively it addresses the defined concern.

(5) Evaluate the risk significance of the concern and identify significant risk contributors:

This step is essentially a detailed extension of step (3), above. In step (3), the risk significance of the concern was evaluated, at a high level, in comparison with the quantitative guidelines provided in Figure 2-2. Given that the concern was determined to be risk-significant in step (3), in this step, available PRA information (e.g., NUREG-1150, or IPEs) is reviewed to determine what is driving

the risk-significance of the concern. For the various types of plants (as defined by their nuclear steam supply systems or containment designs), the risk significant contributors are identified, where possible, in terms of the PRA results (e.g., dominant accident sequences, or dominant containment failure modes).

(6) Evaluate the each requirement:

In this step, each technical requirement identified in step (4) is evaluated to determine if, and how, it should be risk-informed. Options for risk-informing the technical requirements broadly fall into the following three categories:

- eliminate the current requirement
- retain the current requirement
- revise, enhance, or supplant the current requirement

Guidance as to which category each requirement falls into is provided by answering the three questions described below.

1. Does the requirement provide a mechanism to address the concern?

The answer to this question should have been obtained during step (4) above. If the requirement does not provide a mechanism to address the concern, then it should be evaluated to determine whether it is needed to meet any of the defense-in-depth elements. If it is determined that the requirement is needed to maintain defense-in-depth, then the requirement is retained. However, if it is determined that the requirement is not needed to maintain defense-in-depth, then it becomes a candidate for elimination. It is important to note, as before, that all requirements that are identified as candidates for elimination through this process will also be examined to assure that their elimination will not have any adverse impact on the radiation safety and security cornerstones.

If the requirement does provide a mechanism to address the concern, then it is subjected to the following question.

2. Is the requirement needed to meet the quantitative guidelines?

Based on information obtained in steps (3-5), a determination is made as to whether the requirement is necessary in order for the strategies impacted by the concern to meet the associated quantitative guidelines provided in Figure 2-2. If the requirement is determined to not be necessary to meet the quantitative guidelines, then it will be either eliminated or retained based on whether it is needed to meet any of the defense-in-depth elements, as discussed for the previous question. If the requirement is determined to be necessary to meet the quantitative guidelines, then it is subjected to the following question.

3. Does the requirement fully address the concern?

This question is used to determine whether or not a safety enhancement would be appropriate. It is possible that there are aspects of the defined concern which are not fully addressed by the existing requirement (or requirements). In this case, any necessary additional requirements should be identified, so that the concern will be fully addressed.

If the requirement does fully address the concern, then the requirement should be evaluated to determine whether or not it can be relaxed and still maintain risk below the quantitative guidelines. If relaxing the requirement would increase risk above the guidelines, then the requirement is retained, as is. If relaxing the requirement would still maintain risk below the guidelines, then it can be relaxed, as long as it is not needed to meet any of the defense-in-depth elements, as discussed previously.

2.2.2 Developing Alternative Requirements Approach

As noted above the main difference between the two approaches to developing risk-informed changes is that risk-informed changes obtained through implementation of the alternative requirements approach are developed without reference to the existing technical requirements of the regulation. In this approach, as seen from Figure 2-6, risk-informed changes for addressing the concern can be identified during any of steps (2-4) of the figure. This allows changes to be developed from different perspectives. The four steps in an alternative approach that begins afresh from a risk-informed perspective are described below using the four strategies of the framework and again defining the concern.

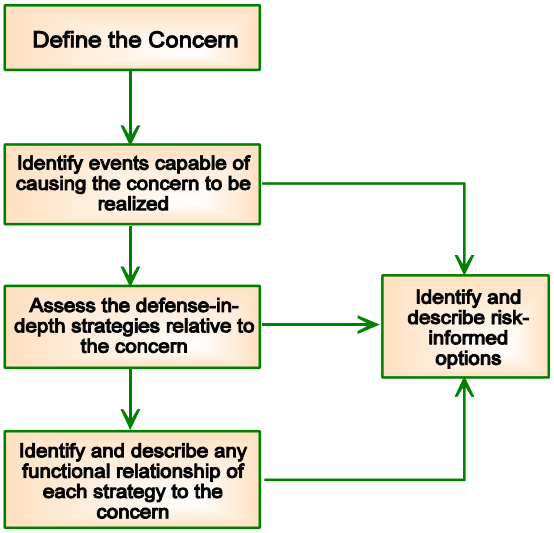

Figure 2.6 Alternative requirements approach to developing risk-informed options

(1) Define the concern:

This step is very similar to step (1) for the revising current requirements approach. As mentioned previously, development of risk-informed changes to a regulation begins with an examination of the concern or concerns that necessitated the regulation. The concern should be expressed in terms of its risk significance (e.g., which risk-significant accidents are impacted, and how significant is this impact).

(2) Identify events capable of causing the concern to be realized:

After the concern is defined, an identification is made at a high-level of events that could cause the concern to be realized. For example, if the concern is that a deflagration/detonation of combustible gas could threaten containment, for the concern to be realized there must be generation of combustible gas from metal-water reactions during an accident in which significant core damage occurs. Existing PRAs can, generally, provide more specific insights regarding specific sequences of events that are most likely to cause an identified concern to be realized.

(3) Assess the defense-in-depth strategies relative to the concern:

As mentioned previously, Section 2.1 of this report identifies four defense-in-depth strategies for limiting accident risk. Three of these strategies also have quantitative guidelines associated with them, as shown in Figure 2-2. In this step, the efficacy of each strategy relative to preventing and mitigating the identified concern is assessed. For those strategies that address the concern, performance-based options can be developed with high-level acceptance criteria, which would allow licensees substantial flexibility in meeting them. In addition, if it is anticipated that it may be difficult for licensees to meet the high-level acceptance criteria based on the strategies that address the concern, similar type options can be developed based on the remaining strategies. For example, the reduction of the frequency of an accident class under which the concern becomes less manageable may be more practical than ensuring the operability of a mitigating system under the same conditions.

(4) Identify and describe any functional relationship of each strategy to the concern:

Understanding the functional relationships between each strategy and the concern allows practical methods of applying each defense-in-depth strategy to the defined concern to be identified, for relevant plant types. These changes are expected to be much more prescriptive than those developed under the preceding step. For example, specific hardware or procedures may be identified in these changes for applying a specific strategy to the concern. As in the previous step, the changes may relate to the strategies that address the concern, or it may prove to be more practical to develop changes related to the other strategies. For example, station blackout accidents may impose the most severe conditions on the plant's ability to successfully control combustible gas concentrations. An option reducing the frequency of station blackout may prove to be more practical for managing the defined concern than attempting to ensure that mitigating systems can successfully operate under station blackout (SBO) conditions.

2.3 Evaluation of Risk-informed Alternative

In the previous step, all changes were developed based on safety and risk implications. These changes were evaluated to arrive at a risk-informed alternative to an existing regulation. In this step, the risk-informed alternative is evaluated in order to estimate the associated NRC and licensee burdens, for both implementing and applying the alternative, and to compare these estimates with similar estimates for the existing regulation. The factors affecting both NRC and licensee burden are listed below.

Factors impacting NRC:
- Need for a rule change
- Impact on other regulations
- Need to revise or modify implementing documents
- Need to create a new implementing document
- Extent of regulatory analysis required
- Need for NRC review of licensee submittals
- Impact on NRC inspection activities

Factors impacting Licensees:
- Need for new or modified equipment
- Need for analysis
- Impact on maintenance and inspection activities
- Impact on technical specifications
- Impact on procedures and training

2.4 References

1. USNRC, “Status Report on Risk-Informing the Technical Requirements of 10 CFR Part 50 (Option 3),” SECY-00-0086, April 12, 2000.

3. EXAMINATION OF 10 CFR 50.44

3.1 Selection of Regulation

SECY-99-264, “Proposed Staff Plan for Risk-Informing Technical Requirements in 10 CFR 50" [1] provides the staff's plan for the study phase of its work to risk-inform the technical requirements of 10 CFR Part 50 (i.e., Option 3 of SECY-98-300 [2]). SECY-99-264 notes that the staff intends to test the process outlined in the plan by using at least two example 10 CFR Part 50 modifications, one of which involves the modification of a single requirement (e.g., hydrogen control requirements in 10 CFR 50.44) and one which involves modification of a set of related requirements (e.g., requirements related to special treatment of SSCs).

The selection of 10 CFR 50.44 as a test application has been prompted in part by the fact that a number of licensees have identified 10 CFR 50.44 as a regulation which includes requirements that may not be risk significant, and whose implementation therefore places unnecessary burden on the licensees. In a Nuclear Energy Institute (NEI) survey [3] on the need and benefit of improving NRC Technical Requirements, 56 plants responded, and 24 units identified 10 CFR 50.44 as a high priority candidate for change. 10 CFR 50.44 also was the subject of an exemption request [4] from a licensee, Southern California Edison, that operates the San Onofre Nuclear Generating Station (SONGS), a pressurized water reactor (PWR) with a large dry containment. Specifically, SONGS requested an exemption from 10 CFR 50.44 to remove requirements for hydrogen control systems in accordance with the pilot program for risk-informed, performance-based regulation. The petition was granted by the NRC and the staff recognized that the basis for the exemption was not SONGS specific, but was applicable on a wider, generic basis. In accordance with NRC Commission guidance, rulemaking should be used to avoid numerous exemption requests. Subsequent to the San Onofre exemption, the NRC staff received additional requests for relaxation of some regulatory requirements found in 10 CFR 50.44, specifically from the Boiling Water Reactor (BWR) Owners Group.

More industry support for 10 CFR 50.44 as a candidate to be risk informed was shown at the NRC-Sponsored Public Workshop on Options for Risk-Informed Revisions to Part 50 [5] held on September 15, 1999 in Rockville, MD. At the workshop, an Open Discussion session focused on the identification of candidate requirements and design basis accidents to be revised, particularly on the selection of top candidate(s) for risk-informing. Several stakeholders expressed views that 10 CFR 50.44 should be such a candidate for risk-informing on the basis that some of the requirements of the current regulation do not contribute to risk reduction and cause unnecessary burden.

10 CFR 50.44 also becomes a viable candidate for risk-informing when the selection criteria described in Section 2.1 are applied:

- 10 CFR 50.44 affects accident prevention and mitigation.
- 10 CFR 50.44 warrants risk-informing it may not address the safety issue of concern most efficiently or effectively, and may impose excess burden.
- 10 CFR 50.44 is directly linked with other regulations (e.g., 10 CFR 50.47).

The ability to control combustible gases is directly tied to the defense-in-depth concept of accident prevention and mitigation. Specifically, hydrogen combustion maybe a direct threat to the containment integrity (i.e., ability to mitigate an accident), but could also be minimized by preventive strategies.

10 CFR 50.44 warrants risk-informing since, when examining current requirements, certain parts of 10 CFR 50.44 appear to be designed to mitigate accidents that are not risk significant, and

consequently, appear to impose unnecessary burden. For instance, it is likely that the removal of some aspects of the hydrogen control systems for LOCA, or a reduction of their surveillance and maintenance requirements would be cost beneficial. In addition, there appear to be risk significant accidents that the current requirement do not explicitly address.

10 CFR 50.44 is related to other regulations, for example, 10 CFR 50.47, Emergency Plans, which requires that the *"emergency preparedness provide reasonable assurance that adequate protective measures can and will be taken in the event of a radiological emergency."* Further, 50.47 requires that this emergency plan meet the requirement of Appendix E, Emergency Planning and Preparedness for Production and Utilization Facilities. Appendix E, Section VI, Emergency Response Data System, requires the licensee to provide data on selected plant parameters, one being hydrogen concentration. In risk-informing 10 CFR 50.44, the impact to the other regulations also needs to be addressed.

3.2 Description of Regulation

The present form of section 44 of part 50 of title 10 of the Code of Federal Regulations (10 CFR 50.44), "Standards for combustible gas control system in light-water-cooled power reactors," results from the original rule of 1978 and two major amendments motivated by the 1979 accident at Three Mile Island Unit 2. One amendment was incorporated into the rule in 1981, the other in 1985. The various requirements are described below in terms of the original rule and its amendments.

3.2.1 Original Rule

Because of the potential for hydrogen generation as a result of a LOCA, the NRC published, on October 21,1976, in the Federal Register (41FR 46167) a notice of proposed rulemaking concerning proposed amendments to 10 CFR Part 50. The proposed rule was published in the Federal Register (43 FR 50162) and became part of the Code of Federal Regulations, as 10 CFR 50.44, in 1978.

The logic of the original rule is illustrated in Figure 3.1 below. The letters below the boxes indicate the part of the rule referred to.

10 CFR 50.44 requires each light-water-cooled reactor (LWR) fueled with oxide pellets encased within zircaloy cladding to have a means for controlling hydrogen gas generated following a postulated LOCA. The hydrogen gas could be generated by: (1) metal-water reaction between the zirconium cladding and the reactor coolant, (2) radiolytic decomposition of the coolant, and (3) corrosion of metals.

In controlling the generated gas, each boiling or pressurized LWR is required to have a capability for:

- measuring the concentration of hydrogen in the containment
- insuring a mixed atmosphere in the containment, and
- controlling combustible gas concentrations in containment following a postulated LOCA.

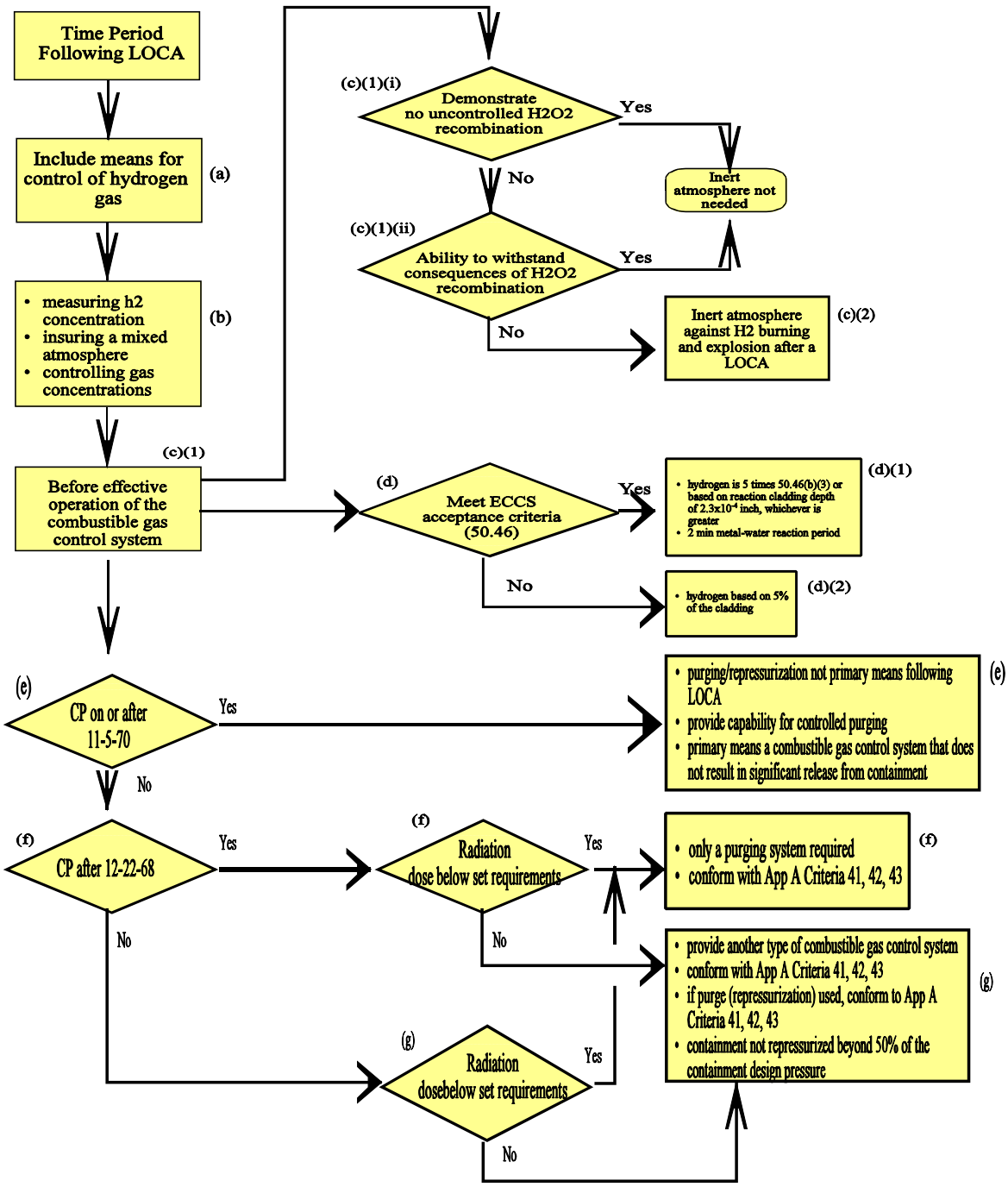

Figure 3.1 Requirements of the Original 10 CFR 50.44 Rule

In addition, for each BWR or PWR, it must be shown, during the time period following a postulated LOCA but prior to effective operation of the combustible gas control system, that either: (1) an uncontrolled H2-O2 recombination would not occur within the containment, or (2) the plant could withstand the consequences of an uncontrolled recombination without loss of safety function. If these two conditions cannot be demonstrated then the containment shall be provided with an

inerted (oxygen deficient) atmosphere to provide protection against hydrogen burning and explosion (e.g., deflagration or detonation) during the time period specified above.

Regarding the amount of hydrogen to be considered for the combustible gas control system, the rule stated the following:

- For facilities that are in compliance with 50.46(b), i.e., the acceptance criteria for emergency core cooling systems, specifically, the peak clad temperature, maximum cladding oxidation, maximum hydrogen generation, coolable geometry, and long-term cooling, the amount of hydrogen due to core metal-water reaction (% of cladding that reacts with water) shall be assumed to be either five times the total hydrogen calculated in demonstrating compliance with 50.46 (b) (3) or the amount that would result from reaction of all the metal on the outside of the cladding on the rods to a depth of 0.00023 inch, whichever is greater. (In calculating the hydrogen generated, 50.46 (b) (3) calls for the assumption of a maximum of 1% clad metal-water reaction). A time period of 2 minutes shall be used as the time interval following the postulated LOCA over which the metal-water reaction occurs.

- For facilities which have no evaluation of compliance with 50.46 (b), the amount of hydrogen generated shall be assumed to be equivalent to that occurring from a 5% clad metal-water reaction

Regarding the type of combustible gas control systems which would be acceptable, the rule stated the following:

- For facilities whose notice of hearing on the application for a construction permit was published on or after November 5, 1970, purging and/or repressurization shall not be the primary means for controlling combustible gases following a LOCA. However, the capability for controlled purging shall be provided. For these facilities, the primary means for controlling combustible gases following a LOCA shall consist of a combustible gas control system, such as recombiners, that does not result in a significant release from containment.

- For facilities with respect to which the notice of hearing on the application for a construction permit was published prior to November 5, 1970, if the incremental radiation dose from purging (and repressurization if a repressurization system is provided) at all points beyond the exclusion area boundary after a postulated LOCA ...*(is within certain limits)...* and if the combined radiation dose at the LPZ outer boundary from purging and the postulated LOCA....*(is within certain limits)*....., only a purging system is necessary, provided that the purging system and any filtration system associated with it are designed to conform with the general requirements of Criteria 41, 42, and 43 of appendix A to part 50. Otherwise the facility shall be provided with another type of combustible gas control system (a repressurization system is acceptable) designed to conform with the general requirements of Criteria 41, 42, and 43 of appendix A to part 50. If a purge system is used as part of the repressurization system, the purge system shall be designed to conform with the general requirements of Criteria 41, 42, and 43 of appendix A to part 50. The containment shall not be repressurized beyond 50 percent of the containment design pressure.

In summary*, the requirements imposed by the original rule of 10 CFR 50.44 include the following:*

Analytical requirements

- *the type of accident considered, viz. postulated LOCA*

- *the sources of hydrogen (fuel-cladding oxidation, radiolysis, and corrosion)*
- *the hydrogen source term (5% oxidation reaction over a 2 minute period)*

Physical requirements

- *measuring hydrogen concentrations*
- *insuring a mixed containment atmosphere*
- *controlling combustible gas concentrations resulting from a postulated LOCA*

3.2.2 Amendments to 10 CFR 50.44

In the aftermath of the TMI accident, the NRC reevaluated the adequacy of the regulations related to H2 control with the intent of providing greater protection in the event of accidents more serious than design basis LOCAs. Specifically, significant quantities of hydrogen from the metal-water reaction, estimated at approximately 400 kg, were generated during the core melt accident at TMI-2 on March 28, 1979. Combustion of the hydrogen released to containment during the accident sequence generated a pressure spike of about 28 psig (peak pressure). Since the design pressure of the large dry containment at TMI-2 was approximately 60 psig, the accident pressure spike did not pose a threat to containment integrity. However, the occurrence of the extensive metal water reaction and subsequent hydrogen burn in the TMI-2 accident gave impetus to the imposition of additional hydrogen control requirements that included additional hardware backfits to the small volume pressure suppression containments such as the BWRs and the ice condenser PWRs.

In addition, during the TMI accident a hydrogen “bubble” was formed in the reactor coolant system, which impeded adequate coolant flow to the reactor core. As a result new requirements were also imposed as part of 10 CFR 50.44 that required installation of high point vents in the RCS of all plants to allow venting of non-condensible gases.

3.2.2.1 1981 Amendment

In 1981, the NRC published (46FR58484) amendments to 10 CFR 50.44, “Interim Requirements Related to Hydrogen Control.” This amendment added Sections (c)(3)(i), (c)(3)(ii), and (c)(3)(iii) to the rule.

As illustrated in Figure 3.2, the 1981 amendment imposed three requirements which included:

- Inerted atmosphere for Mark I and Mark II containments

- Installation of recombiners for LWRs that rely on a purge or repressurization system as a primary means of controlling combustible gases following a LOCA

- Installation of high point vents.

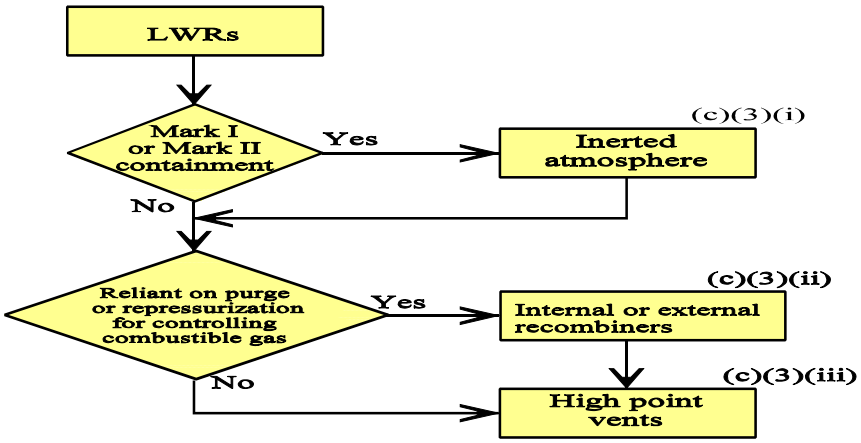

Figure 3.2 Requirements of the 1981 Amendment to 10 CFR 50.44

Regarding BWR plants with Mark I or Mark II containments, Section (c)(3)(i) of the amendment unequivocally stated that: Effective May 4, 1982 or 6 months after initial criticality, whichever is later, an inerted atmosphere shall be provided for each boiling light-water nuclear power reactor with a Mark I or Mark II type containment

Also, each light-water nuclear reactor that relies upon a purge/repressurization system to control combustible gases following a LOCA is required under Section (c)(3)(ii) of the 1981 amendment to 10 CFR 50.44 to be provided with either internal or external recombiners. Whether or not internal or external recombiners are used, they must all meet the combustible gas control requirements. This amendment was subsequently modified by Generic Letter GL 84-09 [6], which exempted plants with a Mark I containment from the amendment. Section (c)(3)(ii) is illustrated in Figure 3.3 below.

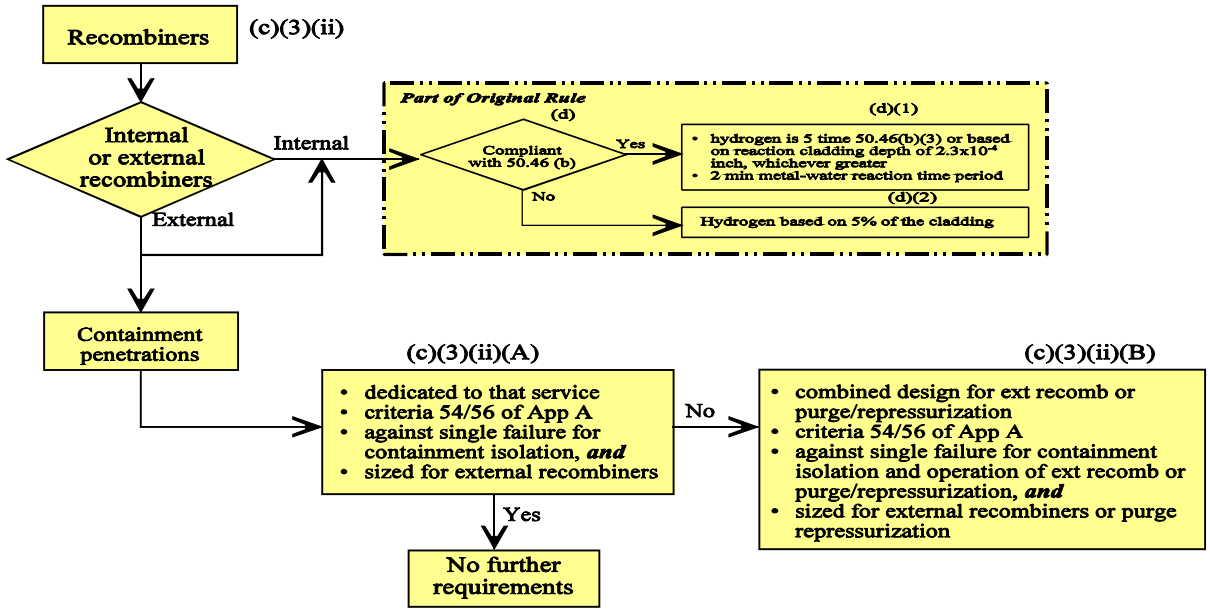

Figure 3.3 Requirements of the 1981 Amendment to 10 CFR 50.44 (Recombiners)

A large fraction of the hydrogen generated during the TMI accident accumulated in the upper region of the reactor vessel head. As this non-condensible gas "bubble" could not be vented it stagnated flow to the core and caused inadequate core cooling. In response to this problem each light-water nuclear power reactor was required, in Section (c)(3)(iii) of the 1981 amendment to 10 CFR 50.44, to be provided with high point vents for the reactor coolant system, the reactor vessel head, and for other systems. High point vents were, however, not required for tubes in u-tube steam generators. The requirements of Section (c)(3)(iii) are listed in Figure 3.4.

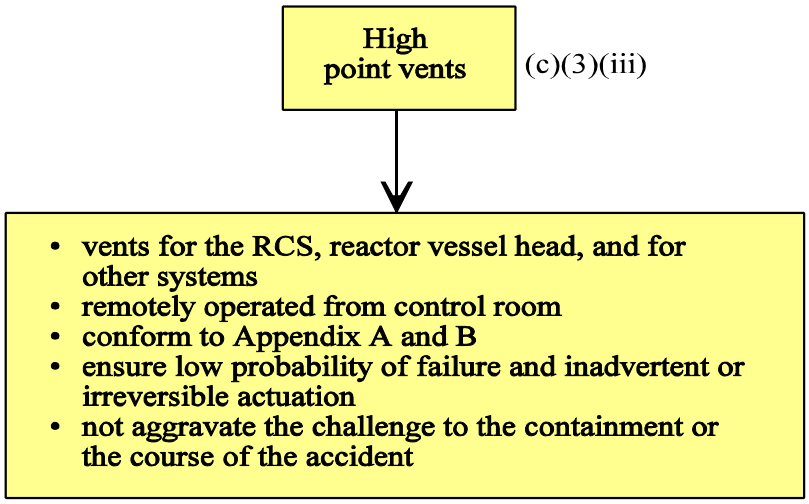

Figure 3.4 Requirements of the 1981 Amendment to 10 CFR 50.44 (High Point Vents)

In summary*, the requirements imposed by the 1981 amendment to 10 CFR 50.44 include the following:*

- *inert Mark I and II containments*
- *recombiners for post LOCA*
- *high point vents*

3.2.2.2 1985 Amendment

In 1985, the NRC published (50FR3498) another amendment to 10 CFR 50.44, "Hydrogen Control Requirements," contained in Section (c)(3)(iv).

The 1985 amendment required a hydrogen control system for BWRs with Mark III containments and PWRs with ice condenser containments justified by a suitable program of experiment and analysis. Mark III and ice condenser plants that do not rely on inerting must have systems and components to establish and maintain safe shutdown and containment integrity and these systems must be able to function in an environment after burning and, possibly, detonation of hydrogen unless it is shown that such events are unlikely to occur. The amount of hydrogen to be considered is that generated from an equivalent 75% metal-water reaction.

Figure 3.5 shows the requirements of 10 CFR 50.44 from the 1985 amendment.

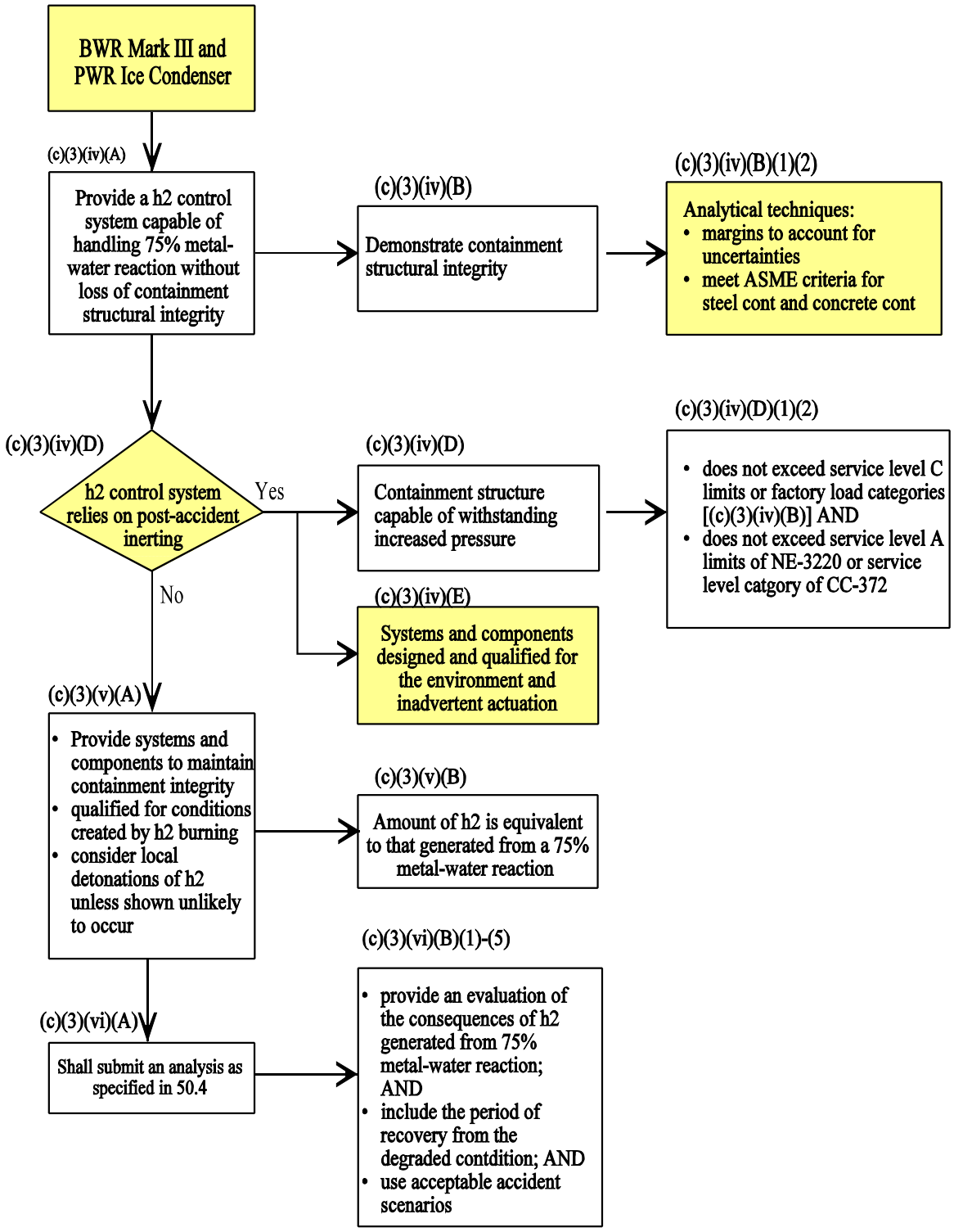

Figure 3.5 Requirements of 1985 Amendment to 10 CFR 50.44

Containment structural integrity must be demonstrated using an analytical technique acceptable to the NRC staff. An acceptable method could include the use of actual material properties with suitable margins to account for uncertainties or alternatively follow specific criteria of the ASME Boiler and Pressure Vessel Code.

If the hydrogen control system relies on post-accident inerting, the containment structure must be capable of withstanding the additional pressure either during the accident (i.e., demonstrate that Service Level C limits are not exceeded) or in the event of an inadvertent full inerting during normal plant operation (i.e., demonstrate that Service Level A limits are not exceeded). The systems required to establish and maintain safe shutdown must be qualified for the environment caused by such inerting. Inadvertent inerting during normal operation must not adversely affect systems and components needed for safe plant operation.

The analysis that Mark III and ice condenser plants are required to submit must be such that it (a) provides an evaluation of the consequences of the large amount of hydrogen (i.e., 75% metal-water reaction) assumed to be generated, including consideration of hydrogen control measures, (b) includes the period of recovery from degraded conditions, (c) uses accident scenarios accepted by the NRC staff, (d) supports design of the hydrogen control system, (e) shows that for those reactors that do not rely upon inerting to control hydrogen, the structural integrity of the containment will be maintained and the systems and components necessary to establish and maintain safe shutdown will be capable of performing their functions in the environment prevailing after hydrogen combustion and, possibly, local detonations (unless it can be shown that these events are unlikely to occur).

As originally proposed, the new requirements were applicable to PWRs with large dry containment. However, the NRC agreed with comments suggesting that implementation for these containments be deferred pending completion of severe accident rule making, at which time the results of research and PRAs would be available.

In summary, *the requirements imposed by the 1985 amendment apply only to Mark III and ice condenser containment plants and include the following:*

Analytical requirements

- *Type of accident, viz. degraded core accident with core remaining in-vessel,*
- *Source of hydrogen (fuel-cladding oxidation)*
- *Hydrogen source term (75% metal-water oxidation reaction)*

Physical requirements

- *Control system capable of mitigating hydrogen from 75% metal-water reaction*

3.3 Relationship of 10 CFR 50.44 to Other Regulations and Implementing Documents

10 CFR 50.44 either references or is referenced by other regulations. In addition, guidance is provided with the requirements in 10 CFR 50.44 or the associated regulations in the form of implementing documents such as regulatory guides, etc. These are summarized and described below.

3.3.1 Relationship of 10 CFR 50.44 to Other Regulations

Table 3-1 provides a list of the regulations referenced in 10 CFR 50.44 and those regulations that have some type of regulatory association with 10 CFR 50.44. The applicable or referenced section in 10 CFR 50.44 is also listed.

Table 3-1 Summary of Related Regulations

Applicable 10 CFR 50.44 Section	Referenced/ Related Regulation	Description of Requirement
(a)	10 CFR 50.82(a)(1)	Excludes from purview of 10 CFR 50.44 nuclear power reactor facilities that have certified permanent cessation of operation.
(b)(1)	10 CFR 50.47, App E	H2 monitors required by Emergency Response data system
	GDC 13	Instruments must be provided to monitor variables for accident conditions
	10 CFR 50.36	Tech Specs on monitor operability and testing
	GDC 43	Monitor testing
	10 CFR 21, App B	Procurement and QA for safety-grade monitors .
(b)(2)	GDC 41	Provide systems to control concentration of H2, O2 to insure containment integrity
	10 CFR 50.36	Tech Specs on mixing systems
(b)(3)	GDC 54,56	Requirements on containment penetrations for external recombiners and purge-repressurization systems
	App B	Quality standards for combustible gas control systems
	GDC 5	Sharing of external recombiners between units at one site
	10 CFR 50.36	Tech Spec requirements and surveillance testing of recombiners
	10 CFR 50.55a	ISI check valve tests
	App J	Testing of containment penetrations (App. J)
(c)(1)(ii)	GDC 50, 16	Containment shall accommodate, with sufficient margin, conditions resulting from a LOCA, including energy sources, as required by 10 CFR 50.44, from metal-water and other chemical reactions resulting from degradation but not total failure of ECCS. Containment shall establish leak-tight barrier against uncontrolled release to environment and assure conditions important to safety are not exceeded for duration of postulated accident.

Table 3-1 Summary of Related Regulations

Applicable 10 CFR 50.44 Section	Referenced/ Related Regulation	Description of Requirement
(c)(3)(ii)	GDC 54, 56	Applies to containment penetrations for external recombiners 54: provides requirements on piping systems penetrating containment 56: provides requirements on primary containment isolation
(c)(3)(iii)	Appendix A and B	Requirements for design of high point vents and associated controls, instruments, and power sources
(c)(3)(iv)	10 CFR 50.55a	ASME Codes for steel containments required to demonstrate structural integrity for Mark III and ice condenser plants
(c)(3)(vi)(A)	10 CFR 50.4	Specifies requirements for written communications from licensees operating Mark III and ice condenser plants that are required to submit accident analyses
(d)(1), (d)(2)	10 CFR 50.46(b)	Specifies maximum H2 generation in postulated LOCA for purposes of complying with ECCS acceptance criteria; referenced in original version of 10 CFR 50.44 as a basis for the design of the H2 control system for facilities in compliance with 10 CFR 50.46(b)
(f)	10 CFR 100.11(a)(2)	Pertains to facilities whose notice of hearing on CP application was published between 12/22/68 and 5/11/1970; applies dose based criteria, with doses calculated in accordance with the regulation in 10 CFR Part 100 used to develop exclusion area and LPZ boundary distances; if criteria are met, only purging system is necessary, if not, a second gas control system is required (repressurization system or a combined purge-repressurization system are acceptable);
	GDC 41,42,43	Both purge and repressurization systems have to comply with GDC 41, 42, 43; containment shall not be repressurized beyond 50% of design pressure
(g)	10 CFR 100.11(a)(2)	Pertains to facilities whose notice of hearing on CP application was published prior to 12/22/68; applies dose based criteria, with doses calculated in accordance with the regulation in 10 CFR 100 used to develop exclusion area and LPZ boundary distances; if criteria are met, only purging system is necessary, if not, a second gas control system is required (repressurization system or a combined purge-repressurization system are acceptable);

Table 3-1 Summary of Related Regulations

Applicable 10 CFR 50.44 Section	Referenced/ Related Regulation	Description of Requirement
	GDC 41,42,43	Both purge and repressurization systems have to comply with GDC 41, 42, 43; containment shall not be repressurized beyond 50% of design pressure
Note (1)	10 CFR 50.34 (f)	10 CFR 50.34 (f) "Additional TMI-related requirements" establishes requirements for combustible gas control for future plants whose applications for a construction permit or manufacturing license were pending as of 2/16/1982
Note (1): Regulations not explicitly referenced in 10 CFR 50.44, but are related to 10 CFR 50.44 requirements.		

10 CFR 50.82(a)(1), "Termination of License" (for power reactor licensees) requires that power reactor licensees who have decided to permanently cease operation must, within 30 days, submit a written certification to the NRC stating the date on which operations have ceased or will cease as required under 10 CFR 50.4(b)(8). Once fuel has been permanently removed from the reactor vessel, the licensee must submit a certificate to that effect to the NRC stating the date on which fuel was removed from the reactor vessel and the disposition of the fuel as required by 10 CFR 50.4(b)(9). Once these certifications have been submitted as required under 10 CFR 50.82(a)(1), then 10 CFR 50.44 ceases to apply to the reactor facility.

10 CFR 50.47 "Emergency Plans" and Appendix E " Emergency Planning and Preparedness for Production and Utilization Facilities" also include the requirement stated in 10 CFR 50.44 (b)(1) to measure the hydrogen concentration in containment. Section VI "Emergency Response Data System" of Appendix E requires the licensee to provide accurate and timely updates of a limited set of parameters to the NRC Operations Center in the event of an emergency. Containment parameters to be supplied for PWRs include pressure, temperature, hydrogen concentration and sump levels. Containment parameters required to be provided for BWRs include drywell pressure, temperature and sump levels, hydrogen and oxygen concentrations, and suppression pool level and temperature.

General Design Criteria 13 of 10 CFR Part 50 Appendix A requires that instruments be provided to monitor variables for accident conditions as appropriate to assure adequate safety, including those variables that can affect the fission process, the integrity of the reactor core, the reactor coolant system boundary, and the containment and its associated systems.

10 CFR 50.36 requires establishment of a technical specification limiting condition of operation for installed instrumentation that is used to detect, and indicate in the control room, a significant abnormal degradation of the reactor coolant pressure boundary. This requirement implies technical specifications on hydrogen monitor operability.

10 CFR Part 50 Appendix A "General Design Criteria for Nuclear Power Plants" and Appendix B "Quality Assurance Criteria for Nuclear Power Plants" apply to the design of the high point vents and the associated controls, instruments and power sources as required by 10 CFR 50.44 (c)(3)(iii).

10 CFR Part 50 Appendix A General Design Criteria 41 "Containment atmosphere cleanup" requires systems to control the concentration of hydrogen, oxygen, and other substances which may be released into the reactor containment following postulated accidents to assure that containment integrity is maintained. Hydrogen monitors fall within the purview of GDC 41.

GDC 42 "Inspection of containment atmosphere cleanup systems" contains requirements on the inspection of systems covered by GDC 41.

GDC 43 "Testing of containment atmosphere cleanup systems" imposes testing requirements on systems covered under GDC 41 which require periodic functional testing to assure operability of the systems as a whole.

10 CFR Part 21 imposes procurement requirements on safety-grade equipment. Since the hydrogen monitors are treated as safety-grade Class 1E electrical equipment they are subject to the requirements of Part 21.

10 CFR Part 50 Appendix B imposes quality assurance requirements on nuclear power plants systems and components.

The requirement (b)(2) in 10 CFR 50.44 is meant to insure a mixed atmosphere in containment. GDC 41, referred to above, requires systems to control the concentration of any releases into containment, including releases of hydrogen and oxygen, to assure containment integrity and thus applies to systems designed to provide a mixed atmosphere in containment. The functional types of systems provided vary by containment design. In some large dry containments, for example, this requirement is met by the containment spray system that promotes convective mixing of the containment atmosphere. Containment sprays are subject to technical specification requirements of 10 CFR 50.36.

Requirement (b)(3) in 10 CFR 50.44 calls for a capability to control combustible gas concentration in the containment following a postulated LOCA and the 1981 amendment to the original rule required via (c)(3)(ii) licensees that relied on purge/repressurization systems as the primary means for controlling combustible gas following a LOCA to install internal recombiners or a capability to install an external recombiner.

GDC 5 "Sharing of Structures, Systems, and Components" has provisions that apply to the sharing of external recombiners between different units at one site. Recombiners are subject to the technical specification and surveillance testing requirements of 10 CFR 50.36. In addition, ISI check valve tests have to be carried out on a quarterly basis.

10 CFR 50.55a "Codes and Standards" defines the inservice testing requirements for various plant systems and components and incorporates references to the requirements of the ASME Boiler and Pressure Vessel Code for steel containments that are required to be met in order to demonstrate containment structural integrity for Mark III and ice condenser containments under 10 CFR 50.44 (c)(3)(iv)(B)(1).

10 CFR Part 50 Appendix J "Primary Reactor Containment Leakage Testing for Water-Cooled Power Reactors" contains requirements that apply to testing of containment penetrations and the quality standards of Appendix B apply to combustible gas control systems.

GDC 50 "Containment design basis" requires that the containment structure shall be designed to accommodate, with sufficient margin, pressure and temperature conditions resulting from a LOCA. The margin shall reflect consideration of energy sources, as required by 50.44, from metal-water and other chemical reactions resulting from degradation, but not complete failure, of emergency core cooling functioning.

GDC 16 "Containment design" requires that the reactor containment and associated systems shall establish an essentially leak-tight barrier against the uncontrolled release of radioactivity to the environment and to assure that design conditions important to safety are not exceeded for the duration of the postulated accident.

10 CFR Part 50 Appendix A, General Design Criteria 54 "Piping systems penetrating containment" and General Design Criteria 56 "Primary containment isolation" apply to containment penetrations used for external recombiners (as well as containment penetrations for purge-repressurization systems) that may be installed by licensees as provided by 10 CFR 50.44 (c)(3)(ii)(A) and 10 CFR 50.44 (c)(3)(ii)(B). GDC 54 requires that piping systems penetrating primary reactor containment be provided with leak detection, isolation, and containment capabilities having redundancy, reliability, and performance capabilities that reflect the importance to safety of isolating these piping systems. GDC 56 requires that each line that connects directly to the containment atmosphere and penetrates primary reactor containment shall be provided with primary isolation valves.

10 CFR 50.4 "Written Communications" specifies requirements for all written communications from licensees operating Mark III and ice condenser containment plants that are required to submit analyses under the provisions of 10 CFR 50.44 (c)(3)(vi)(A). These analyses pertain to an evaluation of the consequences of hydrogen generated during an accident involving up to 75% of the clad metal-water reaction, include consideration of hydrogen control measures, include time period of recovery from the degraded condition, use accident scenarios supported by the NRC staff, and support the design of the selected hydrogen control system.

10 CFR 50.46 "Acceptance criteria for emergency core cooling systems for light-water power nuclear reactors" and Appendix K "ECCS Evaluation Models" establishes the amount of hydrogen generated in a postulated LOCA for the purposes of determining compliance with ECCS performance criteria. As mentioned above, the original version of the rule published as 10 CFR 50.44 based the design of the hydrogen control system on the 10 CFR 50.46 criteria for maximum hydrogen generation from the metal-water reaction with a factor of 5 added as a safety margin against unpredicted events during the evolution of the accident.

10 CFR Part 100 "Reactor Site Criteria" contains section 100.11 that provides a method for determining the distance of the exclusion area and low population zone boundary. 10 CFR 50.44 (f) refers to facilities whose notice of hearing of an application for a construction permit was published between 12/22/68 and 11/5/70. This requirement states that if the incremental dose from purging (and repressurization if a repressurization system is provided) occurring at all points beyond the exclusion area boundary after a postulated LOCA, calculated in accordance with 10 CFR 100.11(a)(2), is less than 2.5 rem whole body and less than 30 rem to the thyroid, and if the combined dose at the low population zone outer boundary from purging and the postulated LOCA calculated in accordance with 10 CFR 100.11(a)(2) is less than 25 rem whole body and 300 rem thyroid, then only a purging system is necessary. The purging system and any associated filtration systems are required to be designed in accordance with GDC 41, GDC 42 and GDC 43 . If the criteria are not met, then another combustible gas control is required which could be a repressurization system or a combined purge-repressurization system. The second system also has to comply with the requirements of GDC 41, 42, and 43.

10 CFR 50.44 (g) applies similar requirements to facilities whose notice of hearing of an application for a construction permit was published on or before 12/22/68.

10 CFR 50.34 "Contents of applications; technical information" that deals with applications for a construction permit has a section, 10 CFR 50.34 (f) "Additional TMI-related requirements", that applies to combustible gas control. Part 50.34 (f) applies to applicants for a LWR construction permit or manufacturing license whose application was pending as of February 16, 1982.

Several paragraphs of this section pertain to hydrogen control measures. Paragraph (f) (2) (ix) requires applicants to provide a system for hydrogen control that can safely accommodate hydrogen generated by the equivalent of a 100% fuel-clad metal water reaction. Applicants are asked to perform an evaluation of alternative hydrogen control systems that would meet this criterion including, as a minimum, hydrogen ignition systems and a post-accident inerting system. The evaluation should include: (a) a comparison of the costs and benefits of the alternatives considered, (b) for the selected system, analyses and test to verify compliance with the performance required, (c) for the selected system, preliminary design descriptions of equipment, function, and layout.

Only preliminary design information on the tentatively preferred option among the alternatives considered is required at the construction permit stage. However, the regulation requires that the hydrogen control system and associated systems shall provide, with reasonable assurance, that:

(a) Hydrogen concentrations uniformly distributed in the containment do not exceed 10% during and following an accident that releases an equivalent amount of hydrogen as would be generated from a 100% clad metal-water reaction, or that the post-accident atmosphere will not support hydrogen combustion,

(b) Combustible concentrations of hydrogen will not collect in areas where unintended combustion or detonation could lead to loss of containment integrity or loss of appropriate mitigating features,

(c) Equipment necessary for achieving and maintaining safe shutdown of the plant and maintaining containment integrity will perform its safety functions during and after being exposed to the environmental conditions attendant with the release of hydrogen generated by the equivalent of a 100% clad metal-water reaction including the environmental conditions created by activation of the hydrogen control system,

(d) If the method selected for hydrogen control is a post-accident inerting system, inadvertent actuation of the system can be safely accommodated during plant operation.

This regulation clearly goes well beyond the design basis LOCA hydrogen generation specified in 10 CFR 50.46 for compliance with ECCS acceptance criteria and modified with a safety margin factor of 5 in 10 CFR 50.44 to serve as a basis for design of hydrogen control systems. In 10 CFR 50.44, plants with Mark III and ice condenser containments are required to demonstrate hydrogen control systems that can mitigate the amount of hydrogen generated by the equivalent of a 75% clad metal-water reaction. However, 10 CFR 50.34 (f) requires plants submitting applications in the post-1982 period to have the capability of handling hydrogen generated from the equivalent of a 100% clad metal-water reaction and also to ensure that hydrogen concentrations in containment do not exceed 10% during and following an accident.

3.3.2 Relationship of 10 CFR 50.44 to Implementing Documents

Guidance that is provided to the licensee in meeting the requirements of 10 CFR 50.44 via the various implementing documents are summarized in Table 3-2 and described below. The applicable section of 10 CFR 50.44 and related regulation is also listed.

Table 3-2 Summary of Implementing Documents

Applicable 50.44 Section	Referenced Document	Description of Guidance
(a)(1)(a)(2) (a)(3)(d)(1) (d)(2)	RG 1.7	Provides guidance on H2 generation following a postulated LOCA, from post-accident radiolysis of water, and metal corrosion.
(b)(1)	RGs 1.70,1.89,1.97 SRP Sec 6.2.5, NUREGs-0737, 0718, 0660 RG 1.97, ANSI-ANS-4.5 RG 1.118	Provide guidance on design bases, system designs, and design evaluation of systems to monitor combustible gas concentrations within containment regions Guidance on instrumentation to assess plant conditions during an accident, establishes H2 concentration in containment or drywell as a Type C variable, recommends H2 monitors as safety-grade Guidance on monitor testing requirements (RG 1.118)
(b)(2)	RG 1.70, SRP 6.2.5	Guidance on design bases, system design, and evaluation of mixing systems
(b)(3) (c)(3)(ii) (d)(1) (d)(2)	RG 1.7 RG 1.70, SRP 6.2.5 NUREG-0737, NUREG-0578, GL 83-02, SECY 80-399 ASME Section XI RG 1.26, SRP 6.2.5 RG 1.29, SRP 6.2.5 GL 84-09 NUREG-0737 RG 1.52, GL 83-13	Guidance on H2 generated in metal-water reaction, radiolysis, corrosion; Design and evaluation of systems to reduce combustible gas concentrations Dedicated penetrations for external recombiners or purge systems Penetration piping leakage surveillance Quality standards for design, fabrication, erection, and testing Designed for SSE For inerted Mark I containments with NOHC<11/5/70 that do not rely on purge-repress systems as primary means of H2 control, recombiners not required provided certain TS are met Containment atmosphere dilution systems considered to be purge systems Design, testing and maintenance criteria for post-accident ESF atmosphere cleanup systems
(c)(3)(iii)	RG 1.92, RG 1.100, IEEE 344-1975 NUREGs-0737,0660	Seismic qualification and EQ of vent systems Guidance on vent system design
(c)(3)(i)	ASME Section XI	Inerting system lines penetration piping leakage surveillance requirements

Table 3-2 Summary of Implementing Documents

Applicable 50.44 Section	Referenced Document	Description of Guidance
(c)(3)(iv)(A)	ASME B&PV Code sections	ASME B&PV code sections for steel containment (Section III, Subsubarticle NE-3220, Service Level C limits); ASME B&PV Code sections for concrete containments (Section III, Subsubarticle CC-3720, Factored Load Category)

Regulatory Guide 1.7 [7] "Control of Combustible Gas Concentrations in Containment Following a LOCA" Rev. 2, Nov. 1978 provides guidance on the implementation of the original version of 10 CFR 50.44 in LWRs with zircaloy clad fuel. As can be surmised from the date of this Regulatory Guide, the implementation guidance deals only with the part of 50.44 which made up the original rule, i.e., hydrogen generation as a result of a LOCA.

This guide references GDC 35 (emergency core cooling), GDC 50 (containment design basis) and GDC 41 (containment atmosphere cleanup). It refers to the "new" 50.44 and states that the guide provides methods for implementing the new regulation.

After a LOCA, hydrogen can result from: (1) metal-water reaction in which the zirconium clad oxidizes and hydrogen is evolved by Zr + 2H20 = ZrO2 + 2H2, (2) post-accident radiolysis of water by released fission products in solution which will lead to both H2 and O2 being evolved, and (3) corrosion of metals inside containment.

If enough hydrogen is generated it can react with O2 in the containment. If the H2-O2 reaction is rapid it can cause high temperatures or pressures and either breach containment or cause leakage above the technical specifications and also potentially damage safety SSCs.

The extent of metal-water reaction and the amount and rate of hydrogen produced depends on the assumptions underlying accident evolution and the effectiveness of emergency core cooling systems (ECCS). The guide references ECCS analytical models described in 36 FR 12248 of June 29, 1971 and amended in 36 FR 26042 of Dec. 18, 1971; and in the record of the rulemaking hearing, Docket RM-50-1, which led to the issuance of Part 50.46 acceptance criteria for ECCS.

The maximum amount of metal-water reaction, following a postulated LOCA, allowed by ECCS acceptance criteria in Part 50.46 is 1% of the cladding mass.

To establish the design basis for containment gas control systems, the guide recommends that the amount of hydrogen should be based on that calculated for establishing compliance with Part 50.46 but should also include a safety margin. This margin is set as at least 5 times the amount calculated for compliance with Part 50.46. However, the guide concedes that this calculated amount could be small for many plants as a result of other requirements for ECCS contained in 50.46. So a lower limit for the amount of hydrogen generated following a postulated LOCA is also recommended in the guide. This is based on the criterion of the 1% of cladding mass reacting in the metal-water reaction. However, in order not to penalize fuel with thicker cladding (since cladding oxidation is a surface phenomenon), a criterion based on hydrogen generated per unit cladding area was selected by specifying a hypothetical uniform depth of cladding surface reacted.

This hypothetical depth was based on 1% of the thickness of the thinnest fuel cladding (0.023") used at the time the guide was issued.

Thus, to comply with 10 CFR 50.44, the hydrogen generated after a LOCA should be 5 times the maximum amount calculated for purposes of compliance with Part 50.46 but not less than the amount generated from a reaction of cladding metal to a depth of 0.00023". (Safety Guide 7, the precursor to RG 1.7, recommended that hydrogen control systems be designed for a 5% metal-water reaction.)

The rate of hydrogen production in the metal-water reaction is assumed to occur on the following basis: the initial reaction takes place over a short period of time early in the LOCA, near the end of the blowdown and the core refill phases of the transient. Since the duration of the blowdown and refill phases is of the order of several minutes, it is assumed that hydrogen will be generated over a 2-minute period, which represents the period of time during which the maximum heatup occurs, at a constant rate. Further, the hydrogen will mix with the steam released from the RCS and be distributed uniformly over the containment volume.

RG 1.70 [8],"Standard Format and Content of Safety Analysis Report for Nuclear Power Plants," Section 6.2.5, "Combustible Gas Control in Containment" provides guidance on the design bases, system design, and design evaluation of systems to mix the containment atmosphere, monitor combustible gas concentrations within containment regions, and reduce combustible gas concentrations in containment. RG 1.70 references GDC 41 that requires provisions of systems to control concentrations of hydrogen and oxygen released into containment from postulated accidents.

NUREG-0800 [9] "Standard Review Plan" Section 6.2.5 provides guidance to the NRC staff on reviewing the portion of the SAR dealing with the production and accumulation of combustible gases in containment following a design basis LOCA, the capability to monitor combustible gas concentrations in containment, the capability to mix the combustible gas concentrations within the containment atmosphere, and the capability to reduce the combustible gas concentrations in containment by suitable means such as purging, dilution or recombination.

Regulatory Guide 1.97 [10] "Instrumentation for Light-Water-Cooled Nuclear Power Plants to Assess Plant and Environs Conditions During and Following an Accident" establishes that hydrogen concentration in the containment and drywell is a Type C variable (i.e., a variable that provides information to the control room operator to indicate the potential for breach or actual breach of the barriers to fission product release). Monitoring of hydrogen concentration is needed in BWRs to detect the potential for breach and accomplishment of mitigation, and in PWRs for detection of the potential for breach, accomplishment of mitigation, and long-term surveillance. Hydrogen monitors in containment are classified safety-grade (Class 1E) based on RG 1.97 recommendations. In the post-TMI period, an ANSI/ANS-4.5 Standard was proposed classifying hydrogen concentration in containment as Type C variable.

Regulatory Guide 1.118 [11] "Periodic Testing of Electric Power and Protection Systems" provides guidance on the periodic testing of electric power and protection systems that are classified as safety-grade systems.

Regulatory Guide 1.89 [12] "Environmental Qualification of Certain Electronic Equipment Important to Safety for Nuclear Power Plants" contains guidance on the environmental qualification of electrical equipment important to safety.

Regulatory Guide 1.52 [13] "Design, Testing and Maintenance Criteria for Postaccident Engineered-Safety-Feature Atmosphere Cleanup System Air Filtration and Adsorption Units of Light-Water-Cooled Nuclear Power Plants" provides guidance on design, testing, and maintenance criteria for post-accident engineered safety features (ESF) of containment atmosphere cleanup systems including HEPA air filters and charcoal adsorption units.

Generic Letter GL 83-13 [14] provides clarification of surveillance requirements for HEPA filters and charcoal adsorber units in standard technical specifications on ESF cleanup systems. In the letter documenting the results of the NEI survey [3], RG 1.52 and GL 83-13 are mentioned by licensees operating plants with large dry PWR containments and BWR Mark I containments as the guidance documents they use in complying with 50.44 (b)(3).

Regulatory Guide 1.92 [15] "Combining Modal Responses and Spatial Components in Seismic Response Analysis" and Regulatory Guide 1.100 [16] "Seismic Qualification of Electrical and Mechanical Equipment for Nuclear Power Plants" contain guidance on seismic qualification that is incorporated by reference in section II.B.1 of NUREG-0737 that provides the requirements for the reactor coolant system high-point vent designs. Environmental qualification of the vents are in accordance with the May 23, 1980 Commission Order and Memorandum (CLI-80-21).

NUREG-0737 [17] "Clarification of TMI Action Plan Requirements" contains several sections relevant to 50.44 requirements. These include section II.B.1 on reactor coolant system vents, section II.B.3 on post-accident sampling capability that calls for sampling of hydrogen levels in the containment atmosphere, section II.E.4.1 on dedicated hydrogen penetrations concerning containment penetration systems for external recombiners or purge systems, and section II.F.1 on containment hydrogen monitors.

NUREG-0737 incorporates, by reference, NUREG-0578 [18] "TMI-2 Lessons Learned Task Force Report and Short-Term Recommendations" of July 1979, NUREG-0660 [19] "NRC Action Plan Developed as a Result of the TMI-2 Accident", August 1980, Regulatory Guide 1.26 [20] on quality standards for design, fabrication, erection, and testing, Regulatory Guide 1.29 [21] on seismic classification, and IEEE 344-1975 on environmental qualification.

Generic Letter 84-09 [6] addresses the recombiner capability requirements of 50.44 (c)(3)(ii) and is directed at BWR Mark I plants for which notices of hearing on applications for construction permits were published before November 5, 1970. For these plants, given the inerting requirements under 50.44(c)(3)(i), it was determined that purging/repressurization systems were not the primary means for controlling combustible gas concentrations following a LOCA. Hence, these plants were exempted from providing recombiners as required under 50.44(c)(3)(ii) subject to meeting certain criteria related to technical specifications on controlling oxygen concentrations in containment. [Under 50.44 (e), plants whose notices of hearing on applications for a construction permit were published on or after November 5, 1970 were not permitted to use purging and/or repressurization systems as the primary means of controlling combustible gases following a postulated LOCA but instead had to install means such as recombiners that would not lead to a significant release from containment].

3.4 Current Industry Implementation of 50.44

Six high-level requirements imposed by 50.44 have been identified above: (1) Measuring hydrogen in containment (established hydrogen monitors) [(b)(1)], (2) Systems to insure mixed containment atmosphere [(b)(2)], (3) Systems to control combustible gases [(b)(3) and (c)(3)(ii)], (4) High-point

vents on the reactor coolant system [(c)(3)(iii)], (5) Inerting of Mark I and II containments [(c)(3)(i)], and (6) Installation of a hydrogen control system to deal with a 75% metal-water reaction in Mark III and ice condenser containments [(c)(3)(iv)..(vii)].

In order to understand the basis on which the industry is implementing the high-level requirements of 50.44, an effort is underway to obtain implementation data from the industry. So far, preliminary information has been obtained from two sources: (1) a review of NRC documents for three specific plants, Grand Gulf 1, Nine Mile Point 2, and Sequoyah 1 and 2, and (2) an NEI survey of licensees to determine the sources of guidance, regulatory, industry, or specific utility, being used to assure implementation of the requirements. Responses to this survey were received from 23 units (PWR large, dry containments) and 10 units (BWR Mark I containments).

Table 3-3 below summarizes this preliminary information received on the systems used to implement the requirements and the special treatment of these systems. Since the sources of information are limited, the data in the table may not reflect implementation practices across the nuclear industry. (No information was received regarding high point vents.)

Table 3-3 Basis of Industry Implementation of 50.44 High-Level Requirements

50.44 requirement	Industry implementation based on review of 3 plants	Guidance/Implementing documents identified in NEI survey
(b)(1) Measure H2 in containment	H2 monitor identified as essential equipment needing safety grade treatment in all 3 plants surveyed. (NUREG-0831)	RG 1.7, RG 1.97, NUREG-0737
(b)(2) Mixed containment atmosphere	***PWR ice condenser: Sequoyah*** For DBA conditions, mixing requirements are met by the air return fans, which are safety grade engineered safety features. For degraded core accidents, EPRI tests will fans operable showed good mixing results. Staff concluded that formation of significant hydrogen concentration gradients in containment is unlikely under these conditions and that detonable pockets will not occur given operation of the mixing and igniter systems operating at the lower hydrogen flammability limit.	NUREG-0800, Reg Guide 1.70, Tech Specs
	BWR Mark III: Grand Gulf For DBA mixing requirements there are no active fan system; codes predict adequate mixing based on differential pressures. For degraded core accidents mixing was confirmed by licensee analysis. Bounding detonation calculation on volume below HCU floor also showed that containment could withstand the loading. (NUREG-0831)	

Table 3-3 Basis of Industry Implementation of 50.44 High-Level Requirements

50.44 requirement	Industry implementation based on review of 3 plants	Guidance/Implementing documents identified in NEI survey
	BWR Mark II: NMP2 Before initiation of the recombiner, the drywell and suppression chamber will be mixed as a result of natural convection arising from temperature differences between the atmosphere and primary containment walls and molecular diffusion. Mixing is further promoted by blowdown of steam and water out the broken pipe and operation post-accident of containment sprays. The combustible gas control system also mixes the primary containment atmosphere. (SRP 6.2.5, NUREG-1047)	
(b)(3) and (c)(3)(ii) Combustible gas control systems, e.g. recombiners	Recombiners are identified as safety grade in the plants surveyed on the basis of RG 1.7. ***BWR Mark II: NMP2*:** Recombiner system is 100% redundant, essential equipment, seismic Category I, safety class 2. In addition, a back-up containment purge capability is provided in accordance with Reg. Guide 1.7 which is used in conjunction with the standby gas treatment system. The applicant calculated that the set point for recombiner operation is not reached for 2.75 days. (SER 2/83, NUREG-1047)	RG 1.7, RG 1.52, ANSI N510, GL 83-13, NUREG-0737, NUREG-0800
(c)(3)(I) Inert Mark I and II	***BWR Mark II: NMP2*:** Plant has a non-seismic Category I liquified nitrogen storage and gas distribution system which limits the oxygen concentration to 4% volume when inerted. (NUREG-1047, SER Feb. 1983)	NA
(c)(3)(iv)(v)(vi)(vii) H2 control system for 75% m-w reaction	***PWR ice condenser: Sequoyah:*** Permanent Hydrogen Mitigation System (PHMS) consists of 64 igniters distributed throughout the upper, lower, and ice condenser compartments. Testing programs in conjunction with Duke Power and American Electric Power were conducted to demonstrate the ability of the system to mitigate the hydrogen threat. CLASIX calculations also performed. Staff required 4 additional igniters as part of SER. Confirmatory analyses performed using CSQ code. Modified COMPARE code used to evaluate containment response. (NUREG-0011, Supplement 6, 12/82)	NUREG-0737

Table 3-3 Basis of Industry Implementation of 50.44 High-Level Requirements

50.44 requirement	Industry implementation based on review of 3 plants	Guidance/Implementing documents identified in NEI survey
	BWR Mark III: Grand Gulf: Hydrogen Ignition System (HIS) installed consisting of 90 igniters distributed throughout the drywell, wetwell, and upper compartment. EPRI sponsored test program for BWR-6/Mark III owners including operability testing and combustion testing. Calculations were performed with CLASIX-3/MARCH codes. (NUREG/CR-2530)	

3.5 Implementation of 50.44

The current implementation of 10 CFR 50.44 is summarized in Tables 3-4 through 3-9 below. This table summarizes the information from Sections 3.2.and 3.4 above. While the sources listed in the tables may not be all exhaustive, they trace the implementation of each specific requirement in the regulation down to practical level of detail.

In each table, for each high level requirement, the supporting requirements contained within 10 CFR 50.44 itself are provided. Additional regulatory requirements, which are not contained in 10 CFR 50.44 itself, but which support the regulation are next provided. Finally, the guidance contained in implementing documents such as Regulation Guides, NUREGs, Sections of the Standard Review Plan, industry codes and standards and other supporting documents, are provided.

3.5.1 Measuring Hydrogen Concentration in Containment

The majority of plants have implemented the requirement for measuring hydrogen concentration in containment by installing continuous safety-grade monitors. These monitors are also credited with meeting the emergency response requirements of 50.47(b)(9) and Part 50 Appendix E. The basis for this implementation is: (1) the recommendation in Regulatory Guide 1.7 that systems to measure combustible gases in containment should meet the requirements for an engineered safety feature, and (2) a post-TMI requirement stated in NUREG-0737, Item II.F.1 that requires all plants to provide a continuous indication of hydrogen concentration in the containment for accident monitoring. This requirement imposed the design and quality criteria of Regulatory Guide 1.97 that treats hydrogen monitors as redundant, safety-grade, Class 1 E electrical equipment and also required that monitors be included in the plant technical specifications. This information is summarized below in Table 3-4.

Table 3-4 Summary of Requirements and Guidance for Measuring Hydrogen Concentration in Containment

Supporting Requirements
NONE
Related Regulatory Requirements
• H2 monitors (50.47, Part 50 App E) • Instruments to monitor variables for accident conditions (GDC 13 Part 50 App A) • Technical Specifications on monitor operability and surveillance testing (50.36) • Monitor testing reqmts (GDC 43) • Monitor (safety-grade) procurement and QA reqmts (10 CFR 21, App B)
Supporting Guidance
• Guidance on H2 monitoring, system design bases, evaluation, and classification (RG 1.70, RG 1.97, RG 1.89, SRP 6.2.5, NUREG-0737, NUREG-0718, NUREG-0660, ANSI-ANS 4.5) • Guidance on testing requirements (RG 1.118)

3.5.2 Ensuring a Mixed Containment Atmosphere

In most plants, systems that ensure mixing of the containment atmosphere are the same as those providing containment heat removal. In plants that have active systems for accomplishing the mixing function, such as air return fans or sprays, licensees have predominantly implemented this requirement by treating these systems as engineered safeguard features on the basis of the design criteria of GDC 41, the guidance contained in Regulatory Guide 1.70, and the provisions of the Standard Review Plan (NUREG-0800). These systems are included in the plant technical specifications. This information is summarized below in Table 3-5.

Table 3-5 Summary of Requirements and Guidance for Ensuring a Mixed Containment Atmosphere

Supporting Requirements
NONE
Related Regulatory Requirements
• Systems to control conc. of H2 & O2 to insure containment integrity (GDC 41) • Tech Specs on mixing systems (50.36)
Supporting Guidance
• Guidance on design bases and evaluation of mixing systems (RG 1.70, SRP 6.2.5)

3.5.3 Control of Post LOCA Combustible Gases

A majority of licensees have complied with the requirement to provide control of post-LOCA combustible gases by installing safety-grade internal recombiners. The recombiners are treated as an engineered safeguard feature and essential equipment on the basis of the guidance provided in Regulatory Guide 1.7 and included in the plant technical specifications. Older plants, whose notice of hearing on a construction permit was received prior to 11/5/1970, are allowed to have only

purge/repressurization systems as a primary means of combustible gas control. However these systems require dedicated containment penetrations per NUREG- 0737 that are subject to the testing requirements of Appendix J. The latter requirements also apply to containment penetrations in plants that use external recombiners. This information is summarized below in Table 3-6.

Table 3-6 Summary of Requirements and Guidance for Control of Post LOCA Combustible Gases

Supporting Requirements
• Following LOCA show: no uncontrolled H2-O2 recombination or plant could withstand consequences; if not, inert containment (c)(1)(i),(c)(1)(ii),(c)(2) • If purge/repress. systems are *primary* means of control, provide recombiners; assume H2 equal to 5% metal-water reaction or 5x that needed to comply with 50.46 (c)(3)(ii),(d)(1),(d)(2) • Containment penetrations for ext. recombiners and purge/repressurization systems (c)(3)(ii)(A),(c)(3)(ii)(B) • If NOHC received — > 11/5/70 require systems other than purge-repress. as primary means of comb gas control (e) — < 11/5/70 require only purging systems if certain dose based requirements calculated on basis of 100.11 are met (f,g)

Table 3-6 Summary of Requirements and Guidance for Control of Post LOCA Combustible Gases

Related Regulatory Requirements
• Amount and rate of H2 generated in LOCA (50.46) • Reqmts. on containment penetrations for ext. recombiners and purge-repress. systems (GDC 54, 56) • Quality standards for comb gas control systems (App B) • Dose calculation methods for 50.44(f,g) compliance (100.11) • Sharing of external recombiners between units at one site (GDC 5) • Tech Spec requirements and surveillance testing of recombiners (50.36) • ISI check valve tests (50.55a) • Testing of containment penetrations (App J)
Supporting Guidance
• Guidance on H2 generated in metal-water reaction, radiolysis, corrosion (RG 1.7) • Design and evaluation of systems to reduce comb gas concentrations (RG 1.70, SRP 6.2.5) • Dedicated penetrations for ext. recombiners or purge systems (NUREG-0737, NUREG-0578, GL 83-02, SECY 80-399) • Penetration piping leakage surveillance (ASME section XI) • Quality standards for design, fabrication, erection, and testing (RG 1.26, SRP 6.2.5) • Designed for SSE (RG 1.29, SRP 6.2.5) • For inerted Mark I containments with NOHC<11/5/70 that do not rely on purge-repress systems as primary means of H2 control, recombiners not required provided certain TS are met (GL 84-09) • Containment atmosphere dilution systems considered to be purge systems (NUREG-0737) • Surveillance reqmts for HEPA filters and charcoal adsorbers in TS on ESF cleanup systems (RG 1.52, GL 83-13)

3.5.4 RCS High Point Vents

All licensees have implemented this requirement on the basis of the post-TMI requirements identified in NUREG-0737, section II.B.1, that specify the quality assurance and design criteria for the vents on the reactor coolant system. This information is summarized below in Table 3-7.

Table 3-7 Summary of Requirements and Guidance for RCS High Point Vents

Supporting Requirements
• vents for the RCS, reactor vessel head and for other systems • remotely operated from control room • conform to Appendix A and B • ensure low probability of failure and inadvertent or irreversible actuation • not aggravate the challenge to the containment or the course of the accident

Table 3-7 Summary of Requirements and Guidance for RCS High Point Vents

Related Regulatory Requirements
• Requirements for design of vents and associated systems (App A, App B) • Vent size smaller than LOCA definition (App A)
Supporting Guidance
• Seismic qualification and EQ of vent systems (IEEE 344-1975, RG 1.100, RG 1.92, CLI-80-21) • Guidance on vent system (NUREG-0737, NUREG-0660)

3.5.5 Inerting Mark I and Mark 11 Containments

Mark I and Mark II containment plants have met this requirement by installing nitrogen inerting systems whose containment penetrations meet the requirements of GDC 54 and 56 and are periodically tested as per provisions of Appendix J. This information is summarized below in Table 3-8.

Table 3-8 Summary of Requirements and Guidance for Inerting Mark I and II Containments

Supporting Requirements
NONE
Related Regulatory Requirements
• Inerting system lines that penetrate containment must meet redundancy and single-failure criteria (GDC 54, 56) • Testing of containment penetrations (App J) • Tech specs on inerting systems (50.36)
Supporting Guidance
• Penetration piping leakage surveillance (ASME section XI)

3.5.6 Requirements for Hydrogen Control System for 75% Metal-water Reaction

Licensees operating Mark III and Ice Condenser containment plants have met this requirement by installing a control system consisting of distributed hydrogen igniters that are powered by at least two separate and independent AC power sources. Licensees have also utilized analytical codes acceptable to NRC staff to demonstrate that the installed system can mitigate the amount of hydrogen generated in a 75% metal-water reaction. This information is summarized below in Table 3-9.

Table 3-9 Summary of Requirements and Guidance for Hydrogen Control System

Supporting Requirements
• Demonstrate containment structural integrity based on actual material properties or ASME B&PV code (c)(3)(iv)(B) • For H2 control system using post-accident inerting show containment can withstand increased pressure during the accident or following inadvertent full inerting in normal operation (c)(3)(iv)(D) • Reqmts. on systems and components for plants with post-accident inerting control systems (c)(3)(iv)(E) • Reqmts. on systems and components for plants that do not rely on inerting for H2 control (c)(3)(v)(A) • For plants with CP issued <3/28/79 provide evaluation of consequences of H2 using accident scenarios acceptable to NRC that support design of control system (c)(3)(vi)(A), (c)(3)(vi)(B)
Related Regulatory Requirements
• Reference to ASME B&PV code reqmts. for steel containments (50.55) • Written communications on accident analyses (50.4)
Supporting Guidance
• ASME B&PV code sections for steel containment (Section III, Subsubarticle NE-3220, Service Level C limits) • ASME B&PV Code sections for concrete containments (Section III, Subsubarticle CC-3720, Factored Load Category)

NOHC = Notice of hearing on application for construction permit
CP = construction permit
SSE = Safe Shutdown Earthquake

3.6 References

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4. Letter from Southern California Edison to NRC, Docket Nos. 50-361 and 50-362, September 10, 1998.

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16. USNRC, “Seismic Qualification of Electrical and Mechanical Equipment for Nuclear Power Plants,” Regulatory Guide 1.100, Revision 2, June 1988.

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20. USNRC, “Quality Group Classifications and Standards for Water-, Steam-, and Radiative-Waste-Containing components of Nuclear Power Plants,” Regulatory Guide 1.26, Revision 3, February 1976.

21. USNRC, “Seismic Design Classification,” Regulatory Guide 1.29, Revision 3, September 1978.

4. RISK SIGNIFICANCE OF COMBUSTIBLE GASES

4.1 Concern Related to Combustible Gases

Combustible gas (namely hydrogen (H2)) can be generated, to a varying extent, in light water reactor (LWRs) during normal plant operation, design basis accidents (DBAs) and accidents involving extensive damage of the reactor core. In addition, during an accident involving extensive core damage, if the core melts through the reactor vessel and interacts with concrete CO can also be formed. Any accident initiator (i.e., loss of coolant, transient, loss of offsite power etc.) coupled with additional system or component failures can result in loss of coolant inventory, and thereby, lead to extensive core damage and hence the generation of large quantities of combustible gases. This concern therefore potentially applies to all core melt accident sequences.

During normal plant operation combustible hydrogen gas can be generated by radiolytic decomposition of the reactor coolant (i.e., water). However because of the configuration (i.e., closed cycle) of the reactor coolant system, hydrogen generation reaches an equilibrium condition and is not released to the containment atmosphere. Hydrogen generation is therefore not a concern in terms of containment integrity during normal plant operation.

In design basis loss of coolant accidents (LOCAs) the reactor core is predicted to be without coolant flow for a relatively short period of time. During this time the reactor core can reach temperatures high enough for the zircaloy cladding to oxidize in a steam environment. This oxidation is exothermic and produces hydrogen gas as a reaction product. In addition, an assumed release of radionuclides to containment, produces hydrogen via radiolytic decomposition of water. However the amount of hydrogen produced by these processes is relatively small and thus is not of major concern in terms of maintaining containment integrity. Hydrogen generation during design basis LOCAs can therefore be accommodated by relatively low capacity systems (such as recombiners and/or purge systems).

Accidents involving extensive core damage can be classified as degraded core or full core melt accidents. A degraded core accident involves extensive core damage (and melting of some constituents of the core) but the emergency core cooling system (ECCS) is restored in sufficient time to reflood the core and terminate the accident progression with the core retained in the reactor vessel. Using this terminology the accident at TMI-2 would be termed a degraded core accident. This definition, however, should not be confused with some earlier definitions of a degraded core accident that were limited to events in which the core was damaged but melting did not occur.

The main source of hydrogen generation for degraded core accidents is clad oxidation. The TMI-2 accident resulted in significant core damage and extensive clad oxidation (approximately 45% of the cladding) which generated a large quantity (400kg) of hydrogen. A significant quantity of hydrogen was released to containment and did ignite and burn (i.e. a deflagration). The resulting pressure pulse however was below the containment design pressure and did not challenge containment integrity.

The TMI-2 containment is a ”large volume” design, which relies on a large free volume and a relatively high design pressure to mitigate the steam released during a design basis LOCA. Containments of this design therefore have a significant capacity for withstanding the pressure loads associated with combustion. This is also true for plants with subatmospheric containments, which have large internal volumes and high design pressures. However other containment designs (PWR ice condenser and BWR Mark I, II and III containments) rely on pressure suppression concepts (i.e., ice chests or water pools) to condense the steam released during a design basis LOCA. Pressure suppression containments therefore have smaller containment volumes and in some cases lower design pressures than large volume or subatmospheric containments.

Consequently the smaller volumes and lower design pressures associated with pressure suppression containment designs makes them more vulnerable to hydrogen deflagrations during degraded core accidents because the pressure loads could cause structural failure of the containment. Also, because of the smaller volume of these containments, detonable mixtures could be formed. A detonation would impose a dynamic pressure load on the containment structure that could be more severe than the static load from an equivalent deflagration.

In a full core melt accident, the ECCS is not restored in time to prevent the damaged core from relocating into the bottom of the reactor vessel and melting through the lower vessel head. At this time several interactions can occur depending on the pressure in the reactor vessel and on conditions in the reactor cavity (i.e., flooded or dry). If the vessel is at high pressure the high temperature core debris can be dispersed as particles into the containment atmosphere. This is called high pressure melt ejection (HPME). During HPME particles can then directly heat the containment atmosphere, generate more hydrogen, and ignite any hydrogen in the containment atmosphere. This phenomena is termed direct containment heating (DCH). If the cavity is flooded the high temperature core debris could contact water in the reactor cavity. Under these circumstances the resulting fuel-coolant interactions (FCI) can generate significant quantities of steam and hydrogen very rapidly, which should be considered when formulating a realistic combustible gas source term. If the vessel is at low pressure and the cavity is dry the high temperature core debris can will interact with concrete in the region below the reactor vessel. Core-concrete interactions (CCI) can generate additional hydrogen from metal-water reactions (cladding and steel) and other non condensible (carbon dioxide) and combustible (carbon dioxide) gases. Limestone concrete generates significant quantities of steam, H2, CO2 and CO during CCI, whereas basalt concrete generates mostly steam and H2.

Containment failure during an accident involving a severely damaged core can lead to the release of a large quantity of radionuclides. The magnitude of the release depends on several containment related factors:

1. the size of the break in containment
2. whether or not the sprays are operating (enhanced aerosol deposition)
3. whether or not the release path passes through a pool of water (aerosol scrubbing), and
4. the time of release relative to time the radionuclides are released from the damaged reactor fuel

Therefore, not all containment failures lead to large releases. In order for the release to be large, the break has to be greater than 100 times the design basis leakage, the sprays should not be operating, and the release path should not be flooded. In addition, containment failures close to the time of reactor vessel melt-through have the potential to release more radionuclides (less time for natural aerosol deposition) than containment failures several hours after the onset of core damage. Failures close to the onset of core damage (less time for evacuation of the population) are, therefore, usually more important contributors to acute health effects. These failure modes are therefore important contributors to the large early release frequency (LERF) which is defined in Chapter 2. However, some late failures (within approximately 24 hours of the onset of core damage) can release large quantities of radionuclides. A definition of a large late release is also provided in Chapter 2.

The intent is to reduce the likelihood of generating significant quantities of combustible gases and to prevent (or control) the combustion of these gases if they should be generated during an accident involving severe damage to the reactor core.

4.2 Risk From Combustible Gases

In this section the evolution of knowledge regarding the generation and behavior of combustible gases is discussed. This evolution is summarized in Table 4-1 in terms of events and research activities that have influenced the regulations.

Table 4-1 Evolution of Knowledge Regarding Risk From Combustible Gases

TIME	EVENT	REGULATORY RESPONSE
1960s/ 1970s	• Core melt accidents not considered credible	• no regulations imposed but designers, operators and regulators of LWRs recognized the potential for generating H2 and regulatory guidance was provided
1975	• Reactor Safety Study (WASH-1400) • Accidents (e.g., transients) other than loss of coolant accidents contribute to the total core damage frequency (CDF) • Large quantities of combustible hydrogen (H2) gas predicted due to cladding oxidation but containment failure dominated by failure modes other than combustion • Large quantities of carbon dioxide (CO2) gas predicted from core-concrete interactions which contribute to containment failure by overpressurization • Reduction of carbon dioxide to combustible carbon monoxide (CO) not modeled	• no regulations imposed a consequence of WASH-1400
late 1970s	• Hydrogen generation predicted from design basis loss of coolant accidents (LOCAs)	• original version of 50.44 — measure concentration — mixed atmosphere — control concentration
1979	• Accident at TMI-2 • Extensive core damage occurs but coolant flow restored in time to terminate accident progression with core retained in the reactor vessel • Large quantity of H2 generated • H2 combustion event in containment	• 1981 amendment — inert Mark I and II — recombiners — high point vents • 1985 amendment — H2 control system
1980s/ 1990s	• Severe Accident Research Program • Confirmed ignition limits for variety of H2/air/steam mixtures • Evaluated effectiveness of H2 mitigative systems; example, — igniters work at low H2 concentrations • Established basis for detonability of H2; examples, — possibility of detonation given composition — not a concern for large volume containments • Studied H2 transport and mixing	• no regulations imposed

Table 4-1 Evolution of Knowledge Regarding Risk From Combustible Gases

TIME	EVENT	REGULATORY RESPONSE
	• Severe Accident Risks (NUREG-1150) • Other accidents (e.g., Station Blackout (SBO)) also found to contribute to CDF • H2 combustion significant contributor to early containment failure for Mark III and ice condensers during SBO • H2 combustion not a contributor to early failure for large volume containments • H2 and CO contributors to late containment failure	
	• Individual Plant Examination (IPE) Program: Perspectives (NUREG-1560) • Wide range of accident initiators found to contribute to CDF • Per IPEs, H2 combustion — not a contributor at ice condensers because of small SBO contribution — contributor at Mark III because of the high SBO contribution	
	Research (Direct Containment Heating (DCH) Issue Resolution) — Analysis of the challenge to containment integrity from DCH for large dry and ice condenser containments — H2 combustion found to be a challenge to containment integrity for containment integrity for ice condensers during SBO	

During the 1960s and 1970s designers, operators and regulators of LWRs recognized the potential for generating hydrogen by the following mechanisms:

- Metal-water reaction involving metals in the reactor core (cladding and metal structures) and the reactor coolant,

- Radiolytic decomposition of the reactor coolant, and

- Corrosion of metals.

Accidents that could generate significant amounts of hydrogen by these mechanisms were considered to be extremely unlikely however, early regulatory guidance was provided which included consideration of H2 generation. Radiolytic decomposition of the reactor coolant and corrosion of metals are extremely slow processes and can be controlled, by systems such as recombiners with relatively long response times. In addition, in order for a metal-water reaction involving the fuel cladding and the reactor coolant to occur, the core has to be at a high (>1800°F) temperature. At these high temperatures the zircaloy cladding will rapidly oxidize in a steam environment. This oxidation is exothermic and produces combustible hydrogen gas as a reaction product. In a design basis loss of coolant accident (LOCA) the length of time that the core is

calculated to be at high temperature prior to ECCS actuation and core reflood is very short and the fraction of the core calculated to be at high temperature is relatively small. Consequently the amount of hydrogen generated is predicted to be relatively small. However, if ECCS is not actuated in a timely manner in this or any other accident sequence, continued oxidation and core degradation can occur.

The WASH-1400 study [1], which was published in 1975, was the first attempt to perform an integrated risk assessment that included accidents in which the reactor core was assumed to melt (i.e., accidents more severe than those considered in the design basis accident (DBA) analysis). Two commercial nuclear power plants (NPPs), namely Surry (a PWR with a subatmospheric containment) and Peach Bottom (a BWR with a Mark I containment) were studied. The results published in WASH-1400 demonstrated that accidents (e.g., transients) other than LOCAs can contribute to the total core damage frequency (CDF). The results also showed that core melt accidents are more important to risk than DBAs.

Significant hydrogen generation was predicted to occur in WASH-1400 as a result of in-vessel clad oxidation during core melt accidents for both NPPs. In addition, the containments were predicted to fail with relatively high conditional probabilities if core melt occurred. Although hydrogen combustion contributed to the high containment failure probabilities reported in WASH-1400 it was not a dominant contributor because other failure mechanisms were considered to be more important at that time. Full core melt accidents were considered in WASH-1400 and core-concrete interactions were modeled including the potential for CO2 generation, which was found to be an important contributor to late overpressurization failure of the containment for some accident sequences. However the reduction of CO2 to combustible CO was not modeled at that time and therefore its impact on late combustion was not determined. Although WASH-1400 was very influential, and it did point out the significance of core melt accidents to risk, it did not impact the regulations related to combustible gas control that were issued during the late 1970s.

The original combustible gas control regulation (10 CFR 50.44) became effective in 1978 with an emphasis on addressing the consequences of only hydrogen generation as a result of the design basis LOCA. This DBA assumed that the initial metal-water reaction would take place over a short period of time early in the LOCA, near the end of the blowdown period and the core refill phase following successful ECCS operation. The duration of the blowdown and core refill phase is on the order of several minutes [Reg Guide 1.7, 1978]. Thus it was felt that the assumption of a 2 minute evolution time for hydrogen (50.44 (d)(1)) from the metal-water reaction, which represents the period of time during which the maximum heat-up occurs, with a constant reaction rate would be conservative for the design of a hydrogen control system. Therefore the limited quantity of hydrogen that had to be addressed in the original regulation resulted in requirements for the installation of recombiners and/or purge systems as discussed in Chapter 3.

The accident at TMI-2 resulted in significant core melting, a large quantity of hydrogen generation (400 kg), and a combustion event in containment. Although the reactor core was severely damaged, coolant injection was restored prior to the core melting through the lower head of the reactor pressure vessel (RPV). Thus no ex-vessel interactions occurred that could release CO during this accident. The accident was, therefore, terminated with the damaged core retained in the RPV. Hydrogen generation occurred as a result of oxidizing approximately 45% of the cladding. The accident had a significant impact on the requirements ultimately imposed by 50.44 and resulted in two amendments to the regulation in 1981 and 1985 (see Table 4-1 and Chapter 3). First, the small volume containments, the Mark I and II BWRs, were required to be inerted, i.e., maintain an oxygen-deficient atmosphere, during power operation. Second, a quantity of hydrogen equivalent to a metal-water reaction of 75% of the clad surrounding the active fuel region was specified in the amendments. This quantity of hydrogen was considered to be representative of

a wide range of degraded core accident sequences. In addition, as the TMI-2 accident was terminated, it was assumed that hydrogen was the only combustible gas to be considered and that power was available (i.e., coolant injection was restored) so that any hydrogen control system installed could be designed to use on-site power (i.e., station blackout (SBO) accidents need not be considered on the basis of low probability). The second amendment was restricted in its application only to the “intermediate volume” BWR Mark III and the PWR ice condenser containments.

The requirements imposed in the 1981 and 1985 amendments to 50.44 were intended to address degraded core accidents and reflected our understanding of hydrogen generation and combustion at that time. It was however recognized when 10 CFR 50.44 was amended that we had limited understanding of the behavior of accidents involving severe core damage. The TMI-2 accident, therefore, had a significant impact on research activities sponsored by the NRC and the nuclear industry. Studies related to combustible gas generation, transport, and combustion were an important component of these activities. The objective of the severe accident research program (SARP) sponsored by NRC was to improve our understanding of core melt phenomena and develop improved models to predict the progression of severe accidents.

During the 1980s and 1990s, NRC sponsored research focused both on experimental phenomena and on model development. Experiments were carried out at a variety of scales and under mixture and combustion conditions characteristic of severe accidents in nuclear power plants. Combustion related issues that were studied included:

- combustible gas generation from zircaloy and steel oxidation, core-concrete interactions (CCI), radiolysis, and corrosion.
- Transport and mixing of combustible gases within containment.
- Flammability limits for a range of combustible gas mixtures.
- Combustion pressure-temperature response.
- Diffusion flames and jets.
- Deflagration-to-detonation transitions and detonation limits.
- Mitigation option, including glow plug igniters.

An accurate understanding of the rate and quantity of combustible gas generation is critical for determining the magnitude of the threat posed by combustion. As noted above the 1985 amendment to 50.44 specified a hydrogen source term representative of a degraded core melt accident. An aspect of SARP was therefore directed at improving our understanding of combustible gas generation during degraded core accidents and improving our ability to predict hydrogen generation from zircaloy oxidation during in-vessel core melting. In addition, the severe accident codes were modified to included steel oxidation (not previously modeled) as an additional in-vessel source of hydrogen. SARP also addressed ex-vessel interactions expected during full core melt accidents and greatly improved our understanding of CCI. The importance of other metal constituents in the core debris as sources of combustible gases was modeled in the severe accident codes. Also the production of combustible CO gas from the CO2 released during the interactions of the molten core with limestone concrete was included in the codes.

The importance of ensuring a well mixed atmosphere when combustible gases are released to containment was recognized in the original version of 50.44. If the atmosphere is not mixed stratification of the combustible gases can occur resulting in locally very high concentrations, which can be detonable. Codes were developed to assess the likelihood of achieving a well mixed atmosphere through natural or forced processes for a variety of containment designs. The codes were benchmarked against several experiments.

An understanding of the pressure-temperature response of the containment atmosphere to combustion events (deflagrations and detonations) is essential if the threat to containment integrity is to be accurately determined. SARP therefore focused on improving codes used to predict the pressure-temperature response to combustion events in several different containment designs. These studies confirmed the robustness of large volume and subatmospheric containments in terms of mitigating combustion events, which supported the position adopted in the amendments to 50.44 that did not required a hydrogen control system to be installed in containments with either of these designs. The studies also confirmed the continuing need for combustible gas control (inerting or igniters) in containments with pressure suppression designs.

For some containment designs (e.g., BWRs with Mark III containments) it is possible for standing diffusion flames to form during some core melt accidents. During a transient initiated core melt accident in a BWR with a Mark III containment, hydrogen and steam are released through the tailpipes into the suppression pool. The steam is condensed in the water and a very rich hydrogen mixture is released from the top of the suppression pool into the outer containment. This source of H2 will continue for as long as the oxidation process continues and if it is ignited (by the thermal igniters) could burn as a standing diffusion flame. A number of experiments, significant code development and analyses were performed to address the potential impacts of diffusion flames. The results of this research was incorporated into assessing the effectiveness of the igniter systems.

A detonation produces a dynamic pressure pulse that is much larger than the static pressure loads associated with deflagrations. Detonations are potentially of concern for all containment types. It is therefore important to understand when a detonation might occur (i.e., establish detonation limits for a range of H2, H2O, CO, and CO2mixtures) and when a flame might accelerate and transition into a detonation wave. A significant number of experiments were conducted under SARP to address these issues. A 10% hydrogen concentration was establish as a limit below which a detonation is unlikely to occur.

The 1985 amendment to 50.44 required BWR Mark I and PWR ice condenser containments to be provided with a system capable of controlling H2 from a metal-water reaction of 75% of the cladding. Thermal igniter systems were installed in all of these containment to control this specified quantity of hydrogen. A component of SARP therefore examined the effectiveness of the igniter systems under a variety of conditions.

The results from some of these research activities were incorporated into severe accident codes which were in turn used in a series of studies (e.g., the NUREG-1150 [2] program and the probabilistic risk assessments (PRAs) performed as part of the Individual Plant Examination (IPE) program[3]) to quantify the risk posed by severe accidents for LWRs.

The research, analyses, and studies led to an improved understanding of combustible gas behavior during severe accidents. These findings led to:

- reduced concern for hydrogen combustion in large dry and subatmospheric containment

- confirmation of the need to inert Mark I and II containments

- understanding of the efficacy of igniters in different scenarios at Mark III and ice condenser containments

- mixing induced by igniters

The NUREG-1150 PRAs provide the most thorough PRA treatment of severe accident phenomena to date. Additional insights can be obtained from the industry IPEs, although these studies are often less thorough with respect to considering severe accident phenomena. PRAs typically consider three time regimes for treatment of threats from combustible gasses:

- During the in-vessel core damage process
- At vessel breach or during other major RCS failures (i.e., hot leg), and
- Later in the accident sequence.

Hydrogen generation during the first two time regimes can influence the probability of early containment failure. In a transient accident sequence in BWRs, this hydrogen is released through the safety relief valve (SRV) tailpipes into the suppression pool. In a transient sequence in a PWR, the evolved hydrogen would be released through the power-operated or safety relief valves to the containment. In LOCAs, the hydrogen would be directly released to the containment atmosphere through the break in the reactor coolant system boundary. At the time of vessel breach hydrogen would be released directly to the region below the reactor pressure vessel. Hydrogen evolved during core degradation can also be released to the containment by operator action through the high point vents on the reactor coolant system.

Combustible gas (H2 and CO) generation from CCI during the last time regime influences the probability of late containment. Hydrogen generation however during the first phases (if not ignited early) can also influence the probability of late failure. If combustible gases from all of these sources is allowed to accumulate in the containment, concentrations can exceed the flammable limits and combustible mixtures can form.

The severe accident risk studies carried out in the NUREG-1150 program addressed (through a process of expert elicitation) issues related to hydrogen and carbon monoxide generation and combustion in terms of the impact on containment failure for each of these three time regimes.

Since combustion, and the means to control it, can directly affect the survivability of the containment during a severe accident, it is useful to discuss the implications of the various risk studies individually for different containment types. 50.44 imposes (refer to Chapter 3) one set of requirements for all containments (i.e., hydrogen monitors, recombiners, and purge/repressurization systems), but also mandates different requirements for specific containment types (e.g., inerting for Mark I and II containments, and, in effect, igniters for Mark III and ice condenser containments). The following section therefore also discusses the current hydrogen combustion challenges in terms of the following three groups of containment designs:

- PWRs with large volume and subatmospheric containments,
- BWRs with Mark I and Mark II containments, and
- BWRs with Mark III and PWRs with ice condenser containments.

4.3 Current Challenge to Containments from Combustible Gases

A discussion of the current risk challenges to the different containment types is presented in this section. The containments are grouped as (1) PWR large volume and subatmospheric, (2) Mark I and Mark II, and (3) Mark III and ice condenser containments. The discussion also addresses each of the current requirements in 50.44 in terms of three containment groups

4.3.1 PWR Large Volume and Subatmospheric Containments

Table 4-2 below shows whether or not there are currently any remaining H_2 combustion challenges, in terms of the conditional large early release probability (CLERP), and the conditional large late release probability (CLLRP) to containment integrity (for these two containment designs) for the three time regimes identified earlier in Section 4.2. The CLERP and CLLRP are defined in Chapter 2. The information in the table is based on the results of the research performed during the 1980s and 1990s.

Table 4-2 CLERP and CLLRP from Combustion for PWR Large Volume and Subatmospheric Containments

Containment Design	CLERP Before Vessel Breach	CLERP at Vessel Breach		CLLRP After Vessel Breach
		With RCS at High Pressure	With RCS at Low Pressure	
PWR Large Volume Containments	<<0.1	<0.1	<<0.1	<0.1
PWR Subatmospheric Containments	<<0.1	<0.1	<<0.1	<0.1

Notes:
(14) The results presented in NUREG-1150 (and in the supporting documentation) and in NUREG-1560 were used extensively when constructing this table.
(15) After vessel breach includes up to approximately 24 hours after the onset of core damage.

Need for Severe Accident Hydrogen Control

The above table indicates that hydrogen combustion is not a significant threat to the integrity of large volume and subatmospheric containments for all three time regimes. These containments have very large internal volumes and are predicted to fail at about three times their design pressures. As previously noted in Section 4.1 these containments have significant capacity for withstanding the pressure loads associated with hydrogen deflagration. Detonations of sufficient magnitude to fail containment were judged to have a low probability.

NUREG-1150 assessed the risk of containment failure at Zion, a PWR with a large volume containment, and at Surry, a PWR with a subatmospheric containment for each time regime. For Zion the mean conditional containment failure probability (CCFP) before and at vessel breach was estimated at ~0.01 and the contribution to this low probability from hydrogen combustion was very small. The results for Surry are similar to those predicted for Zion. These mean probability estimates are low but subject to uncertainty. The NUREG-1150 study did develop uncertainty distributions and the 95th percentile for Surry is predicted to be ~0.1. The equivalent number for Zion is ~0.05. The contribution of hydrogen combustion to these two estimates was again predicted to be relatively small. This implies that even when uncertainties are taken into account,

hydrogen combustion is not a major cause of containment failure before or at the time of vessel breach for this group of containments.

In addition, the magnitude of the release of radioactive material is predicted to be quite large for these containment failures. Typically, consequence analysis codes only predict the occurrence of acute health effects in the surrounding population when the release fractions of the volatile groups (iodine, cesium, and tellurium) exceed approximately ten percent. NUREG-1150 predicted mean releases in the range of 10 percent for these containment failures with the upper end of the uncertainty distribution extending to approximately 30 percent. These containment failures close to the time of vessel breach, while of relatively low probability, would be classified as “large releases” using the definition described in section 4.1.

IPE results for plants with large volume and subatmospheric containments showed that the conditional probabilities of early containment failure ranged from negligible to about 0.3. The main contributor to the higher probabilities, however, was found to be from sequences leading to high pressure melt ejection, not from hydrogen combustion. Early failure due to over pressurization from hydrogen combustion loads was assessed to be unlikely due to the high pressure capabilities and large volumes of these containment types. Another contributor to the low failure probability was the estimates of the likelihood of a spurious ignition source capable of igniting a hydrogen rich mixture and thus controlling excessive hydrogen buildup.

Although hydrogen combustion does not contribute to the CLERP before or at vessel breach, significant quantities of combustible gases (hydrogen and CO) can accumulate to very large concentrations after vessel breach. The major source of combustible gases in this time frame, in addition to the metal-water reaction, is the core-concrete interaction. Depending on the concrete constituents (limestone or basalt), the core-concrete interaction can be a significant source of carbon dioxide which is subsequently reduced to combustible CO. Combustion events in conjunction with an already existing elevated containment pressure were identified in some IPEs as mechanisms leading to containment failure after vessel breach in individual PWR large volume and subatmospheric containment plants [3]. However, the magnitude of the radionuclide release associated with these containment failures after vessel breach was found to be relatively low (less than 1% of the volatiles released) in the IPEs. Only a small fraction (less than 0.1) of the failures resulted in releases that approach 10%. Therefore, the releases that were predicted to occur in the IPEs after vessel breach (but within 24 hours after the onset of core damage) would not meet the requirements for a large release as defined in section 4.1.

The two amendments to 50.44 required the installation of systems to control hydrogen released during a severe accident for all of the pressure suppression containments. PWRs with large volume and subatmospheric containments were not required to install a system to control hydrogen. Generic Issue-121 [4] addressed the problem of hydrogen control in large volume containments. The resolution of this issue was that hydrogen combustion was not a failure threat for large volume containments and that there was no basis for requiring generic hydrogen control measures, such as igniters, in these plants. The results of the risk studies described above confirm the validity of the resolution of GI-121.

Need for Measuring Hydrogen Concentration

The requirement to measure the hydrogen concentration in containment was imposed in the original version of 50.44. However, a hydrogen control system is not required to mitigate the consequences of a full core melt accident in a large volume or subatmospheric containment, therefore, it is not necessary to measure the hydrogen concentration from the perspective of controlling combustion. The requirement to provide a system to measure the hydrogen

concentration in containment does not, therefore, contribute to the risk estimates described above for core melt accidents for these containment designs.

For accident management purposes the hydrogen monitors are used to confirm the amount of core degradation and whether or not an explosive mixture does exists inside containment. Licensees typically define the highest Emergency Action Level, a General Emergency, as a loss of any two barriers and potential loss of the third barrier. Potential loss of a third barrier includes whether or not an explosive mixture exists inside containment. For performing this function the current safety grade monitors with their limited hydrogen concentration range are not the optimum choice. Commercial grade monitors with the ability to monitor a wider range of hydrogen concentration and, preferably, the ability to function under SBO conditions, could be a better solution.

Need for Ensuring Mixed Containment Atmosphere

The requirement to ensure a mixed containment atmosphere was also imposed in the original rule prior to the TMI-2 accident to address the slow evolution of hydrogen from a design basis LOCA accident. Ensuring a well mixed containment atmosphere during a core melt accident is also important because if local pockets of combustible gases accumulate they can form detonable mixtures. However the results of the risk studies noted above indicate that hydrogen combustion is not a significant contributor to CLERP or CLLRP. This statement is true even when uncertainties are considered. This requirement is, therefore, not risk significant for this group of containments.

Need for LOCA Hydrogen Control

The requirement for a hydrogen control system to deal with the slow evolution of hydrogen following a LOCA was also requirement of the original rule. The installation of recombiners and/or vent and purge systems addressed the limited quantity and rate of hydrogen generation that was postulated in the original rule. These systems can only deal with a very limited amount of hydrogen and would be completely overwhelmed by the quantity and rate of hydrogen expected to be evolved during the early stages of a core melt accident in either a large volume or subatmospheric containments. Therefore, these systems are not useful during the three time regimes (identified in Table 4.2) and do not contribute to risk estimates discussed earlier in this section. In addition, in some plants operation of the (backup) purge systems could be problematic in a severe accident situation as it would potentially create a direct path for fission product release outside of containment. When evaluating the need for these systems this potential negative risk impact should be considered.

Need for High-Point Vents

The requirement to install high-point vents was imposed by the first post-TMI amendment to the rule. The vents are actually one of the means by which hydrogen can be introduced into the containment. Design requirements ensure that the potential of the vents as LOCA sources is limited. They were installed to permit venting of non-condensible gases from the reactor coolant system that could potentially impede the operation of the emergency core cooling system, and are therefore more risk significant for ECCS operation than for maintaining containment integrity. The vents could be instrumental for terminating a core damage accident if ECCS operation is restored. Under these circumstances, venting non-condensible gases from the vessel allows emergency core cooling flow to reach the damaged reactor core and thus prevent further accident progression. Since continued accident progression can lead to complete core melt and vessel failure, resulting in a threat to containment integrity, the vents do have some mitigative value for reducing the likelihood for early containment failure. However, the risk studies noted above indicate low CLERP both before vessel breach and at the time of vessel breach. Thus the reduction in the likelihood for early failure does not appear to be significant for these containment designs.

Conclusion: *For PWR large volume and subatmospheric containments, H2 combustion does not pose a challenge to containment integrity and therefore, there is no concern for a large release within 24 hours from the onset of core damage. However, the possibility exists for the accumulation of significant quantities of combustible gases (H2 and CO) in the long term (i.e., after several days), which should be considered during implementing accident management strategies.*

4.3.2 BWR Mark I and Mark II Containments

Table 4-3 below shows whether or not there are currently any remaining H_2 combustion challenges to containment integrity (in terms of the CLERP and CLLRP) for these two containment types. The information in the table is again based on the results of the research performed during the 1980s and 1990s.

Table 4-3 CLERP and CLLRP from Combustion for BWR Mark I and Mark II Containments

Containment Design	CLERP Before Vessel Breach	CLERP at Vessel Breach		CLLRP After Vessel Breach
		With RCS at High Pressure	With RCS at Low Pressure	
BWR Mark I	<<0.1	<<0.1	<<0.1	<0.1
BWR Mark	<<0.1	<<0.1	<<0.1	<0.1

Notes:
(1) The results presented in NUREG-1150 (and in the supporting documentation) and in NUREG-1560 were used extensively when constructing this table.
(2) After vessel breach includes up to approximately 24 hours after the onset of core damage.

Need for Severe Accident Hydrogen Control

The above table indicates that the contribution to from H2 combustion is very low during the three time regimes for these containment designs. This is because in the 1981 amendment to 50.44 all BWRs with Mark I and II containments were required to have an inert atmosphere during normal plant operation. Therefore risk studies for plants with Mark I and Mark II containments all include the fact that the containments are inert and, therefore, containment failure and hence a large release due to hydrogen combustion is not possible.

However, given the potentially large concentration of hydrogen that a core damage accident could cause in these plants the likelihood of containment failure from hydrogen combustion would be very high (essentially unity) if the containment were not inert. It has also been determined in risk studies [2-3] that a significant number of these failures can occur in the drywell so that the release would bypass the suppression pool. Releases that bypass the pool tend to be large (i.e., no pool scrubbing) and would, therefore, contribute to the CLERP. It is, therefore, clear that these containment designs should continue to operate with an inert atmosphere in order to meet the numerical guidance defined in Chapter 2.

Hydrogen combustion is prevented in the Mark I and II containments during the early stages of a core melt accident because they are inert. However, both hydrogen and oxygen are generated by the radiolysis of coolant solutions inside and outside the reactor coolant system due to absorption of the radiation emitted by the released fission products. The rate of production of these gases depends on the amount and quality of radiation energy absorbed in the specific coolant solutions used and the net yield of gases generated from the solutions due to the absorbed radiation energy.

The yield is affected by numerous factors such as coolant flow rates, chemical additives and impurities in the coolant, temperature, etc. Regulatory Guide 1.7 [5] recommends assumptions and values of the fraction of fission product energy absorbed by the coolant and the hydrogen and oxygen yield rates as a function of the absorbed energy that are acceptable for calculating the production of gases from radiolysis. Reg Guide 1.7 also recommends an oxygen concentration limit of 5 v/o if combustion is to be prevented assuming a hydrogen concentration of $\geq$ 6 v/o.

While the evolution of gases from radiolysis takes place at a much lower rate compared to the zirconium-water reaction, a combustible mixture could eventually form late (i.e., on the order of days after the onset of core damage) in the accident sequence from the evolution of oxygen. This implies that potential for hydrogen combustion in the long term should be considered when implementing severe accident management strategies.

Need for Measuring Hydrogen Concentration

The requirement to measure the hydrogen concentration in containment was imposed in the original version of 50.44. However, during the first two time regimes of a full core meltdown accident (identified in Table 4.3) it is not necessary to measure the hydrogen concentration in BWR Mark I and II containments because they are inert and no actions would be taken based on this measurement. The requirement to provide a system to measure the hydrogen concentration in containment is, therefore, not risk significant during the early stages of a core-melt accident.

In BWR Mark I and II containments, hydrogen (and oxygen) monitoring can have value late in an accident sequence when severe accident management considerations apply. Because hydrogen combustion is unlikely in the early stages due to inerting, the hydrogen monitors can provide an accurate indication of core damage in later phases of the accident. For combustion control, oxygen monitoring is more important than hydrogen monitoring for these containment designs. One source of oxygen late in the accident sequence is from the slowly evolving source of radiolysis that can pose a combustion threat, however this source can be controlled with recombiners. If hydrogen and oxygen monitors are unavailable, e.g. during a SBO, so that the concentrations can not be determined, and other indicators show evidence of core damage then current plant procedures recommend containment venting irrespective of the offsite radioactivity release rate.

For BWR Mark I and II containments, hydrogen concentration appears extensively in the emergency procedure guidelines (EPGs)/severe accident guidelines (SAGs), including as an entry condition. As such the need for measuring the H2 concentration should be assessed in the context of supporting the EPGs/SAGs.

Need for Ensuring Mixed Containment Atmosphere

The requirement to ensure a mixed containment atmosphere was also imposed in the original rule prior to the TMI-2 accident to address the slow evolution of hydrogen from a design basis LOCA accident. Ensuring a well mixed containment atmosphere during a core melt accident is also important because if local pockets of combustible gases accumulate they can form detonable mixtures. However, BWR Mark I and II containments are inert and therefore combustion is prevented so that the possibility of forming local pockets of combustible gases is not of concern. This requirement is therefore not relevant to these containment designs.

Need for LOCA Hydrogen Control

The requirement for a hydrogen control system to deal with the slow evolution of hydrogen following a LOCA was a requirement of the original rule. The installation of recombiners and/or

vent and purge systems addressed the limited quantity and rate of hydrogen generation that was postulated in the original rule. These systems are not needed during the three time regimes (refer to Table 4.3) of a core melt accident in BWRs with Mark I and II containments because the atmospheres are inert.

Need for High-Point Vents

The requirement to install high-point vents was imposed by the first post-TMI amendment to the rule. The vents are actually one of the means by which hydrogen can be introduced into the containment. Design requirements ensure that the potential of the vents as LOCA sources is limited. They were installed to permit venting of non-condensible gases from the reactor coolant system that could potentially impede the operation of the emergency core cooling system, and are therefore more risk significant for ECCS operation than for maintaining containment integrity. The vents could be instrumental for terminating a core damage accident if ECCS operation is restored. Under these circumstances, venting non-condensible gases from the vessel allows emergency core cooling flow to reach the damaged reactor core and thus prevent further accident progression. Since continued accident progression can lead to complete core melt and vessel failure, resulting in a threat to containment integrity, the vents do have some mitigative value for reducing the likelihood for early containment failure. However, as the BWR Mark I and II containments are inert all combustion is prevented so that there is no difference between the CLERP before vessel breach and after vessel breach in terms of the threat from combustion. This is not however true if other modes of containment failure are taken into account. There is a significant difference between the CLRP for degraded core and for full core melt accidents when all modes of containment are taken into account.

Conclusion: *For BWR Mark I and Mark II containments, combustion is not a challenge to containment integrity solely because of the inert atmosphere. However, the possibility exists for oxygen generation, and therefore, a combustion challenge to containment integrity in the long term (i.e., after several days), which should be considered during implementation of accident management strategies.*

4.3.3 BWR Mark III and PWR Ice Condenser Containments

Table 4-4 below shows whether or not there are currently any remaining H_2 combustion challenges to containment integrity (in terms of the CLERP and CLLRP) for these two containment types. The information in the table is based on the results of the research performed during the 1980s and 1990s.

Table 4-4 CLERP and CLLRP from Combustion for Mark III and Ice Condenser Containments

Containment Design	CLERP Before Vessel Breach	CLERP at Vessel Breach		CLLRP After Vessel Breach
		With RCS at High Pressure	With RCS at Low Pressure	
Mark III with Igniters Operating	<<0.1	>0.1	<0.1	<0.1
Mark III without Igniters Operating	<0.1	>0.1	>0.1	<0.1
Ice Condensers with Igniters Operating	<<0.1	<0.1	<0.1	<0.1

Table 4-4 CLERP and CLLRP from Combustion for Mark III and Ice Condenser Containments

Containment Design	CLERP Before Vessel Breach	CLERP at Vessel Breach		CLLRP After Vessel Breach
		With RCS at High Pressure	With RCS at Low Pressure	
Ice Condensers without Igniters Operating	>0.1	>0.1	>0.1	>0.1

Notes:
(1) The results presented in NUREG-1150 (and in the supporting documentation), NUREG-1560, and NUREG/CR-6427 were used extensively when constructing the table.
(2) After vessel breach includes up to approximately 24 hours after the onset of core damage.

Need for Severe Accident Hydrogen Control

The 1985 amendment to 50.44 required all BWR Mark III and PWR ice condenser containments to install systems to control hydrogen. Therefore for plants with these containment types existing PRA analyses include the igniter systems in the plant model. Nevertheless, hydrogen combustion was still found to be a significant contributor (as indicated in the above table) to early containment failure, and hence the CLERP, in some of the analyses, mainly from station blackout (SBO) sequences. This result is not unexpected because the amendments to 10 CFR 50.44 were written to mitigate terminated accidents (like TMI-2) in which the reactor core is damaged but retained in the RCS and for which power to operate the igniter system is assumed to be available. However, PRAs consider a wider range of accidents (including full-core events) in which the core melts through the RPV. Accidents in which power is not available to operate either the igniter system or the air return fans (ARF), are also modeled in PRAs.

The risk results for Grand Gulf reporting in NUREG-1150 were obtained from a more detailed report [6]. This report (NUREG/CR-4551, Volume 6) presents results that show (if the igniters are operating) a mean conditional probability of containment failure prior to vessel breach in the range of 0.01 to 0.02. Uncertainty distributions about these mean failure probabilities were not displayed in NUREG/CR-4551, Volume 6, but, based on other uncertainty distributions presented in the report, one could conclude that the 95th percentile would be at about 0.1. However, containment failures before vessel breach do not result in a large release for BWR Mark III containments. This is because the releases are scrubbed by the suppression pool. The CLERP is, therefore, significantly less than 0.1 if the igniters are operating.

NUREG/CR-4551 shows that if the igniters are not operating then the mean conditional probability of containment failure prior to vessel breach is about 0.1 to 0.2. The 95th percentile of the uncertainty distribution would be expected to increase these probability estimates to close to unity. However, even though there is a relatively high probability of containment failure, the releases may not be large because the drywell is predicted to remain intact and the releases would be scrubbed by the suppression pool. The CLERP prior to vessel breach is, therefore likely to be less than 0.1 even if the igniters are not operating however, this result is subject to uncertainty.

Predicting the conditional probability of containment failure at the time of vessel breach was found (in NUREG/CR-4551, Volume 6) to be uncertain and dependent on the RCS pressure and on whether or not the igniters were operating. If the RCS is at high pressure, the conditional probability of containment failure was predicted to be approximately 0.5 even with the igniters

operating. The 95th percentile of the probability distribution is essentially unity. In addition, approximately 50 percent of these containment failures also resulted in simultaneous failure of the drywell, which leads to early suppression pool bypass and relatively large releases. Thus, if the RCS is at high pressure at the time of vessel breach, the CLERP is greater than 0.1 whether or not the igniters are operating.

If the RCS is depressurized at the time of vessel breach and the igniters are not operating, NUREG/CR-4551, Volume 6, reports conditional probabilities of containment failure greater than 0.5 with a 95th percentile failure probability close to unity. Simultaneous failure of the drywell was also predicted for about 50% of these failures at the time of vessel breach. Failure of the drywell leads to pool bypass (i.e., no pool scrubbing) and, hence, large releases. Thus, if the RCS is at low pressure at the time of vessel breach, the CLERP is greater than 0.1 if the igniters are not operating.

The potential for containment failure caused by hydrogen combustion at the time of vessel breach when the RCS is at low pressure and the igniters are operating is not directly assessed in NUREG/CR-4551, Volume 6. However, the conditions prior to vessel breach should be applicable to this situation because the RCS is depressurized and none of the issues associated with HPME would occur. It is, therefore, reasonable to assume that if the RCS is at low pressure at the time of vessel breach, and if the igniters are operating, then the CLERP should be less than 0.1.

After vessel breach (but within 24 hours of the onset of core damage) NUREG/CR-4551, Volume 6, reports conditional probabilities of containment failure from about 0.1 to 0.3 caused by hydrogen combustion and gradual overpressurization. Again, distributions were not provided but the 95th percentiles would be expected to approach unity. However, even though there is a high probability of containment failure, most of the release would be scrubbed by the suppression pool. The CLLRP after vessel breach is, therefore, less than 0.1 because of pool scrubbing.

The NUREG-1150 and IPE results for Sequoyah show that if the igniters and the ARFs are operating the conditional probability of containment failure and, hence, the CLERP, is significantly less than 0.1 for all three time regimes independent of the RCS pressure (i.e., for all accidents except SBO). Therefore if the igniters and ARFs are operating hydrogen combustion is not a challenge to containment. The IPE results also indicated that even if the igniters and ARFs are not operating (i.e., for SBO sequences etc.) then hydrogen combustion is also not a challenge to the integrity of ice condenser containments. However, this is not substantiated by results in NUREG-1150 and NUREG/CR-6427.

The NUREG-1150 results indicate a mean conditional containment failure probability (CLERP) of just over 0.1 for SBO sequences, and these early failures were predicted to result in large releases. A CLERP of just over 0.1 is borderline in terms of remaining a challenge based on the guidelines in the framework document. In addition, the uncertainty associated with predicting the CCFP (and, hence, CLERP) has a very skewed distribution (reported in NUREG-1150) with a significant density of observations at the 95th percentile. This uncertainty distribution appears to be supported by recent work, documented in NUREG/CR-6427 [7] which indicates that hydrogen combustion does pose a very severe challenge to containment integrity if the igniters are not operating. Calculations made with the CONTAIN code indicated that no ice condenser plant is inherently robust to hydrogen combustion events in a SBO accident. If igniters are not available and other ignition sources are absent, large amounts of hydrogen can accumulate in the containment prior to vessel breach in some accident sequences. The combustion of this hydrogen can greatly augment DCH loads and, in fact, combustion of this hydrogen by itself can threaten containment. Furthermore, the ice condenser cannot mitigate this component of the containment loading to any great extent. Hydrogen deflagration and, possibly, detonation, in the upper dome are more credible in ice

condenser plants than in large dry containments. The initial conditions calculated by CONTAIN for SBO scenarios indicate molar hydrogen concentrations of 14%-18% if ignition sources are absent. These calculations are based on hydrogen production calculated by SCDAP/RELAP5 in which in-vessel zirconium oxidation was predicted to be 58%. This value, it should be noted, is less than the 75% clad oxidation postulated for compliance with 10 CFR 50.44. Quantification of containment event trees in NUREG/CR-6427 showed that for both slow and fast station blackout scenarios the conditional probability of containment failure, and, hence, CLERP, due to hydrogen combustion events in the Sequoyah plant is over 0.97 and ranges from 0.22 to 0.95 at other ice condenser containment plants. In the light of these new results hydrogen combustion therefore remains a challenge to the containment integrity of ice condensers in accident scenarios where the igniters are not available.

Need for Measuring Hydrogen Concentration

The requirement to measure the hydrogen concentration in containment was imposed in the original version of 50.44. However, during the three time regimes identified in Table 4.4 it is not necessary to measure the hydrogen concentration in BWR Mark III or PWR ice condenser containments because the igniter systems are actuated based on high pressure. The requirement to provide a system to measure the hydrogen concentration in containment is therefore not risk significant in terms of dealing with the combustion threat during these time regimes of a core melt accident (except for those conditions where the igniters are not operable, e.g., SBO).

For BWR Mark III containments, hydrogen concentration appears extensively in the EPGs/SAGs, including as an entry condition. As such the need for measuring the H2 concentration should be assessed in the context of supporting the EPGs/SAGs.

Need for Ensuring Mixed Containment Atmosphere

The requirement to ensure a mixed containment atmosphere was also imposed in the original rule prior to the TMI-2 accident to address the slow evolution of hydrogen from a design basis LOCA accident. Ensuring a well mixed containment atmosphere during a core melt accident is also important because if local pockets of combustible gases accumulate they can form detonable mixtures. The above results indicate that this an important issue for these containment designs and therefore this requirement is risk significant.

Need for LOCA Hydrogen Control

The requirement for a hydrogen control system to deal with the slow evolution of hydrogen following a LOCA was the third high level requirement of the original rule. The installation of recombiners and/or vent and purge systems addressed the limited quantity and rate of hydrogen generation that was postulated in the original rule. These systems would be completely overwhelmed by the quantity and rate of hydrogen expected to be evolved during the three time regimes identified in Table 4.4. Therefore these systems are not useful during these time regimes and consequently are not risk significant.

Need for High-Point Vents

The requirement to install high-point vents was imposed by the first post-TMI amendment to the rule. The vents are actually one of the means by which hydrogen can be introduced into the containment. Design requirements ensure that the potential of the vents as LOCA sources is limited. They were installed to permit venting of non-condensible gases from the reactor coolant system that could potentially impede the operation of the emergency core cooling system, and are

therefore more risk significant for ECCS operation than for maintaining containment integrity. The vents could be instrumental for terminating a core damage accident if ECCS operation is restored. Under these circumstances, venting non-condensible gases from the vessel allows emergency core cooling flow to reach the damaged reactor core and thus prevent further accident progression. Since continued accident progression can lead to complete core melt and vessel failure, resulting in a threat to containment integrity, the vents do have mitigative value for reducing the likelihood for early containment failure. The above results indicate that there is a significant difference between the CLRP for degraded core and for full core melt accidents for these containment designs. In particular the risk significant issue associated with high pressure core melt accidents at vessel breach for BWR Mark III containments would be avoided if the damage core could be retained in the reactor vessel.

Conclusion: *For BWR Mark III and PWR ice condenser containments, hydrogen combustion is not a challenge to containment integrity solely when igniters are available and operable, unless (for Mark III containments) the RCS is at high pressure when the core debris melts though the reactor vessel. Under these circumstances, even with the igniters operating hydrogen combustion remains a threat to containment integrity.*

4.4 Summary

Research and risk studies related to combustible gas control suggest that a risk-informed 10 CFR 50.44 should address the following:

- All accident types including full core melt (i.e., the core melts through the reactor vessel) accidents that result in a large release of radionuclides to the environment.

- The extent of the challenge to containment integrity depends on the rate and quantity of combustible gases released. A realistic combustible gas source term should, therefore, include combustible gases generated and released to containment from:
  - in-vessel metal-water reactions
  - reactor vessel blow down
  - ex-vessel core-concrete interactions

- Combustible gas control is needed for some containment types during a core melt accident sequence prior to, during, and after vessel failure (up to approximately 24 hours after the onset of core damage).

The results of research and risk studies related to combustible gas control have been compared to the numerical guidelines in the framework document to determine the risk significance of the requirements in 50.44. The following observations were derived from this comparison:

1) Some of the requirements are risk significant for some containment types:
   - inerting Mark I and II containments
   - providing severe accident hydrogen control for Mark III and ice condenser containments
   - ensuring a mixed containment atmosphere for Mark III and ice condenser containments

2) One requirement is not risk significant for any containment type:
   - LOCA hydrogen control

3) Some requirements may need to be enhanced:
   - ensuring severe accident hydrogen control for Mark III and ice condenser containments for all risk significant accident sequences
   - coupling the requirement for ensuring a well mix containment atmosphere to the requirement for severe accident hydrogen control for Mark III and ice condenser containments

4) One requirement is important to safety but not related to the concern being addressed by the rule:
   - the need for high point vents

These perspectives have been integrated with the other aspects of the framework to provide a risk-informed alternative. This work is described in Sections 5 and 6.

4.5 References

1. US NRC, "Reactor Safety Study - An Assessment of Accident Risks in U.S. Commercial Nuclear Power Plants," WASH-1400, NUREG-75/014, October 1975.

2. US NRC, "Severe Accident Risks: An Assessment for Five U.S. Nuclear Power Plants," NUREG-1150, December 1990.

3. US NRC, "Individual Plant Examination Program Perspectives Report," NUREG-1560

4. US NRC, "Issue 121: Hydrogen Control for Large, Dry PWR Containments (Rev.2)," NUREGs/SR-0933.

5. US NRC, "Control of Combustible Gas Concentrations in Containment Following a Loss-of-Coolant Accident," Regulatory Guide 1.7, Revision 2, November 1978.

6. T.D. Brown, et al., "Evaluation of Severe Accident Risks: Grand Gulf, Unit 1," NUREG/CR-4551, Volume 6, Revision 1, Part 1, December 1990.

7. M.M. Pilch et al., "Assessment of the DCH Issue for Plants with Ice Condenser Containments," NUREG/CR-6427, February 2000.

5. POTENTIAL RISK-INFORMED OPTIONS

As discussed in Section 2.2, once the concern associated with a regulation selected as a candidate for the risk-informing process is clearly understood, the two approaches shown in Figure 2.5 are followed. Both approaches have the same overall objective which is to develop risk-informed options for dealing with the identified concern. The identified concern, in this instance, is the threat from hydrogen combustion. The risk significance of hydrogen combustion and the associated needs for controlling it are discussed in detail in Chapter 4.

As the discussion in Chapter 4 indicates, combustible gas control related research and risk studies suggest that any risk-informed alternatives to the current 10 CFR 50.44 should account for the following:

- The combustible gas threat to containment integrity is dominated by accidents that develop to a full core melt with reactor vessel failure
- The rate and quantity of combustible gas released, i.e., the combustible gas source term, considered for accident analysis should be based on realistic calculations which cover all phases of the accident (in-vessel interactions, reactor vessel blowdown, and ex-vessel sources including core-concrete interactions)

The first approach in Figure 2.5 starts from the current set of regulations in Part 50 that address the concern and attempts to develop options based on risk-informing the requirements laid out in the current regulation. The second approach takes a fresh start at developing alternative risk-informed options for addressing the defined concern but without recourse to the existing body of regulations. Although these approaches have different starting points, they should lead in the end to a similar outcome, i.e., risk-informed requirements for dealing with combustible gas concerns.

The first approach is applied to 10 CFR 50.44 by assessing each of the high level requirements of this regulation for their risk significance and assessing the overall regulation for completeness in terms of risk. With this approach options are developed in which individual current requirements may be modified, deleted or left unchanged, and some additional requirements may be added. These options are called “revised” risk-informed options, and are discussed in Section 5.1.

In the second approach, the concern dealt with in 10 CFR 50.44 and analyzed in Chapter 3, i.e, the threat to containment integrity from combustible gas deflagration or detonation, is addressed via options developed by systematically applying the defense-in-depth strategies of the Framework, without regard to the requirements in the current 10 CFR 50.44. The options developed from this “clean sheet” approach are termed “alternate” risk-informed options, and are discussed in Section 5.2. The options developed in Section 5.2 below can each individually replace the current 10 CFR 50.44 regulation, while the options developed in Section 5.1 need to be combined in order to completely address the combustible gas concern. Viable options developed using the both approaches are offered as a comprehensive alternative to the existing 50.44 rule, as discussed in Chapter 6.

As discussed in Section 1.2, this work is intended to demonstrate the feasibility of risk-informed changes to 10 CFR 50.44. If the Commission approves going to rulemaking, additional analyses will be required.

5.1 Revised Risk-Informed Options

Recalling Figure 2.5, the approach based on modifying existing requirements consists of the following five steps:

1. Identify and describe the current requirements
2. Identify and describe related regulations and implementing documents
3. Identify and describe industry implementation of the requirements
4. Determine risk significance of requirements and implementation
5. Identify and describe risk-informed options

The current requirements, imposed by the original rule and two subsequent amendments, can be summarized at a high level as consisting of three analytical requirements and six physical requirements. The analytical requirements, which address the types of accidents examined as well as the sources and amounts of combustible gas to be considered, provide the background and context in which the physical requirements are applied.

The three analytical requirements of the current rule are the following:

- Accidents examined:
  - postulated LOCA (for all reactors, as specified in the original rule), and
  - degraded core accidents (for some containment types, as specified in the amendments).
- Sources of combustible gas:
  - metal-water reaction between the zirconium cladding and the reactor coolant,
  - radiolytic decomposition of the coolant, and
  - corrosion of metals.
- Amount of combustible gas:
  - 5% clad metal/water reaction for all reactors, and
  - 75% clad metal/water reaction for some containment types.

The six high level physical requirements imposed by the current rule are the following:

- measure the concentration of hydrogen in the containment
- insure a mixed atmosphere in the containment
- control combustible gas concentrations in containment following a postulated LOCA.
- install high point vents on all reactors.
- inert the atmosphere in BWR Mark I and Mark II containments
- provide a hydrogen control system for BWRs with Mark III containments and PWRs with ice condenser containments justified by a suitable program of experiment and analysis.

For each of the high level requirements the five steps listed above were carried out in the identification of each of the options discussed below. The first three steps were discussed in detail in Chapter 3. The risk significance of the combustible gas threat was presented in Chapter 4. Risk-informed options are identified below.

5.1.1 Potential Changes to Analytical Requirements

Risk-informed options for the three analytical requirements are developed below.

5.1.1.1 Requirement: Postulated Loss-of-Coolant Accident and Degraded Core Accident

Requirement

10CFR 50.44(a) states the following:

> *"Each boiling or pressurized light-water nuclear power reactor fueled with oxide pellets within cylindrical zircaloy or ZIRLO cladding....include means for control of hydrogen gas that may be generated, following a postulated loss-of-coolant accident..."*

10CFR 50.44(c)(3)(vi)(A) and (c)(3)(vi)(B)(3) states the following:

> *"...for a boiling light-water nuclear power reactor with a Mark III type of containment or for a pressurized light-water nuclear power reactor with an ice condenser type of containment .... Use accident scenarios....resulting in a degraded core."*

Evaluation

As noted in Chapter 3, experience and experiment have shown that during accidents involving core damage sufficient quantities of combustible gases can be evolved to pose a threat for some containments. The most significant risk appears to come from full core melt accidents, which include in-vessel clad metal/water reaction, potentially large quantities of hydrogen entering the containment at vessel failure, and the possibility of core-concrete interaction as the accident continues. On the other hand, design basis LOCA accidents, which involve only minor clad oxidation and in which the reactor vessel and containment does not fail, are not contributors to risk.

Therefore, the emphasis of the current requirement on consideration of postulated loss-of-coolant accidents for all reactors is no longer proper from a risk-informed perspective, and the consideration of degraded core accidents for reactors housed in BWR Mark III or PWR ice condenser containments should be expanded in two ways:

- degraded core accidents should be expanded to full core melt accidents, and
- the emphasis on core melt accidents should extend to all containment types

Proposed Change

- Modify 50.44 (a) by deleting the words "postulated loss-of-coolant accident (LOCA)" in the rule and replacing them by "core melt accident", and add suitable words to indicate that the combustible gas generation during the entire accident progression should be accounted for.

5.1.1.2 Requirement 50.44: Combustible Gas Sources

Requirement

10CFRR 50.44 (a) states the following:

> *"....include means for control of hydrogen gas that may be generated, ... by (1) metal-water reaction involving the fuel cladding and the reactor coolant, (2) radiolytic decomposition of the reactor coolant, and (3) corrosion of metals."*

Evaluation

The only combustible gas mentioned in the current requirement is hydrogen. While hydrogen generated by clad metal/water reaction is the principal source of combustible gas in core melt accidents, a significant amount of carbon monoxide can also be generated from core-concrete interactions (CCI) when the accident has progressed to the ex-vessel stage, given limestone based concrete and a dry reactor cavity.

In addition, for the in-vessel reaction there may be other oxidation sources present besides the clad metal, such as the channel boxes in BWRs.

Proposed Change

- Modify 50.44 (a) by adding suitable words to the rule to indicate hydrogen generation from metal-water reaction also involves other sources of metal in the core besides the fuel cladding, and that carbon monoxide evolved from core-concrete interaction is another combustible gas that should be considered. Therefore the wording should indicate that combustible gases may be generated following a full core melt accident by:

  (1) Metal-water reaction involving, principally, the fuel cladding and the reactor coolant but also including other sources in the core such as channel boxes in BWRs,
  (2) Radiolytic decomposition of the reactor coolant,
  (3) Corrosion of metals, and
  (4) Metal reactions during core-concrete interaction.

5.1.1.3 Requirement 50.44: Combustible Gas Source Term

Requirement

For reactors with BWR Mark III or PWR ice condenser containments, 10CFR 50.44(c)(3)(iv)(A) states the following:

> *"Each ...reactor with a Mark III type of containment and .... with an ice condenser type of containment....The hydrogen control system much be capable of handling....hydrogen equivalent to that generated from a metal-water reaction involving 75% of the fuel cladding..."*

10CFR 50.44 (c)(3)(v)(B) states the following:

> *"The amount of hydrogen to be considered is equivalent to that generated from a metal-water reactions involving 75% of the fuel cladding...."*

10CFR 50.44 (c)(3)(vi)(B)(1) states the following:

> *"...hydrogen resulting from the metal-water reactions of up to and including 75% of the fuel cladding..."*

For all reactors, 10CFR 50.44 (d) states the following:

> *"...the amount of hydrogen contributed by core metal-water reaction (percentage of fuel cladding that reacts with water)....shall be assumed either to be* [5%]*or ...from*

reaction of all the metal ... to a depth of 0.00023 inch, whichever amount is greater..."

Evaluation

The amount of hydrogen generated in a 75% metal/water reaction specified in 10 CFR 50.44 (c)(3)(iv), (v) and (vi) for Mark III and ice condenser containments focuses on core degradation. However, it is presently not conclusively demonstrated that this is a realistic amount of combustible gas for risk-significant accident scenarios in all reactor types. Also, the rate at which hydrogen is assumed to enter the containment in the analyses required under the present 10 CFR 50.44 (c)(3)(v)(B) is representative of a degraded core accident and not a full core melt accident.

The amount of combustible gas proposed in 10 CFR 50.44 (d) for consideration by all reactors is based on a postulated design basis LOCA. As noted in Chapter 3, understanding of the combustion threat has matured to the realization that this small amount of hydrogen is not the principal contributor to risk, and is dwarfed by the comparatively large, quickly evolving amounts of combustible gas generated in a core melt accident.

Proposed Change

- Modify the appropriate sections of 50.44 by calling for the use a specified combustible gas source term, generated by the NRC staff, with this risk-informed requirement. A series of specific source terms, tailored to containment types and accident scenarios would be described in a Regulatory Guide. The source terms would account for all phases of an accident (as discussed in 5.1.1.2 above), including in-vessel metal/water reaction, vessel blowdown, and ex-vessel core/concrete interaction in the later stages of the accident.

5.1.2 Potential Changes to Physical Requirements

The six high level physical requirements of the current rule are the following:

- measuring the concentration of hydrogen in the containment
- insuring a mixed atmosphere in the containment
- controlling combustible gas concentrations in containment following a postulated LOCA
- installation of high point vents on all reactors
- an inerted atmosphere for Mark I and Mark II containments
- a hydrogen control system for BWRs with Mark III containments and PWRs with ice condenser containments justified by a suitable program of experiment and analysis.

5.1.2.1 Requirement 50.44 : Measure H2 Concentration

Requirement

10 CFR 50.44 (b)(1) states the following:

> *"...(b) Each boiling or pressurized light-water reactor fueled with oxide pellets within cylindrical zircaloy or ZIRLO cladding must be provided with the capability for ... (1) Measuring the hydrogen concentration in the containment..."*

Licensees have met this requirement by installing continuous safety-grade monitors.

Implementing guidance is provided by the following:

Regulatory Guide 1.7 [1] recommends that systems to measure combustible gases in containment should meet the requirements for an engineered safety feature.

Regulatory Guide 1.97 [2] treats hydrogen monitors as redundant, safety-grade Class 1E electrical equipment. Consequently, they are subject to the procurement requirements of 10 CFR 21 and the quality assurance requirements of Appendix B to Part 50.

Regulatory Guide 1.101, Revision 3 [3] endorses NEI-NESP-007, Revision 2 which states that a General Emergency is a loss of any two barriers and potential loss of the third barrier. Potential loss of a third barrier includes whether or not an explosive mixture exists inside containment. The continuous hydrogen monitors are credited for making this determination.

Evaluation

The current requirement 50.44(b)(1) to provide a measurement capability is specifically stated in the context of a postulated loss-of-coolant-accident (LOCA). The intent of the current regulation is to provide a measurement capability to alert the operators to initiate and verify hydrogen control measures (systems such as recombiners, purge systems, etc.) to keep the hydrogen concentration below the 4% flammability limit (or the oxygen concentration below the 5% limit in BWRs) following a design basis LOCA. As stated earlier, the DBA LOCA is not a risk-significant accident, hence the measures used to control the amounts of hydrogen generated in this accident and the monitoring used to actuate these measures are also not risk-significant.

In terms of the risk-significant core melt accidents, the risk of early containment failure from hydrogen combustion is limited by the following mitigative features: (1) inerting in Mark I and II containments, (2) igniters in Mark III and ice condenser containments, and (3) the large volumes and likelihood of spurious ignition in large dry and sub-atmospheric containments that help prevent the build-up of detonable concentrations. Hydrogen monitoring is not needed to initiate or activate any of these measures, hence hydrogen monitors have a limited significance in mitigating the threat to containment in the early stages of a core melt accident.

In BWR Mark I and II containments, hydrogen (and oxygen) monitoring can have value late in an accident sequence when severe accident management considerations apply. Because hydrogen combustion is unlikely in the early stages due to inerting, the hydrogen monitors can provide an accurate indication of core damage in later phases of the accident. For combustion control, oxygen monitoring is more important than hydrogen monitoring for these containment designs. One source of oxygen late in the accident sequence is from the slowly evolving source of radiolysis that can pose a combustion threat, however this source can be controlled with recombiners. If hydrogen and oxygen monitors are unavailable, e.g. during a SBO, so that the concentrations can not be determined, and other indicators show evidence of core damage then current plant procedures recommend containment venting irrespective of the offsite radioactivity release rate.

For accident management purposes the hydrogen monitors are used to confirm the amount of core degradation and whether or not an explosive mixture does exists inside containment. Licensees

typically define the highest Emergency Action Level, a General Emergency, as a loss of any two barriers and potential loss of the third barrier. Potential loss of a third barrier includes whether or not an explosive mixture exists inside containment. For performing this function the current safety grade monitors with their limited hydrogen concentration range are not the optimum choice. Commercial grade monitors with the ability to monitor a wider range of hydrogen concentration and, preferably, the ability to function under SBO conditions, could be a better solution.

NUREG-0737 [4], Item II.F.1, Attachment 6 requires that all plants provide a continuous indication of hydrogen concentration in the containment for accident monitoring. The post-TMI requirement also imposed the design and quality criteria of Regulatory Guide 1.97 and required that the hydrogen monitors be included in a plant's technical specifications. The continuous hydrogen monitors are also credited in meeting 10 CFR 50.47 (b)(9) and Appendix E to Part 50 for assessing and monitoring offsite consequences. The staff recently granted an exemption to NUREG-0737, Item II.B.3, postaccident sampling of containment atmosphere hydrogen concentration, because the continuous hydrogen monitors were an acceptable alternative.

It is also important to note that this requirement is redundant to NUREG-0737, Item II.F.1, Attachment 6, 50.47, and Part 50 Appendix E.

Therefore, since the need is the capability of establishing hydrogen concentration levels, under degraded core conditions, for long term accident management, and since the hydrogen monitors are not necessary to meet any of the defense-in-depth elements (as listed in Section 2), the recommendation is to delete the requirement from 10 CFR 50.44, and that the guidance provided by NUREG-0737, Item II.F.1, Attachment 6 and RG 1.97, Revision 2 be revised to allow commercial-grade hydrogen monitors with a range from 0 to an amount of hydrogen generated from 100% of the active fuel clad reacting with water, or 30%, which ever is less. In addition, it would be desirable that the monitors be available during SBO sequences and be able to survive the effects of a degraded core accident including those initiated by external events. It is not recommended that design and quality criteria be changed for the containment high range radiation monitors or the oxygen monitors based on the above risk insights.

Proposed Change

- Eliminate the requirement for measuring hydrogen concentration by removing 50.44 (b)(1), redundant to NUREG-0737, Item II.F.1, Attachment 6, 50.47, and Part 50 Appendix E.

- Given the need for the capability of establishing hydrogen concentration levels, under degraded core conditions, for long term accident management, recommend that related regulations be revised to remove continuous measuring and safety-grade requirements and call for an increased measurement range.

5.1.2.2 Requirement 50.44: Insure a Mixed Containment Atmosphere

Requirement

10 CFR 50.44 (b)(2) states the following:

> *"...(b) Each boiling or pressurized light-water nuclear reactor fueled with oxide pellets within cylindrical zircaloy or ZIRLO cladding must be provided with the capability for ... (2) Insuring a mixed atmosphere in containment..."*

Licensees have met this requirement by using other equipment already in the plant to perform this function. This equipment varies according to containment type, but generally involves fan systems and/or containment spray systems. In ice condenser containments, for example, both the safety-grade Air Return Fans (ARFs) and the sprays are used. These systems serve a number of safety functions including containment heat removal. The systems must comply with the General Design Criteria (GDC) 41, 42, and 43 of Appendix A of Part 50.

Evaluation

Although the requirement of 50.44 (b)(2) was promulgated to address post-LOCA hydrogen accumulation, a mixed containment atmosphere is beneficial for core melt accident conditions also since a well mixed atmosphere prevents local accumulation of combustible or detonable gas concentrations which could threaten containment integrity. The risk significance of a well mixed atmosphere varies depending on containment type.

For the smaller volume containments, i.e., the BWR Mark I and Mark IIs, the risk significance of a mixed atmosphere could be very high since the small volumes and confined spaces of these containments could easily lead to build-up of significant hydrogen concentrations, given a core melt accident. However, another part of 50.44 requires the BWR Mark I and Mark II containments to be inerted. Inerting is an effective hydrogen control system for all risk-significant degraded core and full core melt accidents in these containments. Therefore, because of the inerted nature of these containments, the risk-significance of keeping the atmosphere mixed to prevent hydrogen combustion is actually quite low for BWR Mark I and Mark IIs.

For the intermediate containments, i.e., the BWR Mark IIIs and the PWR ice condensers, the risk-significance of a mixed atmosphere could again be very high for reasons similar to those mentioned above for BWR Mark I and Mark II containments; i.e., relatively small volumes and geometries susceptible to hydrogen pocketing. However, as required by other parts of 50.44, these containments also have hydrogen control systems, i.e, deliberate ignition systems, effective for mitigating the hydrogen threat from degraded and full core melt accidents. If these deliberate ignition systems operate for all risk-significant sequences, then the risk-significance of ensuring a mixed atmosphere is also relatively low for BWR Mark III and PWR ice condenser containments.

The large volume and relatively open geometry of large dry containments makes the accumulation of high concentrations of hydrogen unlikely in these plants. This open geometry also supports atmospheric mixing brought about by the phenomena of the core melt accident itself, such as blowdowns from pipe ruptures or reactor vessel failure. During the IPE process licensees with large dry containments were asked to evaluate their containments for susceptibility to local hydrogen concentration. These evaluations indicated that either no possibility for local hydrogen accumulation was identified, or that locations where accumulations could occur did not contain equipment whose failure (as a result of hydrogen combustion) would affect plant risk. Therefore, for large dry containments the risk-significance of ensuring a mixed atmosphere is relatively low even with no dedicated hydrogen control systems in place, as long as the open geometry is maintained.

Although the risk-significance of this requirement is relatively low, provided hydrogen control systems are in place for risk-significant accident sequences in all BWR containments and in PWR ice condenser containment, it is retained for defense-in-depth reasons. As discussed in the framework document and in Chapter 2 of the present report, one of the considerations in the defense-in-depth approach for applying the four strategies of Figure 2-1 is that the intent of the General Design Criteria (GDC) of Appendix A to 10 CFR 50 is maintained. GDC 50 addresses the containment design basis and notes that the containment and its compartments shall

accommodate, with sufficient margin, the effects of potential energy sources including those of 50.44, i.e., energy from metal-water and other chemical reactions. Retaining this requirement will ensure that the current features that promote atmospheric mixing in the existing plants will not be degraded by any future modifications of these plants.

Proposed Change

- Retain the requirement for insuring a mixed containment atmosphere stipulated by 50.44 (b)(2).

5.1.2.3 Requirement 50.44: Control Combustible Gases in Containment Following a Postulated LOCA

Requirement

50.44(b)(3) states the following:

> *"...(b) Each boiling or pressurized light-water nuclear reactor fueled with oxide pellets within cylindrical zircaloy or ZIRLO cladding must be provided with the capability for ... (3) Controlling combustible gas concentrations in the containment following a postulated LOCA..."*

50.44(b)(3) has several supporting requirements. Specifically, 50.44(c)(1) requires licensees to show that during the time period following the postulated LOCA but prior to effective operation of the combustible gas control system, either an uncontrolled hydrogen-oxygen recombination would not occur or the plant could safely withstand it, and if such a showing cannot be made then 50.44(c)(2) requires that plant to inert its containment. 50.44(c)(3)(ii) requires plants that relied upon a purge/repressurization system as the primary means for controlling combustible gases to install an internal recombiner or have a capability to install an external recombiner and has further requirements on the containment penetrations used with the external recombiners. 50.44(d)(1) and (d)(2) specify the quantity and rate of hydrogen assumed to be generated in the postulated LOCA. 50.44(e) requires plants whose notice of hearing on the application for a construction permit was received after 11/5/70 to have systems other than purge-repressurization systems as the primary means of combustible gas control and 50.44(f) and (g) allow plants whose notice of hearing on the application for a construction permit was received before 11/5/70 to have only purging systems if certain dose based criteria are met.

Licensees have met these requirements in a variety of ways. Many plants have classified recombiners as essential equipment and installed redundant, safety grade, internal recombiners. Some plants do not have internal recombiners but have provisions to install an external recombiner if needed. Some plants also maintain a filtered purge system as a backup system to control post-LOCA hydrogen concentrations.

Evaluation

The risk significance of the systems used to meet the post-LOCA combustible gas requirements of 50.44 is low. There are basically three reasons for this conclusion. First, the risk of the design basis LOCA accident itself is low, as pointed out above in the discussion under 5.1.1. Second, the recombiners can only process a very limited amount of hydrogen and would be completely overwhelmed by the quantity and rate of hydrogen expected to be evolved in a more risk significant severe accident. The only useful role for recombiners is in mitigating hydrogen (and oxygen) released in the long-term from phenomena such as radiolytic decomposition of the reactor coolant

and metal corrosion. Third, in some plants operation of the (backup) purge systems would be problematic in a severe accident situation as it would potentially create a direct path for fission product release outside of containment.

In addition, the provisions of this requirement are not necessary to meet any of the defense-in-depth elements (as listed in Section 2).

Proposed Change

- Eliminate requirement for combustible gas control systems following a postulated LOCA from 50.44 by the following means:
  - Remove 50.44(c)(1) and 50.44(c)(2) — requires plants to demonstrate no uncontrolled hydrogen combustion following postulated LOCA but before operation of control system
  - Remove 50.44(c)(3)(ii) including 50.44(c)(3)(ii)(A) and 50.44(c)(3)(ii)(B) — requires internal or external recombiners and imposes requirements on external recombiner containment penetrations
  - Remove 50.44(d)(1) and 50.44(d)(2) — specifies the post-LOCA hydrogen amounts evolved in the accident.
  - Remove 50.44(e), 50.44(f) and 50.44(g) — impose requirements relative to recombiners and purge-repressurization systems as means of hydrogen control following postulated LOCA
  - Remove 50.44(h) — as all of the definitions it contains refer to text in earlier portions of the regulation that are already proposed to be deleted.

5.1.2.4 Requirement 50.44: High Point Vents

Requirement

50.44(c)(3)(iii) states the following:

> *"...To provide improved operational capability to maintain adequate core cooling following an accident.....each light-water nuclear reactor shall be provided with high point vents for the reactor coolant system, for the reactor vessel head, and for other systems required to maintain adequate core cooling if the accumulation of noncondensible gases would cause the loss of function of these systems...."*

Licensees have met this requirement by installing high point vents. The vent system and components are safety-grade and seismically and environmentally qualified and subject to appropriate technical specifications and maintenance, testing, and surveillance requirements

50.44(c)(3)(iii) also provides associated requirements for the high point vents:

> *"... Since these vents form a part of the reactor coolant pressure boundary, the design of the vents and associated controls, instruments and power sources must conform to the requirements of appendix A and appendix B of this part....*"

Appendices A and B impose the safety-grade, seismic and environmental qualification requirements.

Evaluation

From the containment standpoint, the vents are actually one of the means by which hydrogen can be introduced into the containment. They were installed after the TMI accident to permit venting of non-condensible gases from the reactor coolant system that could potentially impede the operation of the emergency core cooling system. In terms of the framework for risk-informing Part 50 they are not directly related to the preventive strategy to limit the core damage frequency, since core damage precedes hydrogen generation. The vents could be instrumental for terminating a core damage accident by allowing natural circulation to occur and thus preventing further accident progression. Since continued accident progression can lead to complete core melt and vessel failure, resulting in a threat to containment integrity, the vents do have a mitigative value for reducing the likelihood for early containment failure. In any case, PRAs typically do not model scenarios in which a core damage accident is terminated as a result of using the high point vents, and therefore the risk significance of the vents is difficult to quantify. The vents do provide a means for removing non-condensible gas pockets which could impeded ECCS or natural circulation core cooling. Design requirements ensure that the potential of the vents as LOCA sources is limited.

Proposed Change

No change to the existing requirement 50.44(c)(3)(iii) and to the related regulations is proposed. Although this requirement is not directly related to mitigating the hydrogen threat to containment integrity, it has some risk-significance and moving the regulation would entail administrative costs.

5.1.2.5 Requirement 50.44: Hydrogen Control for BWR Mark I and II Containments

Requirement

10 CFR 50.44(c)(3)(i) states the following:

> *"...an inerted atmosphere shall be provided for each boiling light-water nuclear power reactor with a Mark I or Mark II type containment..."*

Licensees have met this requirement by providing systems for inerting the containment. The only requirements that plants have to meet relate to the inerting system lines that penetrate containment.

Evaluation

The risk significance of inerting for the small volume containments such as Mark I and II is extremely high. Studies have demonstrated that the conditional probability of containment failure from combustible gas deflagration and detonation events would be very high if the containment was not inerted. In terms of a high-level tie to the framework for risk-informing Part 50, inerting of Mark I and II containments is related to the mitigating strategy, i.e., limit radionuclide releases and limit public health effects. The slow accumulation of oxygen generated from radiolysis could deinert the containment atmosphere in the later stages of a core melt accident, and should therefore be addressed during the severe accident management phase.

Proposed Change

- Retain an inerted containment for BWR Mark I and Mark II plants by keeping 50.44 (c)(3)(i), and address continued inerting later in the accident by providing sufficient O2 control during the severe accident management phase.

5.1.2.6 Requirement 50.44: H2 Control System for Mark III and Ice Condenser Containments

Requirement

10 CFR 50.44(c)(3)(iv) states the following:

> *"(iv) (A) Each licensee with a boiling light-water nuclear power reactor with a Mark III type of containment and each licensee with a pressurized light-water nuclear power reactor with an ice condenser type of containment issued a construction permit before March 28, 1979, shall provide its nuclear power reactor with a hydrogen control system justified by a suitable program of experiment and analysis. The hydrogen control system must be capable of handling without loss of containment structural integrity an amount of hydrogen equivalent to that generated from a metal-water reaction involving 75% of the fuel cladding surrounding the active fuel region (excluding the cladding surrounding the plenum volume)."*

Licensees have met this requirement by installing a distributed glow plug igniter system in containment. The igniters are deployed in two separate groups, each group with its own independent and separate power supplies and controls.

10 CFR 50.44(c)(3)(iv) has a number of other supporting requirements in 50.44:

- Demonstrate containment structural integrity based on actual material properties or ASME B&PV code (c)(3)(iv)(B);
- for H2 control system using post-accident inerting show containment can withstand increased pressure during the accident or following inadvertent full inerting in normal operation (c)(3)(iv)(D);
- requirements on systems and components for plants with post-accident inerting control systems (c)(3)(iv)(E);
- requirements on systems and components for plants that do not rely on inerting for H2 control (c)(3)(v)(A); and
- for plants with construction permits issued prior to 3/28/79 provide evaluation of consequences of H2 using accident scenarios acceptable to NRC that support design of control system (c)(3)(vi)(A), (c)(3)(vi)(B).

There are other regulations in Part 50 that impose associated technical requirements: references to the ASME Boiler & Pressure Vessel (B&PV) code requirements for steel containments (50.55) and written communications on accident analyses (50.4).

For both 50.44(c)(3)(iv) and the related regulations, there are associated implementation guidance documents: ASME B&PV code sections for steel containment (Section III, Subsubarticle NE-3220, Service Level C limits), and ASME B&PV Code sections for concrete containments (Section III, Subsubarticle CC-3720, Factored Load Category).

Evaluation

The risk significance of the igniter system is high in the intermediate volume Mark III and ice condenser containments. A severe accident in these plants generating significant amounts of hydrogen from the metal-water reaction (on the order of that generated in the TMI accident) would pose a severe threat to containment integrity in the absence of a hydrogen control system. However, the igniters need AC power to operate and are thus not available during station blackout (SBO) accident sequences. Recent studies have demonstrated that the conditional containment failure probability from hydrogen combustion during SBO is very high. During an SBO sequence in an ice condenser, neither the igniters nor the air return fans are operational.

In terms of a high-level tie to the framework for risk-informing Part 50, a hydrogen control system in Mark III and ice condenser containment plants is part of the mitigation strategy, i.e., it belongs to the strategies to limit radionuclide releases and limit public health effects. At a lower level, the hydrogen control system would be used to limit the conditional large early probability and the conditional late large release probability to low values (e.g, the value 0.1 recommended in the framework for risk-informing Part 50). However, as currently configured, there is some question whether the lower level objective on the conditional probabilities can be met. The option below considers providing hydrogen control during SBO sequences, or demonstrating that these sequences are unlikely.

Hydrogen control systems have not been considered for large volume containments including large dry and sub-atmospheric containments. Risk studies for individual plants have demonstrated that the containment could withstand the pressure spike from a hydrogen combustion event and the probability of reaching a concentration where a deflagration-to-detonation transition can occur is low.

Proposed Change

- Modify 50.44 (c)(3)(iv) to include combustible gas control during all risk significant accidents (e.g., SBO sequences) in BWR Mark III and PWR ice condenser containments.

This option is aimed at ensuring that the hydrogen control system called for under the current 50.44(c)(3)(iv) would also operate during any risk significant accident (e.g., station blackout, i.e., loss of all AC power). Since all operating Mark III and ice condenser plants meet this requirement via a glow-plug igniter system, this option would translate in practical terms into requiring that all igniters (or a limited set of igniters with the number having to be demonstrated by the licensee) would be operable during risk-significant accidents (e.g., SBO). Alternatively, the implementing documents for this regulation could also allow licensees to demonstrate that the core damage frequency contribution from all sequences without hydrogen control is not risk significant, e.g., demonstrate that SBO,had a low frequency (a frequency below a threshold, such as 1E-6/year, that would be quantified in the accompanying Regulatory Guide). The rationale here is based on the discussion provided under the quantitative objectives for risk-informing regulatory requirements in the framework for risk-informing Part 50. The perspective is that for accident sequences or accident classes where one of the high level defense-in-depth strategies is precluded, more emphasis needs to be placed on the strategies that remain. Therefore for accident classes where the high-level conditional early containment failure probability goal of 0.1 specified in the framework for risk-informing Part 50 cannot be achieved a more stringent guideline needs to be imposed on their contribution to the core damage frequency.

5.2 Alternate Risk-Informed Options

The approach adopted for developing alternative risk-informed requirements is described at a high level in Chapter 2. The approach involves the following three stages/steps in the process at which risk-informed requirements can be developed:

(1) Identify the combustible gas concern

(2) Assess the defense-in-depth strategies

(3) Identify and describe the functional relationship of each strategy

Potential risk-informed options are identified and described below for each of these stages. Each proposed requirement includes consideration of the six considerations described in Section 2.2.1.

The concern is the structural failure (early or late in the accident sequence) of the containment caused by the deflagration/detonation of combustible gases. The problem that gives rise to the early containment failure concern is the rapid generation of large quantities of hydrogen generated from the reaction of zirconium clad and steam during an accident in which significant core damage occurs while it is in the reactor vessel and at the time of vessel breach . The risk significance of early containment failure is potentially very high because it can lead to the release of a large quantity of radionuclides relatively early in an accident sequence. If the release is prior to the effective evacuation of the close in population early health effects can occur. A late release is also possible because core-concrete interactions can produce large quantities of combustible gases (i.e., hydrogen and carbon monoxide) for a long time after vessel breach. If these gases ignite then late containment failure is possible and, if the sprays are not operating, a significant amount of radionuclides can be released. A late release source term to the environment is generally less severe than a corresponding early release source term, but it can still cause long-term health effects and extensive land contamination.

5.2.1 Options Dealing with Combustible Gas Concern

At this stage options can be developed, based on the characteristics noted above, to either eliminate the problem altogether or ensure that the frequency of accidents leading to significant core damage are very low.

Two options have been identified for addressing this concern in a risk-informed manner as follows:
(1) eliminate the concern
(2) lower the frequency of concern

First Option: Eliminate the Combustible Gas Concern

Proposed Change

- eliminating the concern by replacing the current regulation with a high level requirement to demonstrate that large amounts of combustible gas can not be generated at high temperature. One way of making this demonstration is via the selection of materials for the reactor core and/or the reactor coolant (e.g., the reactor cores be constructed of materials that will not react with the coolant to produce large quantities of combustible gas at high temperatures).

This requirement, however, is unlikely to be practical for the current population of operating nuclear power plants (NPPs) because it would require extensive redesign and reconstruction of the existing reactor cores. Such a massive undertaking would be difficult to justify based on cost-benefit arguments.

A risk-informed requirement of this nature however may be an option potentially applicable to the design of future reactors.

Evaluation

Implementation of such a requirement would reduce the conditional containment failure probability from combustible gases to a negligible probability. Remaining possible sources of combustible gas generation, such as steel/water interaction and core/concrete interaction, are unlikely to produce sufficient amounts of combustible gases to threaten containment integrity.

Second Option: Lower the Frequency of Concern

Proposed Change

- replace the current regulation with a high level requirement to demonstrate that the containment integrity is not challenged by accidents leading to significant core damage (and hence large quantities of combustible gas production).

Specific ways of making such a demonstration would be spelled out in a Reg Guide. The Reg Guide could specify quantitative core damage frequency targets as one way of demonstrating compliance.

Evaluation

A large number of the current population of operating nuclear power plants (NPPs) have demonstrated that the risk posed by combustion varies significantly between the various containment designs (refer to Chapter 4).

In order to meet the overall quantitative goal for large release probability (described in the framework document), by using only preventative strategies, the CDF for the individual NPPs would have to be sufficiently low (e.g., lower than 1E-5/ry as specified in the framework for risk-informing Part 50). As the risk from combustion events in plants with large dry and subatmospheric containments is relatively small (refer to Chapter 4), requiring that these plants operate with a very low CDF (e.g., below 1E-5/ry) in order to simply lower the frequency of the threat to containment from combustible gases cannot be justified based on cost-benefit arguments.

Studies have shown however that the risk from combustion is higher in ice condenser and Mark III containments, and much higher in Mark I and II containments. Therefore, before making recommendations, cost-benefit arguments should be explored in greater detail for plants with these containment designs.

5.2.2 Options based on Framework Defense-in-depth Strategies

As noted above, the framework document defines four defense-in-depth strategies for limiting accident risk at a high level, and quantifies three of them. These strategies aim to both prevent core-damage accidents (two high-level preventive strategies) and mitigate the public impact should a core-damage accident occur (two high-level mitigative strategies). Therefore, options can be

developed based on each strategy. In this section each strategy is examined relative to preventing and mitigating the combustible gas concern.

Proposed Change

- Replace the current regulation with a regulation that specifies the following specific mitigative and preventative goals designed to address the combustible gas concern:
  - — demonstrate that any risk significant core damage accident does not result in an un acceptable conditional large early release probability (CLERP) and conditional large late release probability (CLLRP) as a result of combustible gases, if not
  - — demonstrate that any risk significant core damage accident does not result in an unacceptable large early release frequency (LERF) and large late release frequency (LLRF) as a result of combustible gases, if not
  - — demonstrate adequate emergency preparedness for each core damage accident class for which the above criteria are not met.

Specifics on demonstrating compliance would be provided in a Reg Guide and would be consistent with the framework guidelines. The Reg Guide could elaborate on how compliance can be demonstrated relative to the framework guidance, as follows. As the combustible gas concern is directly related to the challenge to containment integrity posed by the deflagration/detonation of combustible gases, the first strategy considered is the goal of limiting the CLERP and CLLRP to <0.1 (conditional on core damage). If this cannot be demonstrated the next option would be to use the preventative strategies to require that the LERF and LLRF goals are met. Note the early goal can be met by CLERP or LERF and the late goal can be met by CLLRP or LLRF. Consequently it is possible to meet the early and late goals with combinations of mitigative and preventative strategies i.e., LERF in combination with CLLRP. If low conditional probabilities or frequencies cannot be achieved, then the final step would be to resort to the last mitigative strategy related to emergency preparedness. These three steps are consistent with the framework approach which prefers a balance between prevention and mitigation, but recognizes that in some cases the quantitative goals of individual high level preventive or mitigative strategies cannot be met. In these cases the framework advocates more stringent quantitative goals for the remaining requirements.

The steps involved in this process can be stated as follows:

Meet mitigative strategy

- demonstrate the CLERP and CLLRP from combustible gases is sufficiently low (e.g.< 0.1as specified in the framework) for each core damage accident class

if not,

Meet a combination of the preventive and mitigative strategies

- demonstrate the LERF and LLRF from combustible gases is sufficiently low (e.g.< 1E-6) for each core damage accident class

if not,

Meet emergency preparedness criteria

- demonstrate adequate emergency preparedness for each core damage accident class for which the above criteria are not met.

Evaluation

Implementing the elements in this proposed change, would ensure that the risk from combustible gases would be low since their risk significance would be below the framework guidelines.

5.2.3 Options Based on Functional Relationship of Framework Defense-in-Depth Strategies

In this section functional relationships are identified with the aim of addressing the combustible gas concern. The focus is on limiting the conditional large release probability to sufficiently low values (e.g., <0.1) conditional on core damage and the generation and release to containment of significant quantities of combustible gases. Ways of preventing combustion or achieving controlled burning are presented in the Table 5.1 below:

Table 5.1 Combustible Gas Control Systems

Hydrogen Control System	Pros	Cons
Pre accident inerting	Will prevent combustion with high reliability	Cost is high and access to containment is restricted
Other options, e.g., passive autocatalytic recombiners (PARS), passive igniters	Will prevent combustion and/or prevent uncontrolled deflagration and detonation provided system functions	The reliability and effectiveness of the system has to be demonstrated and the impact of the additional pressure/temperature loads (caused by controlled deflagration) taken into account.
Combustible gas control systems: Glow plug igniters	Designed to burn combustible gas at low concentrations and prevent uncontrolled deflagration or detonations	The reliability and effectiveness of the system has to be demonstrated and the impact of the additional pressure/ temperature loads (caused by controlled deflagration) taken into account.

Other systems designed to control combustible gas (i.e., recombiners or vent-purge systems in operating plants) or remove heat from containment (i.e., sprays or fan cooler systems) have response times that cannot mitigate combustion of large amounts of combustible gas in a short time interval.

A number of combustible gas control systems, along with their pros and cons, are discussed in NUREG/CR-2726, “Light Water Hydrogen Control Manual” [5]. More recently an experimental program was conducted at the Surtsey facility at Sandia National Laboratories [6] to evaluate a PAR design developed by the NIS Ingenieurgesellschaft Mbh of Hanau, Germany [7].

The concern posed by combustion resulting from full-core melt accidents depends on the specifics of the containment design. Extensive research and analysis has demonstrated (refer to Chapter 3) that the six containment designs currently in use in the US can be grouped into the following three classes for the purposes of assessing the impact of combustion.

BWRS with Mark I and Mark II Containments

Risk analyses, performed for plants with Mark I and II containment buildings, model the containment atmospheres as inert. Containment failure due to combustion is therefore found to be not significant in most PRAs. However, sufficient calculations have been performed for these small volume containments, assuming that they are not inerted, to demonstrate that the containment will be severely challenged by combustion during a full core meltdown accident. Given the large concentration of combustible gases that a core damage accident in these plants could cause, the likelihood of early containment failure from combustion is very high for these containment designs. This means that an igniter system designed to burn combustible gas in a controlled manner would not prevent failure in these containment designs. Also, a post-accident inerting system is not practical because it would impose significant pressure loads caused by the addition of inert gas. Therefore, it appears that pre-accident inerting is the optimum strategy for mitigating combustion.

Although combustion would be prevented during the early stages of a core melt accident if the containment is inert, oxygen is gradually generated during accidents of this type and a combustible mixture could eventually be reached late (on the order of days) in the accident sequence. A means of controlling combustible gases during the long term severe accident management is therefore needed for these containment types even if the containment atmospheres are inert during normal plant operation.

BWRs with Mark III and PWRs with Ice Condenser Containments

For plants with Mark III and ice condenser containments, existing PRA analyses include the igniter systems in the plant model. Nevertheless, combustion was still found (refer to Chapter 4) to be a significant contributor to early containment failure in some of the analyses, mainly from station blackout sequences. It is likely that the combustion contribution to early failure would increase significantly for other sequences if the igniters were not present. Therefore, it appears that an igniter system capable of operating during SBO accidents is appropriate for these containment designs providing it can be demonstrated that controlled burning does not threaten containment integrity.

PWRs with Large Volume and Subatmospheric Containments

Numerous risk studies have demonstrated that combustion is not a significant threat during the first 24 hours of a core melt accident in large volume, dry containments. Generic Issue-121 [8] addressed the problem of combustible gas control in large, dry containments housing PWRs. The resolution of this issue was that combustion was not a failure threat for large, dry containments and that there was no basis for requiring combustible gas control measures, such as inerting or igniters, in these plants. While combustion is not a threat to containment integrity during the first 24 hours of a core meltdown accident in these containments, for severe accident management purposes it should be remembered that significant quantities of combustible gases (hydrogen and CO) could accumulate over a long period of time (on the order of days) to significant concentrations. Severe accident management strategies should account for a threat to containment integrity from a combustion event late in a core meltdown accident sequence.

Based on the above discussion the following option, based on the functional relationships of the Framework defense-in-depth strategies, is proposed that would specify specific systems to be installed or requirements to be met for the three different containment classes to either prevent or control combustion.

- *Identify Functional Relationships to address the Combustible Gas Concern*

Proposed Change

- Replace the current regulation with a regulation that specifies specific requirements to address combustible gas concern for each containment type. The following control systems or requirements would be included in the alternate option:

  (a) An inert atmosphere shall be provided for each boiling water reactor (BWR) with a Mark I or Mark II containment. Severe accident management strategies should consider that oxygen can be generated in the long term during a core meltdown, perhaps necessitating a system to prevent or control combustion late in the accident sequence.

  (b) A combustible gas control system shall be provided for each BWR with a Mark III containment and each pressurized water reactor (PWR) with an ice condenser containment. The effectiveness of the control system shall be justified by a data from a suitable program of experiment and analysis.

  (c) Licensees with a PWR with a large volume or subatmospheric containment design should include, in their severe accident management plans, strategies to demonstrate that the containment can safely accommodate a specified combustible gas source term representative of a full-core meltdown accident.

If the option includes provision for a combustible gas control system and associated systems then the attributes of the system(s) will also be described. At a minimum such a system(s) should provide, with reasonable assurance, that:

- Combustible gas concentrations uniformly distributed in the containment do not exceed 10% assuming the specified combustible gas source term, or that the post-accident atmosphere will not support combustion,

- Combustible gas concentrations will not collect in areas where unintended combustion or detonation could lead to loss of containment integrity or loss of appropriate mitigating features,

- Equipment necessary for achieving and maintaining safe shutdown of the plant and maintaining containment integrity will perform its safety functions during and after being exposed to the environmental conditions attendant with the specified combustible gas source term including the environmental conditions created by activation of the control system,

- Equipment necessary for achieving and maintaining safe shutdown of the plant and maintaining containment integrity will also function for all risk important full-core meltdown accident sequences,

- If the method selected for combustible gas control is a post-accident inerting system, inadvertent actuation of the system can be safely accommodated during plant operation.

Evaluation

The above option is derived from risk insights, consistent with the framework document (i.e. it is based on the high level mitigative strategies) and supports the defense-in-depth philosophy. The

option, as constructed, is very specific and specifies the systems to be installed or requirements to be met for each containment that will ensure that the deterministic large release goal of CP of < 0.1 is achieved.

5.3 Summary

In Section 5.1 the three analytical and six physical requirements of the current 10 CFR 50.44 were examined, and risk-informed options to change or replace each individual requirement were identified and discussed. The three analytical requirements were modified based on the results of risk studies which suggest that full core melt accidents dominate the combustible gas risk, and that all potential sources for combustible gas generation should be accounted for in a realistic manner when assessing the robustness of a plant relative to the combustible gas concern. The risk-informed analytical requirements are: (1) full core melt accidents must be considered, (2) combustible gas generation from metal/water reaction and core/concrete interaction must be accounted for, and (3) realistic rates and amounts of combustible gas should be assessed. Based on these considerations the six physical requirements of the current rule were risk-informed as well, and , taken together, the risk-informed options developed in Section 5.1 form a complete and comprehensive alternate means to address the threat to containment integrity posed by combustible gases

In Section 5.2 the combustible gas concern for containments was examined without reference to the existing 10 CFR 50.44, but again with the objective of developing a risk-informed alternate to the existing rule. The same risk-informed analytical requirements formulated in Section 5.1, based on current understanding of the combustible gas risk, apply here also. Four options for a risk-informed combustible gas rule were identified in Section 5.2. Two of these options were dismissed as not feasible for current reactors, while the other two were examined further. One of these latter two was based on the framework defense-in-depth strategies while the other one was based on the framework functional relationships supporting the defense-in- depth strategies. The option based on the framework defense-in-depth strategies represents a comprehensive, performance-based means to control combustible gases, as discussed further in Chapter 6. The option based on the functional relationships can be seen to lead to the same requirements as the sum of the options derived in Section 5.1, and therefore does not need to be discussed separately.

A risk-informed alternative to the existing 10 CFR 50.44 regulation is one which achieves compliance with the three risk-informed analytical requirements, which articulate the current state of knowledge regarding the combustible gas threat. Practically this would mean demonstrating that the NRC developed, realistic combustible gas source term, can be accommodated without unacceptably high risk to public safety. Such a demonstration could be accomplished by either employing the sum of the options developed in Section 5.1, or by adopting the option of Section 5.2 based on the framework defense-in-depth strategies. Both methods lead to the implementation of a risk-informed alternative to the existing 10 CFR 50.44, as discussed further in Chapter 6.

5.4 References

1. US NRC, “Control of Combustible Gas Concentrations in Containment Following a Loss-of-Coolant Accident,” Regulatory Guide 1.7, Revision 2, November 1978.

2. US NRC, “Instrumentation for Light-Water Cooled Nuclear Power Plants To Assess Plant and Environs Conditions During and Following an Accident,” Regulatory Guide 1.97, Revision 3, May 1983.

3. US NRC, “Emergency Planning and Preparedness for Nuclear Power Reactors,” Regulatory Guide 1.101, Revision 3, August 1992.

4. US NRC, “Clarification of TMI Action Plan Requirements,” NUREG-0737, November 1980.

5. Allen L. Camp, et al., “Light Water Reactor Hydrogen Manual,” NUREG/CR-2726, SAND 82-1137, Sandia National Laboratories, August 1983.

6. T.K. Blanchat and A. Malliakos, “Performance Testing of Passive Autocatalytic Recombiners,” NUREG/CR-6580, SAND 97-2632, Sandia National Laboratories, 1998.

7. NIS Ingenieurgesellschaft, “NIS Control Module for Hydrogen Removal in Containment Atmosphere,” Information Brochure, Hanau, Germany, 1992.

8. US NRC, “Resolution of Generic Safety Issues,” NUREG-0933, 1999.

6. EVALUATION OF RISK-INFORMED ALTERNATIVE TO THE EXISTING 10 CFR 50.44

6.1 Achieving Goals of Risk-Informed Alternative

In Chapter 5 options were identified for the development of a risk-informed alternative to the existing combustible gas rule specified in 10 CFR 50.44. Two paths were followed in identifying options: one evaluated the existing set of technical requirements for either elimination, modification, or enhancement, depending on how well they addressed the concern the rule focused on; the other applied the four framework strategies to identify performance-based means to address the concern without regard to the existing requirements.

However, both paths are grounded in the same considerations. The current state of knowledge regarding the threat to containment integrity from combustible gases was reviewed, based on available risk studies and industry experience, and the three analytical requirements, which provide the foundation for a risk-informed alternative, were established. These are that any risk-informed alternative should account for: (1) full core melt accidents, (2) combustible gas generation from metal/water reaction and core/concrete interaction, and (3) realistic rates and amounts of combustible gas generated. Furthermore, all options are consistent with the quantitative guidelines of the framework and are based on proven technology.

The risk-informed alternative to the existing 10 CFR 50.44 is shown in Figure 6.1. As the figure illustrates, the objectives of the alternative, embodied in the three analytical requirements, can be met by two different methods, corresponding to the two paths discussed above.

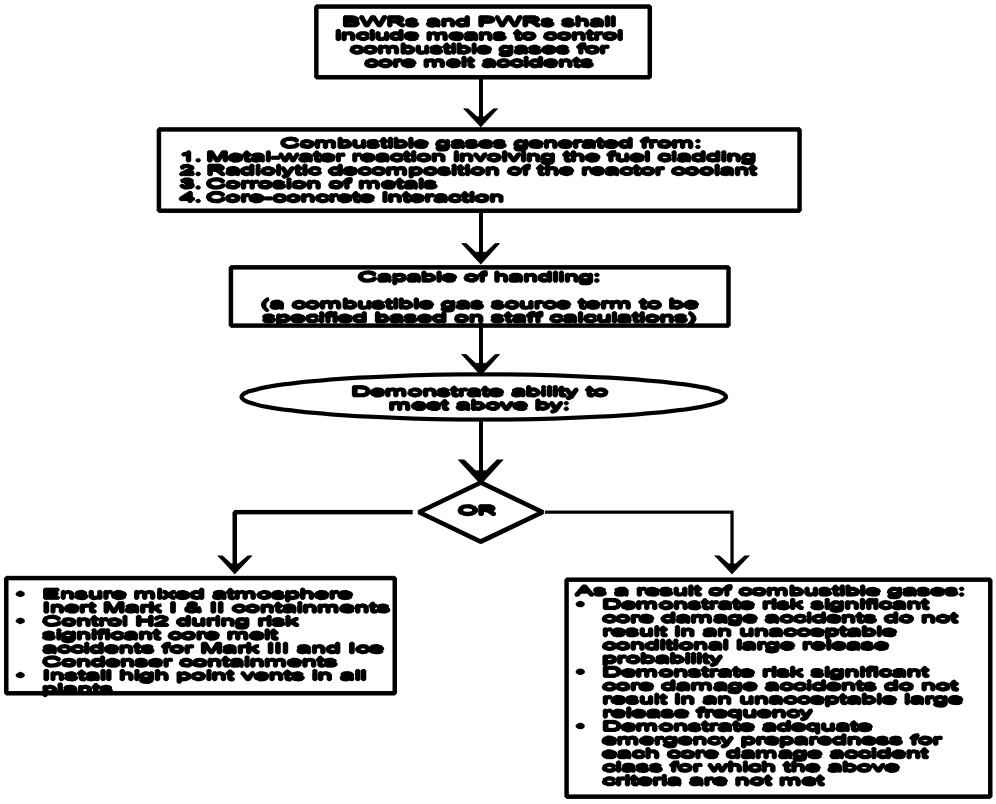

Figure 6-1 Risk-Informed Alternative for 10 CFR 50.44

First Method

The method summarized in the box on the left side is the result of eliminating, modifying or enhancing the physical requirements of the existing rule. This was done, consistent with the framework, by examining how well each existing requirement addressed the combustible gas concern. As discussed in Section 5.1, the result of this examination led to the following suggested changes to the existing physical requirements:

- Eliminate the requirement for measuring hydrogen concentration by removing 50.44 (b)(1), redundant to NUREG-0737 [1], Item II.F.1, Attachment 6, 50.47, and Part 50 Appendix E. In addition, given the need for the capability of establishing hydrogen concentration levels, under degraded core conditions, for long term accident management, recommend that related regulations be revised to remove continuous measuring and safety-grade requirements and call for an increased measurement range.

- No change to the requirement for insuring a mixed containment atmosphere, i.e., retain 50.44 (b)(2).

- Eliminate requirement for combustible gas control systems following a postulated LOCA from 50.44 by the following means:

- Remove 50.44(c)(1) and 50.44(c)(2) — requires plants to demonstrate no uncontrolled hydrogen combustion following postulated LOCA but before operation of control system

- Remove 50.44(c)(3)(ii) including 50.44(c)(3)(ii)(A) and 50.44(c)(3)(ii)(B) — requires internal or external recombiners and imposes requirements on external recombiner containment penetrations

- Remove 50.44(d)(1) and 50.44(d)(2) — specifies the post-LOCA hydrogen amounts evolved in the accident.

- Remove 50.44(e), 50.44(f) and 50.44(g) — impose requirements relative to recombiners and purge-repressurization systems as means of hydrogen control following postulated LOCA

- Remove 50.44(h) — as all of the definitions it contains refer to text in earlier portions of the regulation that are already proposed to be deleted.

- No change to the existing requirement of 50.44(c)(3)(iii) regarding the high point vents and to the related regulations is proposed. Although this requirement is not directly related to mitigating the hydrogen threat to containment integrity, it has some risk-significance and moving the regulation would entail administrative costs.

- Retain an inerted containment for BWR Mark I and Mark II plants by keeping 50.44 (c)(3)(i), and address continued inerting later in the accident by providing sufficient O2 control during the severe accident management phase.

- Modify 50.44 (c)(3)(iv) to include combustible gas control during all risk significant accidents (e.g., SBO sequences) in BWR Mark III and PWR ice condenser containments.

Some implications of this method for NRC are summarized in Table 6.1 while some implications for industry are listed in Table 6.2. The tables present just a preliminary assessment. Implications for both the industry and the NRC will eventually have to be carefully evaluated via a Regulatory Analysis.

Table 6.1 First Method, NRC Implications

Item	yes/no	Description/Comments
Rule change	Yes	10 CFR 50.44 would be revised by making the changes indicated in Section 5.1, and summarized above, to both the analytical and physical requirement contained in the current rule.
Impact on other regulations	Yes	NUREG-0737 would be revised to allow commercial grade monitors. Part 50.47 and Appendix E may be revised.
Revise/modify implementing documents	Yes	Existing regulatory guidance on safety grade monitors in Regulatory Guide 1.97 would be revised. Regulatory guidance on recombiners will need modification.

Table 6.1 First Method, NRC Implications

Item	yes/no	Description/Comments
Create implementing documents	Yes	New regulatory guides would be needed on providing acceptable methods for compliance with different parts of the revised regulation.
Analysis	Yes	A realistic combustible gas source term, as specified in the third risk-informed analytical requirement, will have to be developed by the NRC staff.
Review	Yes	Licensee submittals will need to be reviewed to verify compliance. If the analysis is based on recommended guidance the review should be straightforward. If an alternative approach is selected, a longer review will be required.
Inspection	Maybe	Depends on way in which compliance is achieved.

Table 6.2 First Method, Licensee Implications

Item	yes/no	Description/Comments
Equipment	Maybe	Elimination of monitoring requirement would allow commercial grade monitors for Appendix E concerns. Changes would allow removal of recombiners, and purge systems. Hardware changes would be needed to make igniters operable during SBO.
Analysis	Yes	If the licensee elects to use recommended methods for demonstrating compliance then a limited amount of analysis may be needed, depending on the plant type. If the licensee elects to use an alternative method to demonstrate compliance significant additional analysis may be required.
Maintenance/inspection	Maybe	Will depend on the way compliance is achieved
Tech Specs	Maybe	Remove tech specs from monitors and recombiners and vent/purge systems.
Procedures/Training	Maybe	Will depend on the way compliance is achieved

Implicit in this alternative is the assumption that large dry and subatmosppheric containments are not challenged by combustible gases, i.e. that the conclusions of Generic Issue 121 would still apply if the capacity of these containments were assessed against a realistic combustible source term. Some confirmatory analysis may be needed.

The development of a realistic combustible gas source term by the NRC staff is discussed further in Section 6.2.

Second Method

A second method to achieve the goals of the risk-informed alternative is summarized in the box on the right hand side of Figure 6-1. This method was derived from the defense-in-depth strategies contained in the framework document for risk informing Part 50. The proposed change would be to replace the current regulation with a regulation that specifies specific mitigative and preventive goals based on the defense-in-depth strategies, that, if met, would address the combustible gas concern.

Licensees would be asked to demonstrate that:

- any risk significant core damage accident does not result in an unacceptable conditional large early release probability (CLERP) and conditional large late release probability (CLLRP) as a result of combustible gases, if not then demonstrate that
- any risk significant core damage accident does not result in an unacceptable large early release frequency (LERF) and large late release frequency (LLRF) from combustible gases, if not then demonstrate that
- adequate emergency preparedness is in place for each core damage accident class for which the above criteria are not met.

The specific means of demonstrating that the goals are met would be outlined in a Reg. Guide and would be consistent with the framework guidelines. For example the early goal can be met by CLERP or LERF and the late goal can be met by CLLRP or LLRF Consequently it is possible to meet the early and late goals with combinations of mitigative and preventative strategies, i.e., LERF in combination with CLLRP. The steps involved in this process can be stated as follows:

Meet mitigative strategy

- demonstrate the CLERP and CLLRP from combustible gases is sufficiently low (e.g.< 0.1as specified in the framework) for each core damage accident class

if not,

Meet a combination of the preventive and mitigative strategies

- demonstrate the LERF and LLRF from combustible gases is sufficiently low (e.g.< 1E-6) for each core damage accident class

if not,

Meet emergency preparedness criteria

- demonstrate adequate emergency preparedness for each core damage accident class for which the above criteria are not met.

These three steps are consistent with the framework approach which prefers a balance between prevention and mitigation, but recognizes that in some cases the quantitative goals of individual high level preventive or mitigative strategies cannot be met. In these cases the framework advocates more stringent quantitative goals for the remaining requirements.

If the above goals for large release are met, it is very likely that the plant will have risks consistent with the quantitative health objectives for the risk of early and late fatality of the Commission's Safety Goal Policy. This method embodies the high level defense-in-depth strategies articulated in the framework for risk-informing Part 50, specifically the two mitigation strategies consisting of limiting the radionuclide releases during core damage accidents and limiting public health effects due to core damage accidents. At a lower level in the hierarchy, this method is also based on the reactor safety cornerstones of ensuring the integrity of the containment boundary and the adequacy of the emergency preparedness functions.

This second method has several ways of addressing the combustible gas concern as discussed below.

Demonstrate the CLERP and CLLRP of containment failure from combustible gases is sufficiently low (e.g., < 0.1)

The framework document recommends a goal of limiting the CLERP and CLLRP to <0.1 conditional on core damage. The option is derived from risk insights, consistent with the framework document (i.e. it uses the high level mitigative strategies) and supports the defense-in-depth philosophy. However, it could be difficult to demonstrate that this goal has been met given the significant amount of uncertainty associated with predicting containment performance during core melt accidents. This option, although it appears to be flexible, would likely require significant regulatory guidance in the form of supporting documentation. For example guidance would have to be provided on the combustible gas source term (refer to Section 6.2) and on acceptable methods for demonstrating that the conditional probability goal has been met.

Acceptable methods for demonstrating that the conditional probability goal has been met could be probabilistic or deterministic in nature. Currently a PRA standard is being developed which if endorsed by the NRC could potentially form the basis for an acceptable approach for demonstrating that this goal has been met. The PRA standard currently being developed by the American Society of Mechanical Engineers (ASME)however includes only a simplified approach (which focuses on estimating Large Early Release Frequency (LERF)) for performing a level 2 PRA. The current level 2 approach in the standard is therefore only suitable for generating a simplified estimate of LERF and is not capable of demonstrating that the CLLRP goal has been met. A deterministic approach to demonstrate that the goal has been met would be to specify a combustible gas source term to containment and prescribe a method for calculating the CLERP and the CLLRP.

The combustible source term has two components, namely the total quantities of the gases to be considered and the rate of release to containment. The quantities of gases to be considered should appropriately reflect those conditions that would be expected in containment during a core melt accident. The existing regulations (refer to Chapter 3) were written to mitigate accidents like TMI-2 in which the reactor core is damaged but retained within the reactor coolant system (RCS). The combustible gas source term was therefore restricted to hydrogen (i.e., core-concrete interactions were assumed not to occur) and the amount assumed to be generated was based on a metal-water reaction limited to 75% of the clad surrounding the active fuel region. The rates of hydrogen and steam assumed to be released to containment were also determined from analyses of accidents in which core damage was terminated in-vessel.

Analyses performed (refer to Chapter 4) since TMI-2 have shown that accidents in which the core melts through the reactor pressure vessel (RPV) can pose a more severe threat to containment integrity (and thus are more risk-significant) than if the damaged core is retained within the vessel. This implies that the proposed option should address full-core meltdown accidents in which significantly more hydrogen (i.e. perhaps more than a 100% metal water reaction) and also CO may be generated. In addition, the combustible gases and steam flow rates to containment have to reflect the rapid blow-down rates associated with reactor pressure vessel (RPV) failure if it occurs at high pressure.

Demonstrate the LERP and LLRP from combustible gases is sufficiently low (e.g.,< 1E-6)

If the above criteria related to CLERP and CLLRP cannot be met then conformance can be demonstrated by calculating the LERF and LLRF and comparing the results to the above goal.

Using frequencies to demonstrate conformance introduces the two preventative strategies discussed in the framework document in addition to the one mitigative strategy used for the previous two options. In addition, as the focus is on calculating frequencies for this option the level 2 approach in the PRA standard should be an appropriate way of demonstrating that the LERF goal is met provided that NRC endorses the method.

The above numerical goals, when referring to conditional probabilities of release and release frequencies from ”combustible gases,” include both direct and indirect failures and releases resulting from combustible gases. In other words, containment failures and releases which arise because combustible gas phenomena lead to failure of mitigating systems needed to achieve and maintain safe shutdown and/or containment integrity, are included.

Demonstrate adequate emergency preparedness

If the above criteria cannot be met then, by resorting to the last mitigative strategy identified in the framework document, conformance would have to be demonstrated by ensuring adequate emergency preparedness. This option would focus on those accident sequences for which the criteria could not be met. Hence it would imply that the emergency preparedness strategies used to demonstrate adequate preparedness would focus on scenarios consistent with such accident sequences. For example, emergency preparedness plans, drills, and exercises would be held under simulated conditions consistent with an SBO scenario.

Some NRC and licensee implications of the second method for achieving the risk-informed alternative goals are shown in Tables 6.3 and 6.4 respectively.

Table 6.3 Second Method, NRC Implications

Item	yes/no	Description/Comments
Rule change	Yes	This alternative would replace the existing rule with a new rule based on four preventative and mitigative strategies
Impact on other regulations	No	The new rule would not reference other existing regulations, but depending on how the quantitative guidelines of this alternative are met the licensee may have to be in compliance with related regulations (see impact on licensee, below).
Revise/modify implementing documents	No	Depending on how the quantitative guidelines of this alternative are met the licensee may have to be in compliance with related guidance (see impact on licensee, below).
Create implementing documents	Yes	New guidance would have to be provided on acceptable methods for demonstrating compliance with the conditional probability goals. New guidance would also have to be provided on an acceptable approach for demonstrating adequate emergency preparedness for those accident sequences for which the above criteria can not be met.
Analysis	Yes	Analysis would be needed to develop an appropriate source term.

Table 6.3 Second Method, NRC Implications

Item	yes/no	Description/Comments
Review	Yes	If the methods for demonstrating compliance and the recommended source term contained in the implementing documents are used then the review process should be relatively straight forward. If however an alternative approach is used to demonstrate compliance with the criteria then a significant review process would be needed.
Inspection	Yes	The way in which compliance is achieved (characteristics of the system installed) will determine the level of (i.e., added or reduced) inspection needed.

Table 6.4 Second Method, Licensee Implications

Item	yes/no	Description/Comments
Equipment	Yes	The way in which compliance is achieved will determine what, if any, equipment is needed. If needed, this would be a backfit issue where justification would likely require cost/benefit analysis.
Analysis	Yes	If the licencee uses the recommended methods for demonstrating compliance and the specified source term contained in the implementing documents then minimal analysis will be needed If however the licencee elects to use an alternative approach to demonstrate compliance with the criteria then significant additional analysis could be needed.
Maintenance/inspection	Yes	The way in which compliance is achieved (characteristics of the system installed) will determine the level of additional maintenance/inspection, the role of technical specifications, and need for procedures/training.
Tech Specs		
Procedures/Training		

The collective characteristics of both methods reflect the common insights gathered from plant specific PRAs, and industry experience regarding risk significance and unnecessary burden. Besides PRA insights and industry experience, the proposed alternative also exhibits the characteristics noted in Chapter 2:

- consistency with the quantitative guidelines identified in the framework document
- reasonable cost burden
- proven technology
- suitability for performance-based monitoring

The second method discussed above can be related directly to the quantitative guidelines of the framework. However, both methods clearly emphasize measures to reduce conditional probability of early and late large releases, in keeping with the framework goals.

The first method (left hand box in Figure 6.1) represents a more prescriptive approach to combustible gas control than does the second method. The first method requires either specific combustible gas control systems, or specifies fairly detailed requirements for such systems. The second method poses the combustible gas control requirements in terms of goals to be met, rather than in terms of specific measures to be implemented. In that sense, the second method is more performance based, since it relies on a measurable outcome to be achieved and provides flexibility for a licensee as to how to achieve this outcome. The second method, as described here, meets the four point test for performance based regulation: (1) it is based on measurable or calculable parameters, i.e., on conditional probabilities or on frequencies, (2) objective criteria to assess performance are established based on risk insights, deterministic analyses and/or performance history, i.e., criteria were established based on PRA insights, the TMI-2 accident, and a number of experimental programs, (3) licensees have flexibility to determine how to meet the established performance criteria in ways that will encourage and reward improved outcomes, i.e., licensees are free to use any number of means at their disposal to meet the combustible gas threat to containment integrity as long as the specified probability and/or frequency goals are met, (4) a framework exists in which the failure to meet a performance criterion, while undesirable, will not in and of itself constitute or result in an immediate safety concern, i.e., straying above the specified probability and/or frequency goals will not be an immediate cause for alarm if the situation is addressed and corrected. It should be noted, however, that method one can also be made performance based to varying degree, depending on the guidance in the implementing documents accompanying the requirements of that method.

6.2 Required Supporting Analyses

Two methods for risk-informing the existing Part 50.44 requirements are described in Section 6.1. The first method is based on modifying, eliminating or enhancing the existing requirements in the rule. The second method does not review the existing requirements, instead it derives risk-informed requirements based on the defense-in-depth strategies contained in the framework document. It is anticipated that if this risk-informed alternative is adopted that operating plants will select the first method whereas the second method may be more attractive to future reactors. However, both methods need the development of a realistic combustible gas source term. The context in which the source term will be used and the attributes of the source term are discussed in this section.

First Method

The requirements proposed in the first method were based on the three analytical requirements (i.e., a realistic combustible gas source term) described above in Section 6.1. The staff will perform supporting analyses to define a realistic combustible gas source term, which will be used by the staff to confirm the appropriateness of the proposed requirements. The calculations will use the best available calculational methods for severe accidents that include in-vessel (and ex-vessel) hydrogen and CO generation. It is anticipated that the analyses will not change any of the proposed requirements or impose new requirements on plants with Mark I or Mark II containments (provided the containment atmospheres continue to be inert during operation) or on plants with large dry or sub-atmospheric containments.

However, for plants with ice condenser or Mark III containments, if the first method is adopted then the licensees will have to provide combustible gas control during all risk significant accidents. Existing igniter systems provide effective combustible gas control but are not available during SBO sequences. SBO sequences can be addressed in the following manners:

Demonstrate SBO sequences are not risk significant (e.g., CDF<1E-5/year)

if not,
provide additional back-up power to the igniter system so that they function during an SBO.

If not,
demonstrate that containment integrity is not challenged assuming a realistic combustible gas source term.

The licensee can develop a realistic combustible gas source term or use the source term developed by the NRC.

Second Method

As noted above it is anticipated that the second method of risk-informing 10 CFR 50.44 will be more useful for future reactors. Under these circumstances it is expected that realistic combustible gas source terms will be developed by the applicant. The NRC developed source term is therefore not expected to be used and in fact may not be applicable (depending on the proposed reactor design).

However, licensees of operating plants may also use this second method for risk-informing 10 CFR 50.44. Under these circumstances the licensee could use the NRC source term or develop their own plant-specific source term.

6.3 References

1. USNRC, “Clarification of TMI Action Plan Requirements,” NUREG-0737, November 1980.