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CONTROL OF COMBUSTIBLE GAS CONCENTRATIONS IN CONTAINMENT FOLLOWING A LOSS-OF-COOLANT ACCIDENT*

A. INTRODUCTION

Criterion 35, "Emergency Core Cooling," of Appendix A, "General Design Criteria for Nuclear Power Plants," to 10 CFR Part 50, "Licensing of Production and Utilization Facilities," presently requires that a system be provided to provide abundant emergency core cooling. Criterion 50, "Containment Design Basis," presently requires that the reactor containment structure be designed to accommodate, without exceeding the design leakage rate, conditions that may result from degraded emergency core cooling functioning. Criterion 41, "Containment Atmosphere Cleanup," presently requires that systems to control hydrogen, oxygen, and other substances that may be released into the reactor containment be provided as necessary to control the concentrations of such substances following postulated accidents and ensure that containment integrity is maintained.

In addition, the Commission has published proposed amendments to Part 50 containing standards for combustible gas control systems. This guide describes methods that would be acceptable to the NRC staff for implementing the proposed regulation, assuming it is promulgated as an effective rule by the Commission after consideration of public comments, for light-water reactor plants with cylindrical, zircaloy-clad oxide fuel. Light-water reactor plants with stainless steel cladding and those with noncylindrical cladding will continue to be considered on an individual basis.

B. DISCUSSION

Following a loss-of-coolant accident (LOCA), hydrogen gas may accumulate within the containment as a result of

1. Metal-water reaction involving the zirconium fuel cladding and the reactor coolant,

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*This guide replaces Safety Guide 7, dated 3/10/71, and Supplement to Safety Guide 7, dated 10/27/71.

2. Radiolytic decomposition of the postaccident emergency cooling solutions (oxygen will also evolve in this process),

3. Corrosion of metals by solutions used for emergency cooling or containment spray.

If a sufficient amount of hydrogen is generated, it may react with the oxygen present in the containment atmosphere or, in the case of inerted containments, with the oxygen generated following the accident. The reaction would take place at rates rapid enough to lead to high temperatures and significant overpressurization of the containment, which could result in a leakage rate above that specified as a limiting condition for operation in the Technical Specifications of the license. Damage to systems and components essential to the continued control of the post-LOCA conditions could also occur.

The extent of metal-water reaction and associated hydrogen production depends strongly on the course of events assumed for the accident and on the effectiveness of emergency cooling systems. Evaluations of the performance of emergency core cooling systems (ECCS) included as engineered safety features on current light-water-cooled reactor plants have been made by reactor designers using analytical models described in the "Interim Acceptance Criteria for Emergency Core Cooling Systems for Light-Water Power Reactors" published in the Federal Register on June 29, 1971, and as amended on December 18, 1971.* These calculations are further discussed in the staff's concluding statement in the rule making hearing on the Acceptance Criteria, Docket RM-50-1.** The result of such evaluations is that, for plants of current design operated in conformance with the Interim Acceptance Criteria, the calculated metal-water reaction amounts to only a fraction of one percent of the fuel cladding mass. As a result of the rule making hearing (Docket RM-50-1), the Commission adopted regulations dealing with the effectiveness of ECCS (10 CFR Part 50, § 50.46).

The staff believes it is appropriate to consider the experience obtained from the various ECCS-related analytical studies and test programs, such as code developmental efforts, fuel densification, blowdown and core heatup studies, and the PWR and BWR FLECHT tests, and to take account of the increased conservatism for plants with ECCS evaluated under § 50.46 in setting the amount of initial metal-water reaction to be assumed for the purpose of establishing design requirements for combustible gas control systems. The staff has always separated the design bases for ECCS and for containment systems and has required such containment systems as the combustible gas

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*36 FR 12248 and 36 FR 24082.

**A copy of the docket file may be examined in the NRC public document room.

control system to be designed to withstand a more degraded condition of the reactor than the ECCS design basis permits. The approach is consistent with the provisions of General Design Criterion 50 in which the need to provide safety margins to account for the effects of degraded ECCS function is noted. Although the level of degradation considered might lead to an assumed extent of metal-water reaction in excess of that calculated for acceptable ECCS performance, it does not lead to a situation involving a total failure of the ECCS.

The staff feels that this "overlap" in protection requirements provides an appropriate and prudent safety margin against unpredicted events during the course of accidents.

Accordingly, the amount of hydrogen assumed to be generated by metal-water reaction in establishing combustible gas control system performance requirements should be based on the amount calculated in demonstrating compliance with § 50.46, but the amount of hydrogen required to be assumed should include a margin above that calculated. To obtain this margin, the assumed amount of hydrogen should be no less than five times that calculated in accordance with § 50.46.

Since the amounts of hydrogen thus determined may be quite small for many plants (as a result of the other more stringent requirements for ECCS performance in the criteria of § 50.46), it is consistent with the consideration of the potential for degraded ECCS performance discussed above to establish also a lower limit on the assumed amount of hydrogen generated by metal-water reactions in establishing combustible gas control system requirements. In establishing this lower limit, the staff has considered the fact that the maximum metal-water reaction permitted by the ECCS performance criteria is one percent of the cladding mass. Use of this "one percent of the mass" value as a lower limit for assumed hydrogen production, however, would unnecessarily penalize reactors with thicker cladding, since for the same thermal conditions in the core in a postulated LOCA, the thicker cladding would not, in fact, lead to increased hydrogen generation. This is because the hydrogen generation from metal-water reaction is a surface phenomenon. A more appropriate basis for setting the lower limit would be an amount of hydrogen assumed to be generated per unit cladding area. It is convenient to specify for this purpose a hypothetical uniform depth of cladding surface reaction. The lower limit of metal-water reaction hydrogen to be assumed is then the hypothetical amount that would be generated if all the metal to a specified depth in the outside surfaces of the cladding cylinders surrounding the fuel (excluding the cladding surrounding the plenum volume) were to react.

In selecting a specified depth to be assumed as a lower limit for all reactor designs, the staff has calculated the depth that could correspond to the "one percent of the mass" value for the current core design with the

thinnest cladding. This depth (0.01 times the thickness of the thinnest fuel cladding is used) is 0.00023 inch.

In summary, the amount of hydrogen to be generated by metal-water reaction in determining the performance requirements for combustible gas control systems should be five times the maximum amount calculated in accordance with § 50.46, but no less than the amount that would result from reaction of all the metal in the outside surfaces of the cladding cylinders surrounding the fuel (excluding the cladding surrounding the plenum volume) to a depth of 0.00023 inch.

It should be noted that the extent of initial metal-water reaction calculated for the first core of a plant and used as a design basis for the hydrogen control system becomes a limiting condition for all reload cores in that plant unless the hydrogen control system is subsequently modified and reevaluated.

The staff believes that hydrogen control systems in plants receiving operating licenses on the basis of ECCS evaluations under the "Interim Acceptance Criteria" should continue to be designed for the 5 percent initial metal-water reaction specified in the original issuance of this guide (Safety Guide 7). As operating plants are reevaluated as to ECCS performance under § 50.46, a change to the new hydrogen control basis enumerated in Table 1 may be made by appropriate amendments to the Technical Specifications of the license. For plants receiving construction permits on the basis of ECCS evaluations under the Interim Acceptance Criteria, the applicant would have the option of using either a 5 percent initial metal-water reaction or five times the maximum amount calculated in accordance with § 50.46, but no less than the amount that could result from reaction of all the metal in the outside surfaces of the cladding cylinders surrounding the fuel (excluding the cladding surrounding the plenum volume) to a depth of 0.00023 inch.

No assumption as to rate of evolution was associated with the magnitude of the assumed metal-water reaction originally given in Safety Guide 7. The metal-water reaction is of significance when establishing system performance requirements for containment designs that employ time-dependent hydrogen control features. The staff recognizes that it would be unrealistic to assume an instantaneous release of hydrogen from an assumed metal-water reaction. For the design of a hydrogen control system, therefore, it should be assumed that the initial metal-water reaction would occur over a short period of time early in the LOCA transient, i.e., near the end of the blowdown and core refill phases of the LOCA transient. Any hydrogen thus evolved would mix with steam and would be rapidly distributed throughout the containment compartments enclosing the reactor primary coolant system by steam flowing from the postulated pipe break. These compartments include the "drywell" in typical boiling water reactor containments, the

"lower volume" of ice condenser containments, and the full volume of "dry" containments. The duration of the blowdown and refill phase is generally several minutes, and the assumptions of a two-minute evolution time, which represents the period of time during which the maximum full heatup occurs, with a constant reaction rate and with the resulting hydrogen uniformly distributed in the containment compartments enclosing the primary coolant system, are appropriately conservative for the design of hydrogen control systems. The effects of steam within the subcompartments and containment should be considered in the evaluation of the mixture composition.

The rate of production of gases from radiolysis of coolant solutions depends on (1) the amount and quality of radiation energy absorbed in the specific coolant solutions used and (2) the net yield of gases generated from the solutions due to the absorbed radiation energy. Factors such as coolant flow rates and turbulence, chemical additives in the coolant, impurities, and coolant temperature can all exert an influence on the gas yields from radiolysis. The hydrogen production rate from corrosion of materials within the containment, such as aluminum, depends on the corrosion rate, which in turn depends on such factors as the coolant chemistry, the coolant pH, the metal and coolant temperatures, and the surface area exposed to attack by the coolant. Accurate values of these parameters are difficult to establish with certainty for the conditions expected to prevail following a LOCA.

Table 1 defines conservative values and assumptions that may be used to evaluate the production of combustible gases following a LOCA.

If these assumptions are used to calculate the concentration of hydrogen (and oxygen) within the containment structures of reactor plants following a LOCA, the hydrogen concentration is calculated to reach the flammable limit within periods of less than a day after the accident for the smallest containments and up to more than a month for the largest ones. The hydrogen concentration could be maintained below its lower flammable limit by purging the containment atmosphere to the environs at a controlled rate after the LOCA; however, radioactive materials in the containment would also be released. Therefore, purging should not be the primary means for controlling combustible gases following a LOCA. It is advisable, however, that the capability for controlled purging be provided to aid in containment atmosphere cleanup.

The Bureau of Mines has conducted experiments at its facilities with initial hydrogen volume concentrations on the order of 4 to 12 volume percent. On the basis of these experiments and a review of other reports, the NRC staff concludes that a lower flammability limit of 4 volume percent hydrogen in air or steam-air atmospheres is well established and is adequately conservative. For initial concentrations of hydrogen greater than about 6 volume percent, it is possible in the presence of sufficient ignition

sources that the total accumulated hydrogen could burn in the containment. For hydrogen concentrations in the range of 4 to 6 volume percent, partial burning of the excess hydrogen above 4 volume percent may occur. The staff believes that a limit of 6 volume percent would not result in effects that would be adverse to containment systems. Applicants or licensees proposing a design limit in the range of 4 to 6 volume percent hydrogen should demonstrate through supporting analyses and experimental data that containment features and safety equipment required to operate after a LOCA would not be made inoperative by the burning of the excess hydrogen.

In small containments, the amount of metal-water reaction postulated in Table 1 may result in hydrogen concentrations above acceptable limits. The evolution rate of hydrogen from the metal-water reaction would be greater than that from either radiolysis or corrosion, and since it is difficult for a hydrogen control system to process large volumes of hydrogen very rapidly, an alternative approach is to operate some of the smaller containments with inert (oxygen-deficient) atmospheres. This measure, the "inerting" of a containment, provides sufficient time for combustible gas control systems to become effective following a LOCA before a flammable mixture is reached in the containment. Hydrogen recombiners can process the containment atmosphere at a rate of only 100 scfm per recombiner. Therefore, for a 300,000 cubic foot containment with a 13 volume percent hydrogen concentration that was generated in the first two minutes of the LOCA, an inordinately larger number of recombiners would be required. There are presently no other methods of combustible gas control except for purge systems, which release radioactive materials.

For all containments, it is advisable to provide means by which combustible gases resulting from the postulated metal-water reaction, radiolysis, and corrosion following a LOCA can be mixed, sampled, and controlled without releasing radioactive materials to the environment.

Since any system for combustible gas control is designated for the protection of the public in the event of an accident, the system should meet the design and construction standards of engineered safety features. Care should be taken in its design to ensure that the system itself does not introduce safety problems that may affect containment integrity; for example, if a flame recombiner is used, propagation of flame into the containment should be prevented.

In most reactor plants, the hydrogen control system would not be required to be operated for seven days or more following a postulated design basis LOCA. Thus, it is reasonable that hydrogen control systems need not necessarily be installed at each reactor. Provision for either onsite or offsite storage or a shared arrangement between licensees of plants in close proximity to each other may be developed. An example of an acceptable arrangement would be to provide at least one hydrogen control

system per site with the provision that a redundant unit would be available from a nearby site.

C. REGULATORY POSITION

1. Each boiling or pressurized light-water nuclear power reactor fueled with uranium oxide pellets within cylindrical zircaloy cladding should have the capability to measure the hydrogen concentration in the containment, mix the atmosphere in the containment, and control combustible gas concentrations without relying on purging of the containment atmosphere following a LOCA.

2. The continuous presence of redundant combustible gas control equipment at the site may not be necessary provided it is available on an appropriate time scale. However, appropriate design and procedural provisions should be made for its use. In addition, centralized storage facilities that would serve multiple sites may be used, provided these facilities include provisions such as maintenance, protective features, testing, and transportation for redundant units to a particular site.

3. Combustible gas control systems and the provisions for mixing, measuring, and sampling should meet the design, quality assurance, redundancy, energy source, and instrumentation requirements for an engineered safety feature. In addition, the system itself should not introduce safety problems that may affect containment integrity. The combustible gas control system should be designated Seismic Category I (see Regulatory Guide 1.29, "Seismic Design Classification"), and the Group B quality standards of Regulatory Guide 1.26, "Quality Group Classifications and Standards for Water-, Steam-, and Radioactive-Waste-Containing Components of Nuclear Power Plants," should be applied.

4. All water-cooled power reactors should also have the installed capability for a controlled purge of the containment atmosphere to aid in cleanup. The purge or ventilation system may be a separate system or part of an existing system. It need not be redundant or be designated Seismic Category I (see Regulatory Guide 1.29), except insofar as portions of the system constitute part of the primary containment boundary or contain filters.

5. The parameter values listed in Table 1 should be used in calculating hydrogen and oxygen gas concentrations in containments and evaluating designs provided to control and to purge combustible gases evolved in the course of loss-of-coolant accidents. These values may be changed on the basis of additional experimental evidence and analyses.

6. Materials within the containment that would yield hydrogen gas due to corrosion from the emergency cooling or containment spray solutions should be identified, and their use should be limited as much as practical.

D. IMPLEMENTATION

This guide will be used by the staff in the evaluation of licensees' and applicants' compliance with the specified portions of the Commission's regulations, including the proposed § 50.44 when it is adopted as an effective regulation. If the proposed regulations are not adopted or are adopted in substantially different form, this guide will be withdrawn or appropriately revised.

Table 1. Acceptable Assumptions for Evaluating the Production of Combustible Gases Following a Loss-of-Coolant Accident (LOCA)

Parameter	Acceptable Value
Fraction of fission product radiation energy absorbed by the coolant*	(a) Beta (1) Betas from fission products in the fuel rods: 0 (2) Betas from fission products intimately mixed with coolant: 1.0 (b) Gamma (1) Gammas from fission products in the fuel rods, coolant in core region: 0.1** (2) Gammas from fission products intimately mixed with coolant, all coolant: 1.0
Hydrogen yield rate $G(H_2)$	0.5 molecule/100Ev
Oxygen yield rate $G(O_2)$	0.25 molecule/100Ev
Extent and evolution time of initial core metal-water reaction hydrogen production from the cladding surrounding the fuel	Hydrogen production is 5 times the extent of the maximum calculated reaction under 10 CFR Part 50, §50.46, or that amount that would be evolved from a core-wide average depth of reaction into the original cladding of 0.00023 inch, whichever is greater, in 2 minutes.
Aluminum corrosion rate for aluminum exposed to alkaline solutions	200 mils/yr (This value should be adjusted upward for higher temperatures early in the accident sequence.)
Fission product distribution model	50% of the halogens and 1% of the solids present in the core are intimately mixed with the coolant water.

Table 1 (Continued)

Parameter	Acceptable Value
	All noble gases are released to the containment. All other fission products remain in fuel rods.
Hydrogen concentration limit	4 v/o***
Oxygen concentration limit	5 v/o (This limit should not be exceeded if more than 6 v/o hydrogen is present.)

*For water, borated water, and borated alkaline solutions; for other solutions, data should be presented.

**This fraction is thought to be conservative; further analysis may show that it should be revised.

***The 4 v/o hydrogen concentration limit should not be exceeded if burning is to be avoided and if more than 5 v/o oxygen is present in the containment.

This amount may be increased to 6 v/o, with the assumption that the 2 v/o excess hydrogen would burn in the containment (if more than 5 v/o oxygen is present). The effects of the resultant energy and burning should not create conditions exceeding the design conditions of either the containment or the safety equipment necessary to mitigate the consequences of a LOCA. Applicants and licensees should demonstrate such capability by suitable analyses and qualification test results.