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OFFICE OF SECRETARY
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ADJUDICATIONS STAFF

Via Electronic Mail

October 14, 2011

Annette L. Vietti-Cook, Secretary
U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001
Attention: Rulemakings and Adjudications Staff

Subject: NRDC's Petition for Rulemaking to revise 10 C.F.R. § 50.44

Dear Madam Secretary:

Pursuant to 10 C.F.R. § 2.802, the Natural Resources Defense Council, Inc. ("NRDC") hereby petitions the U.S. Nuclear Regulatory Commission ("NRC") to institute a rulemaking to amend the regulations applicable to nuclear facilities licensed under 10 C.F.R. § 50, § 52, § 100 and other applicable regulations.

The rationale and the bases for this petition can be found in the enclosed materials, which cite numerous reports and studies that illustrate the need for requiring measures to effectively measure and control combustible gas generation and dispersal within a reactor system. The petition research and authoring was conducted by NRDC consultant Mark Leyse.

Please do not hesitate to contact us at (202) 289-6868 if you have any questions. NRDC appreciates your prompt consideration of this matter.

Sincerely,

C. Jordan Weaver, Ph.D.
Project Scientist

Template = SECY-051

DS10

October 14, 2011

Annette L. Vietti-Cook
Secretary
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PETITION FOR RULEMAKING

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PETITION FOR RULEMAKING

I. NEEDED REGULATIONS

This petition for rulemaking is submitted pursuant to 10 C.F.R. § 2.802 by Natural Resources Defense Council ("NRDC").[1]

First, NRDC (hereinafter "Petitioner") requests that United States Nuclear Regulatory Commission ("NRC") revise 10 C.F.R. § 50.44 to require that all pressurized water reactors ("PWR") (with large dry containments, sub-atmospheric containments, and ice condenser containments) and boiling water reactor ("BWR") Mark IIIs operate with systems for combustible gas control that would effectively and safely control the potential *total* quantity of hydrogen that could be generated in different severe accident scenarios (this value is different for PWRs and BWRs), which could exceed the quantity of hydrogen generated from a metal-water reaction of 100 percent of the fuel cladding active length because of significant contributions to the total quantity of hydrogen produced by oxidation of non-fuel components of the reactor, including steel components. Systems for combustible gas control also must effectively and safely control the potential *total* quantity of hydrogen that could be generated *at all times* throughout different severe accident scenarios, taking into account the potential *rates* of hydrogen production.

Second, Petitioner requests that NRC revise 10 C.F.R. § 50.44 to require that BWR Mark Is and BWR Mark IIs operate with systems for combustible gas control or inerted containments that would effectively and safely control the potential *total* quantity of hydrogen that could be generated in different severe accident scenarios, which could exceed the quantity of hydrogen generated from a metal-water reaction of 100 percent of the fuel cladding active length. Systems for combustible gas control or inerted containments also must effectively and safely control the potential *total* quantity of

[1] Mark Leyse wrote this 10 C.F.R. § 2.802 petition for NRDC.

hydrogen that could be generated *at all times* throughout different severe accident scenarios, taking into account the potential *rates* of hydrogen production.

Third, Petitioner requests that NRC revise 10 C.F.R. § 50.44 to require that all PWRs and BWR Mark IIIs operate with systems for combustible gas control that would be capable of precluding local concentrations of hydrogen in the containment from exceeding concentrations that would support combustions, fast deflagrations, or detonations that could cause a loss of containment integrity or loss of necessary accident mitigating features.

Fourth, Petitioner requests that NRC revise 10 C.F.R. § 50.44 to require that all PWRs and BWR Mark IIIs operate with combustible gas and oxygen monitoring systems that are qualified in accordance with 10 C.F.R. § 50.49. Petitioner also requests that NRC revise 10 C.F.R. § 50.44 to require that after the onset of a severe accident, combustible gas monitoring systems be functional within a timeframe that enables the proper monitoring of quantities of hydrogen indicative of core damage and indicative of a potential threat to the containment integrity. The current requirement that hydrogen monitors be functional within 90-minutes after the initiation of safety injection is inadequate for protecting public and plant worker safety.

Fifth, Petitioner requests that NRC revise 10 C.F.R. § 50.44 to require that licensees of PWRs and BWR Mark IIIs perform analyses that demonstrate containment structural integrity would be retained in the event of a severe accident. Such analyses must use the most advanced codes, such as computational fluid dynamics ("CFD") codes, to model hydrogen distribution in the containment and loads from flame acceleration ("FA") as well as include sufficient supporting justification to show that the simulation realistically models the containment response to the structural loads involved. Petitioner also requests that NRC revise 10 C.F.R. § 50.44 to require that licensees of BWR Mark Is and BWR Mark IIs perform analyses (*e.g.*, modeling the performance of inerted containments), using the most advanced codes, which demonstrate containment structural integrity would be retained in the event of a severe accident. Such analyses must address severe accidents that release the potential *total* quantity of hydrogen that could be generated in different scenarios (this value is different for PWRs and BWRs), which could exceed the quantity of hydrogen generated from a metal-water reaction of 100 percent of the fuel cladding active length. Such analyses must also consider the potential *total* quantity of hydrogen that could be generated *at all times* throughout different severe accident scenarios, taking into account the potential *rates* of hydrogen production. Systems necessary to ensure containment integrity must also be demonstrated to perform their function under these conditions.

Sixth, Petitioner requests that NRC revise 10 C.F.R. § 50.44 to require that licensees of PWRs with ice condenser containments and BWR Mark IIIs (and any other nuclear power plants ("NPP") that would operate with hydrogen igniter systems) perform analyses that demonstrate hydrogen igniter systems would effectively and *safely* mitigate hydrogen in different severe accident scenarios.

II. STATEMENT OF PETITIONER'S INTEREST

Petitioner is a national non-profit membership environmental organization with offices in Washington, D.C., New York City, San Francisco, Chicago, Los Angeles, and Beijing. Petitioner has a nationwide membership of over one million combined members and activists. Petitioner's activities include maintaining and enhancing environmental quality and monitoring federal agency actions to ensure that federal statutes enacted to protect human health and the environment are fully and properly implemented. Since its inception in 1970, Petitioner has sought to improve the environmental, health, and safety conditions at the nuclear facilities licensed by NRC and its predecessor agency.

III. BACKGROUND

NRC Policy Statement, "Combustible Gas Control in Containment," states that "[the] requirements [for "future water-cooled reactors with the same potential for the production of combustible gas as currently-licensed light-water reactor designs"[2]] reflect the Commission's expectation that future designs will achieve a higher standard of severe accident performance,"[3, 4] and that "[a]dditional advantages of providing hydrogen

[2] NRC Policy Statement, "Combustible Gas Control in Containment," Federal Register, Vol. 68, No. 179, September 16, 2003, p. 54128.

[3] NRC Policy Statement, "Severe Reactor Accidents Regarding Future Designs and Existing Plants," Federal Register, Vol. 50, August 8, 1985

control mitigation features (rather than reliance on random ignition of richer mixtures) include the lessening of pressure and temperature loadings on the containment and essential equipment."[5]

Petitioner believes that current NPPs regulated by NRC also need to achieve a higher standard of severe accident performance. Given the fact that hydrogen explosions damaged primary and secondary BWR Mark I containment structures in the Fukushima Dai-ichi accident, it would seem appropriate to enhance hydrogen mitigation at all NPPs regulated by NRC. This 10 C.F.R. § 2.802 petition requests regulations that would help NRC achieve a higher standard of severe accident performance for all NPPs.

A. NRC's Current Regulations for Different Types of NPPs, Regarding Mitigating the Hydrogen that would be Generated in a Severe Accident and the Design Pressures and Estimates of the Failure Pressures of Different Types of NPP Containments

In this section Petitioner provides information on NRC's current regulations for different types of NPPs, regarding mitigating the hydrogen that would be generated in the event of a severe accident and provides information on the design pressures and estimates of the failure pressures of different types of NPP containments.

1. NRC does not Require PWRs with Large Dry Containments or Sub-Atmospheric Containments to Mitigate the Hydrogen that would be Generated in a Severe Accident

NRC does not require PWRs with large dry containments or sub-atmospheric containments ("a sub-atmospheric variation of the large dry containment"[6]) to have any means to effectively mitigate the hydrogen that would be generated in the event of a severe accident. If there were a severe accident at a PWR with a large dry containment or

[4] NRC Policy Statement, "Combustible Gas Control in Containment," Federal Register, Vol. 68, No. 179, p. 54128.
[5] *Id.*
[6] M. F. Hessheimer, *et al.*, Sandia National Laboratories, "Containment Integrity Research at Sandia National Laboratories: An Overview," NUREG/CR-6906, July 2006, available at: www.nrc.gov, NRC Library, ADAMS Documents, Accession Number: ML062440075, p. 6 (hereinafter "Containment Integrity Research at SNL").

sub-atmospheric containment, it is highly likely that there would be hydrogen combustion in the form of a deflagration[7] or a detonation.[8]

In the Three Mile Island Unit 2 ("TMI-2") accident, a rapid pressure increase of approximately 28 psi in the containment[9] was attributed to the combustion of hydrogen in the form of a deflagration that was most likely caused by an electric spark;[10] the deflagration may have even been initiated by a ringing telephone.[11] In the TMI-2 accident, "the hydrogen burn...resulted from a hydrogen concentration of 8.1 volume percent."[12]

For PWRs with large dry containments or sub-atmospheric containments, it is highly unlikely that a hydrogen deflagration in the containment that caused a rapid pressure increase of approximately 28 psi would cause a breach in the containment. However, it is entirely possible that in the event of a severe accident at a PWR with a large dry containment or sub-atmospheric containment, that a hydrogen deflagration or detonation could cause a rapid pressure increase in the containment that exceeded 28 psi.

2. Design Pressures and Estimates of the Failure Pressures of PWR Large Dry Containments and PWR Sub-Atmospheric Containments

According to a Sandia National Laboratories ("SNL") report, "Containment Integrity Research at Sandia National Laboratories: An Overview," the typical design pressure of PWR large dry containments is 53 psig and the typical design pressure of

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[7] A deflagration is a combustion wave traveling at a subsonic speed, relative to the unburned gas. A subsonic speed is a speed that is less than the speed of sound.

[8] A detonation is a combustion wave traveling at a supersonic speed, relative to the unburned gas. A supersonic speed is a speed that is greater than the speed of sound.

[9] W. E. Lowry, *et al.*, Lawrence Livermore National Laboratory, "Final Results of the Hydrogen Igniter Experimental Program," NUREG/CR-2486, February 1982, p. 4.

[10] E. Studer, *et al.*, Kurchatov Institute, "Assessment of Hydrogen Risk in PWR," [undated], p. 1.

[11] OECD Nuclear Energy Agency, "State-of-the-Art Report on Flame Acceleration and Deflagration-to-Detonation Transition in Nuclear Safety," NEA/CSNI/R(2000)7, August 2000, available at: www.nrc.gov, NRC Library, ADAMS Documents, Accession Number: ML031340619, p. 1.2 (hereinafter "Report on FA and DDT").

[12] Kahtan N. Jabbour, NRC, letter regarding Turkey Point Units 3 and 4, Exemption from Hydrogen Control Requirements, December 12, 2001, Attachment 2, "Safety Evaluation by the Office of Nuclear Reactor Regulation, Turkey Point Units 3 and 4," available at: www.nrc.gov, NRC Library, ADAMS Documents, Accession Number: ML013390647, p. 4.

PWR sub-atmospheric containments is 52 psig.[13] Additionally, according to the same SNL report, the estimated containment failure pressure of Zion (which has been permanently shutdown[14]), a PWR with a large dry containment, is between 108 and 180 psig and the estimated containment failure pressure of Surry, a PWR with a sub-atmospheric containment, is between 95 and 150 psig.[15]

Regarding the estimated containment failure pressure of Zion, in more detail, "Containment Integrity Research at SNL" states that for Zion, at the 5th percentile the failure pressure is 108 psig, at the 50th percentile the failure pressure is approximately 135 psig, and at the 95th percentile the failure pressure is 180 psig.[16] Regarding the estimated containment failure pressure of Surry, in more detail, "Containment Integrity Research at SNL" states that for Surry, at the 5th percentile the failure pressure is 95 psig, at the 50th percentile the failure pressure is approximately 130 psig, and at the 95th percentile the failure pressure is 150 psig.[17]

Below are examples of the containment failure pressures of different PWRs that were estimated in the respective licensees' plant-specific containment integrity analyses:

1) The design pressures of Indian Point Units 2 and 3's ("IP-2 and -3") containments are 47 psig;[18] and the failure pressures of IP-2 and -3's containments are estimated to be 126 psig.[19]

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[13] M. F. Hessheimer, *et al.*, "Containment Integrity Research at SNL," NUREG/CR-6906, p. 24.
[14] To avoid confusion this 10 C.F.R. § 2.802 petition will refer to Zion in the present tense as if it were still in operation, because Zion's containment failure pressure was estimated in NUREG-1150 and this petition refers to that estimate.
[15] M. F. Hessheimer, *et al.*, "Containment Integrity Research at SNL," NUREG/CR-6906, p. 29; the source of this information is NRC, "Severe Accident Risks: An Assessment or Five U.S. Nuclear Power Plants," NUREG-1150, December 1990 (hereinafter "NUREG-1150").
[16] *Id.*, p. 28; the source of this information is NRC, NUREG-1150.
[17] *Id.*; the source of this information is NRC, NUREG-1150.
[18] Entergy, "Technical Facts: Indian Point Unit 2, Plant Specific Information," available at: http://www.entergy-nuclear.com/content/resource_library/IPEC_EP/TechnicalFacts2.pdf (last visited August 14, 2011); and Entergy, "Technical Facts: Indian Point Unit 3, Plant Specific Information," available at: http://www.entergy-nuclear.com/content/resource_library/IPEC_EP/TechnicalFacts3.pdf (last visited August 14, 2011).
[19] Power Authority of the State of New York, Consolidated Edison Company of New York, "Indian Point Probabilistic Safety Study," Vol. 8, 1982, available at: www.nrc.gov, NRC Library, ADAMS Documents, Accession Number: ML102520201, p. 4.2-1 and Appendix 4.4.1, p. 14.

2) The design pressures of Calvert Cliffs Units 1 and 2's ("CC-1 and -2") containments are 50 psig; and the failure pressures of CC-1 and -2's containments are estimated to be 132 psig.[20]

3) The failure pressure of Three Mile Island Unit 1's ("TMI-1") containment is estimated to be between 137 psig and 147 psig.[21]

4) The failure pressures of Oconee Units 1, 2, and 3's containments are estimated to be 140 psig.[22]

5) The failure pressures of Turkey Point Units 3 and 4's ("TP-2 and -3") containments are estimated to be 145 psig.[23]

3. NRC Requires PWRs with Ice Condenser Containments and BWR Mark IIIs to Mitigate the Hydrogen that would be Generated from a Metal-Water Reaction of 75 Percent of the Fuel Cladding Active Length in a Severe Accident

The containment design pressures and estimated containment failure pressures of PWRs with ice condenser containments and BWR Mark IIIs are lower than those of PWRs with large dry containments or sub-atmospheric containments, so NRC requires that PWRs with ice condenser containments and BWR Mark IIIs operate with systems for combustible gas control that would effectively and safely control the quantity of hydrogen that would be generated from a metal-water reaction of 75 percent of the fuel cladding active length. Hydrogen igniter systems have been installed in the containments

[20] Peter E. Katz, Constellation Energy Group, letter regarding Calvert Cliffs Units 1 and 2, Request for Exemption to 10 CFR 50.44, Etc., March 28, 2003, Attachment 1, available at: www.nrc.gov, NRC Library, ADAMS Documents, Accession Number: ML030930055, p. 2.

[21] T. G. Colburn, NRC, letter regarding Three Mile Island Unit 1, license amendment from hydrogen control requirements, February 8, 2002, Attachment 2, "Safety Evaluation by the Office of Nuclear Reactor Regulation, Related to Amendment No. 240 to Facility Operating License No. DPR-50, Three Mile Island Unit 1," available at: www.nrc.gov, NRC Library, ADAMS Documents, Accession Number: ML020100578, p. 5.

[22] D. E. LaBarge, NRC, letter regarding Oconee Units 1, 2, and 3, Exemption from Hydrogen Control Requirements, July 17, 2001, Attachment 2, "Safety Evaluation by the Office of Nuclear Reactor Regulation, Hydrogen Recombiner Exemption, Oconee Units 1, 2, and 3," available at: www.nrc.gov, NRC Library, ADAMS Documents, Accession Number: ML011710267, p. 3.

[23] Kahtan N. Jabbour, NRC, letter regarding Turkey Point Units 3 and 4, Exemption from Hydrogen Control Requirements, December 12, 2001, Attachment 2, "Safety Evaluation by the Office of Nuclear Reactor Regulation, Turkey Point Units 3 and 4," p. 3.

of PWRs with ice condenser containments and BWR Mark IIIs in order to mitigate the hydrogen that would be generated in the event of a severe accident.

Regarding the deliberate ignition concept for PWRs with ice condenser containments and BWR Mark IIIs, "Light Water Reactor Hydrogen Manual" states:

> A typical Mark III BWR containment contains approximately 1.5 million cubic feet of free air volume. If one assumes a metal-water reaction similar to the one believed to have occurred at TMI-2, the resultant deflagration (or possible detonation) in a containment of this volume might challenge the containment integrity. Since the PWR ice condenser containment free air volume and design pressure (about 15 psig) are similar to those of the Mark III containment, the same type of concern exists for it. Hence, for these containment designs, the deliberate ignition concept has become an attractive scheme to mitigate the consequences of possible metal-water reactions that could take place during a LOCA.[24]

The integrity of a PWR ice condenser containment or BWR Mark III containment could be compromised by a hydrogen deflagration of the same magnitude of the deflagration that occurred in the TMI-2 accident. In the TMI-2 accident, the hydrogen deflagration "resulted from a hydrogen concentration of 8.1 volume percent"[25] and caused a rapid pressure increase of approximately 28 psi in the containment.[26]

Of course, it is entirely possible that in the event of a severe accident that a hydrogen deflagration or detonation could cause a rapid pressure increase in a containment that exceeded 28 psi. There is also no reason to believe that the quantity of hydrogen generated in a severe accident would either be limited to the quantity that was generated in the TMI-2 accident or limited to the quantity of hydrogen that would be generated from a metal-water reaction of 75 percent of the fuel cladding active length.

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[24] Allen L. Camp, *et al.*, Sandia National Laboratories, "Light Water Reactor Hydrogen Manual," NUREG/CR-2726, August 1983, p. 4-107.

[25] Kahtan N. Jabbour, NRC, letter regarding Turkey Point Units 3 and 4, Exemption from Hydrogen Control Requirements, December 12, 2001, Attachment 2, "Safety Evaluation by the Office of Nuclear Reactor Regulation, Turkey Point Units 3 and 4," p. 4.

[26] W. E. Lowry, *et al.*, "Final Results of the Hydrogen Igniter Experimental Program," NUREG/CR-2486, p. 4.

4. Design Pressures and Estimates of the Failure Pressures of PWR Ice Condenser Containments and BWR Mark III Containments

According to "Containment Integrity Research at SNL," the typical design pressure of PWR ice condenser containments is 20 psig and the typical design pressure of BWR Mark III containments is 15 psig.[27] Additionally, according to the same SNL report, the estimated containment failure pressure of Sequoyah, a PWR with a ice condenser containment, is between 40 and 95 psig and the estimated containment failure pressure of Grand Gulf, a BWR Mark III, is between 38 and 72 psig; and the estimated failure pressure of Grand Gulf's drywell is between 50 and 120 psig.[28]

Regarding the estimated containment failure pressure of Sequoyah, in more detail, "Containment Integrity Research at SNL" states that for Sequoyah, at the 5th percentile the failure pressure is 40 psig, at the 50th percentile the failure pressure is approximately 67 psig, and at the 95th percentile the failure pressure is 95 psig.[29] And regarding the estimated containment failure pressure of Grand Gulf, in more detail, "Containment Integrity Research at SNL" states that for Grand Gulf, at the 5th percentile the failure pressure is 38 psig, at the 50th percentile the failure pressure is approximately 52 psig, and at the 95th percentile the failure pressure is 72 psig; and for Grand Gulf's drywell, at the 5th percentile the failure pressure is 50 psig, at the 50th percentile the failure pressure is approximately 87 psig, and at the 95th percentile the failure pressure is 120 psig.[30]

5. NRC's Current Regulation for BWR Mark Is and BWR Mark IIs, Regarding Mitigating the Hydrogen that would be Generated in a Severe Accident, the Design Pressures of BWR Mark Is and IIs, and Estimated Failure Pressures of BWR Mark Is

NRC requires that BWR Mark Is and BWR Mark IIs operate with containments that have an inerted atmosphere. An inerted containment atmosphere is an atmosphere with less than four percent oxygen by volume.

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[27] M. F. Hessheimer, *et al.*, "Containment Integrity Research at SNL," NUREG/CR-6906, p. 24.
[28] *Id.*, p. 29; the source of this information is NRC, NUREG-1150.
[29] *Id.*, p. 28; the source of this information is NRC, NUREG-1150.
[30] *Id.*; the source of this information is NRC, NUREG-1150.

According to "Containment Integrity Research at SNL," the typical design pressure of BWR Mark I containments is 58 psig and the typical design pressure of BWR Mark II containments is 50 psig.[31] Additionally, according to the same SNL report, the estimated containment failure pressure of Peach Bottom, a BWR Mark I, in cases without the effects of high temperatures, is between 120 and 174 psig; in a case in which the drywell temperature reaches 800°F, the estimated failure pressure is between 75 and 150 psig; and in a case in which the drywell temperature reaches 1200°F, the estimated failure pressure is between 6 and 67 psig.[32]

("Containment Integrity Research at SNL" does not provide information on the estimated containment failure pressure of a BWR Mark II.)

Regarding the estimated containment failure pressure of Peach Bottom, in more detail, "Containment Integrity Research at SNL" states that for Peach Bottom, in cases without the effects of high temperatures, at the 5th percentile the failure pressure is 120 psig, at the 50th percentile the failure pressure is approximately 148 psig, and at the 95th percentile the failure pressure is 174 psig; in a case in which the drywell temperature reaches 800°F, at the 5th percentile the failure pressure is 75 psig, at the 50th percentile the failure pressure is approximately 124 psig, and at the 95th percentile the failure pressure is 150 psig; and in a case in which the drywell temperature reaches 1200°F, at the 5th percentile the failure pressure is 6 psig, at the 50th percentile the failure pressure is approximately 52 psig, and at the 95th percentile the failure pressure is 67 psig.[33]

6. The Accuracy of Containment Failure Pressure Estimates is Questionable

The estimates of containment failure pressures for Zion, Surry, and other NPPs that "Containment Integrity Research at SNL" discusses were originally conducted for "Severe Accident Risks: An Assessment or Five U.S. Nuclear Power Plants," NUREG-1150.

[31] *Id.*, p. 24.
[32] *Id.*, p. 29; the source of this information is NRC, NUREG-1150.
[33] *Id.*, p. 28; the source of this information is NRC, NUREG-1150.

"Containment Integrity Research at SNL" provides a quote regarding a review comment on NUREG-1150 that questions the ability to accurately estimate containment failure pressure.

The review comment states:

> Experimental data on the ultimate potential strength of containment buildings and their failure modes are lacking. This lack of data renders questionable the methods used in draft NUREG-1150 for assigning probabilities and locations of failure.[34]

One of the authors of NUREG-1150 responded:

> The present data on the potential strength of containment structures under severe accident loadings and the potential modes of failure are limited...[35]

Therefore, it is important to remember that estimates of containment failure pressure are not necessarily accurate.

B. Calculations of the Pressure Loads Resulting from Combustion of the Quantity of Hydrogen Produced from a Metal-Water Reaction of 100 Percent of the Fuel Cladding Active Length Indicate that PWR Containments could Fail

In this section Petitioner discusses the results of analyses of the pressure loads that the containments of different PWRs could incur in the event of severe accidents, in which there would be hydrogen deflagrations from the quantity of hydrogen produced from a metal-water reaction of either 75 percent or 100 percent of the active fuel cladding length.

These analyses were done for different PWRs, which have containments with different free volumes and different quantities of fuel cladding (active length) in their cores; these PWRs would also have different containment failure pressures. Therefore, the results of these analyses do not directly apply to all PWRs. However, the results of these analyses can still be used to provide a general idea of the magnitude of the pressure loads that PWR containments might be expected to incur if a hydrogen deflagration or detonation were to occur in a the event of a severe accident, in which there was a quantity

[34] *Id.*, p. 28.
[35] *Id.*

of hydrogen produced from a metal-water reaction of either 75 percent or 100 percent of the active fuel cladding length.

Discussing calculations of the adiabatic isochoric complete combustion ("AICC") pressure[36] loads that could possibly compromise the large dry containment of a French PWR, an IAEA report, published July 2011, "Mitigation of Hydrogen Hazards in Severe Accidents in Nuclear Power Plants," states:

> A typical example of pressure loads is given in ["Hydrogen Behaviour and Mitigation in Water-Cooled Nuclear Power Reactors"],[37] which indicates the AICC pressure loads on the large dry containments of French PWRs (with no [passive autocatalytic recombiners ("PAR")] applied). The pressure loads resulting from hydrogen deflagration vary about 6.2–6.5 [bar (89.9-94.3 psi)] for 75% active cladding length and about 7.7–8 [bar (111.7-116 psi)] for 100% active cladding length.
>
> *It should be noted that these loads do not include any consideration of flame acceleration or [deflagration-to-detonation transition ("DDT")]*; if such processes are taken into account, higher loads may result [emphasis added].[38]

Regarding containment failure and different types of containment failure, "Mitigation of Hydrogen Hazards in SA" states:

> If the loads exceed the design strength, the containment may fail. Usually, the containment has a considerable margin to failure, so that damage will first occur at higher loads. ... [T]he containment will not fail unless exposed to loads about 1.5-2.0 larger than the design loads.
>
> The failure mechanism can be of [a] different nature. As the containment exists of a main structure plus a number of penetrations (hatches, pipe and cable penetrations), failure may either be a gross failure of the containment or a failure of one or more of the penetrations. Concrete containments often show initiation of cracks as the first indication of

[36] The AICC pressure is often termed the Constant Volume Explosion Pressure. See M. P. Sherman, S. R. Tieszen, W. B. Benedick, SNL, "FLAME Facility: The Effect of Obstacles and Transverse Venting on Flame Acceleration and Transition to Detonation for Hydrogen-Air Mixtures at Large Scale," NUREG/CR-5275, April 1989, available at: www.nrc.gov, NRC Library, ADAMS Documents, Accession Number: ML071700076, p. 6.
[37] E. D. Loggia, "Hydrogen Behaviour and Mitigation in Water-Cooled Nuclear Power Reactors," European Commission, EUR 14039, 1992.
[38] IAEA, "Mitigation of Hydrogen Hazards in Severe Accidents in Nuclear Power Plants," IAEA-TECDOC-1661, July 2011, p. 61 (hereinafter "Mitigation of Hydrogen Hazards in SA").

failure. If the cracks are large enough, they will prevent gross containment failure.[39]

"Mitigation of Hydrogen Hazards in SA" also states:

Containment failure is often represented in a probability curve: the higher the pressure the larger the probability of failure, see Fig. 17 [Failure Probability of the Containment as a Function of the Pressure]. That is to say, once combustion loads are known, it is possible to calculate the failure probability of the containment.[40]

Fig. 17 of "Mitigation of Hydrogen Hazards in SA" is a chart with a curve illustrating that the failure probability of a containment is 80 percent when the absolute pressure reaches approximately 8 bar (116 psi),[41] which is the same value calculated to possibly result from the pressure loads caused by a hydrogen deflagration of the quantity of hydrogen generated from a metal-water reaction of 100 percent of the fuel cladding active length.[42]

There are also calculations of the pressure loads that could result from the quantity of hydrogen generated from a metal-water reaction of 100 percent of the fuel cladding active length that indicate that American PWR containments could fail.

Regarding the high pressures that could result from hydrogen combustion, an NRC document regarding TMI-1 states:

The NRC staff estimates the pressure for an adiabatic and complete hydrogen burn involving up to 75 percent core metal-water reaction to be 94 psig. ... For sequences involving up to 100 percent core metal-water reaction, the NRC staff estimated a pressure of 114 psig.[43]

Describing the calculations the same NRC document regarding TMI-1 states:

The NRC staff used the methodology in Section 2.6 of NUREG/CR-5662, "Hydrogen Combustion, Control, and Value-Impact Analysis for PWR Dry Containments," June 1991; assumed a containment free volume of 61,200 cubic meters [2.16×10^6 ft^3], and assumed the inventory of

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[39] *Id.*, pp. 60-61.
[40] *Id.*, p. 61.
[41] *Id.*
[42] *Id.*
[43] T. G. Colburn, NRC, letter regarding Three Mile Island Unit 1, license amendment from hydrogen control requirements, February 8, 2002, Attachment 2, "Safety Evaluation by the Office of Nuclear Reactor Regulation, Related to Amendment No. 240 to Facility Operating License No. DPR-50, Three Mile Island Unit 1," p. 5.

zirconium in the core to be 18,700 [kilograms ("kg")], to estimate the pressure.[44]

The two passages above most likely are intended to pertain to metal-water reactions of 75 percent and 100 percent of the fuel cladding *active length*, excluding the cladding surrounding the plenum volume. For one thing, a different document regarding the same TMI-1 issue states that "NUREG/CR-5662 (1991) reports the computed containment peak pressure due to [a] global hydrogen burn based on *a 75% fuel cladding metal-water reaction*... [emphasis added]"[45]

It would definitely be a cause for concern if the TMI-1 containment were to incur a pressure load of either 94 psig or 114 psig, in the event of a severe accident. Yet calculations for other PWRs indicate the possibility that their containments could incur even higher pressure loads in severe accidents.

Regarding the high pressures that could result from hydrogen combustion, an NRC document regarding Oconee Units 1, 2, and 3 states:

> Table 2.6.1 of NUREG/CR-5662, "Hydrogen Combustion, Control, and Value-Impact Analysis for PWR Dry Containments," June 1991, estimates the pressure for an adiabatic and complete hydrogen burn involving up to 75 percent core metal-water reaction to be 105 psig. ... For sequences involving up to 100 percent core metal-water reaction, Table 2.6.1 estimated a pressure of 129 psig.[46]

Additionally, regarding the high pressures that could result from hydrogen combustion, an NRC document regarding Turkey Point Units 3 and 4 states:

> The staff estimates the pressure for an adiabatic and complete hydrogen burn involving up to 75 percent core metal-water reaction to be 109 psig. ... For sequences involving up to 100 percent core metal-water reaction, the staff estimates a pressure of 135 psig.[47]

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[44] *Id.*

[45] Mark E. Warner, AmerGen Energy Company, letter regarding Three Mile Island Unit 1, Request for Exemption to 10 CFR 50.44, Etc., Attachment 1, available at: www.nrc.gov, NRC Library, ADAMS Documents, Accession Number: ML003756521, p. 6.

[46] D. E. LaBarge, NRC, letter regarding Oconee Units 1, 2, and 3, Exemption from Hydrogen Control Requirements, July 17, 2001, Attachment 2, "Safety Evaluation by the Office of Nuclear Reactor Regulation, Hydrogen Recombiner Exemption, Oconee Units 1, 2, and 3," pp. 3-4.

[47] Kahtan N. Jabbour, NRC, letter regarding Turkey Point Units 3 and 4, Exemption from Hydrogen Control Requirements, December 12, 2001, Attachment 2, "Safety Evaluation by the Office of Nuclear Reactor Regulation, Turkey Point Units 3 and 4," p. 3.

Describing the calculations the same NRC document regarding Turkey Point Units 3 and 4 states:

> The staff is using the methodology in Section 2.6 of NUREG/CR-5662, "Hydrogen Combustion, Control, and Value-Impact Analysis for PWR Dry Containments," June 1991, a containment free volume of 43,900 cubic meters [1.55 x 10^6 ft^3], and the inventory of zirconium in the core to be 16,500 kg, to estimate the pressure.[48]

Stating that the estimates are considered conservative, the same NRC document regarding Turkey Point Units 3 and 4 states:

> These estimates are considered conservative because of the adiabatic assumption and the hydrogen burn is expected at much lower hydrogen concentrations than those assumed in the estimate, 13.0 and 16.0 volume percent, respectively. For example, the hydrogen burn during the accident at Three Mile Island, Unit 2, resulted from a hydrogen concentration of 8.1 volume percent. Therefore, the licensee's estimated limiting pressure for containment failure bounds conservative estimates of the most likely hydrogen combustion modes.[49]

The claim that the estimates are considered conservative also applies to the other calculations discussed above in the NRC documents regarding TMI-1 and Oconee Units 1, 2, and 3: the same claim is made in those documents.

The calculations discussed in the three NRC documents found that the pressure different PWR containments could incur from an adiabatic and complete hydrogen burn involving up to 75 percent core metal-water reaction could be 94 psig, 105 psig, or 109 psig; and that the pressure resulting from an adiabatic and complete hydrogen burn involving up to 100 percent core metal-water reaction could be 114 psig (7.86 bar), 129 psig (8.89 bar), or 135 psig (9.31 bar).

It would definitely be a cause for concern if any PWR containment were to incur such high pressure loads, because it could fail. For example, "Indian Point Probabilistic Safety Study" states that the failure pressures of IP-2 and -3's containments are both approximately 126 psig.[50]

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[48] *Id.*

[49] *Id.*, p. 4.

[50] Power Authority of the State of New York, Consolidated Edison Company of New York, "Indian Point Probabilistic Safety Study," Vol. 8, p. 4.2-1 and Appendix 4.4.1, p. 14.

As mentioned before, Fig. 17 of "Mitigation of Hydrogen Hazards in SA" is a chart with a curve illustrating that the failure probability of a containment is 80 percent when the absolute pressure reaches approximately 8 bar (116 psi).[51] This chart's curve also illustrates that the failure probability of a containment is 100 percent when the absolute pressure reaches 9 bar (130.5 psi).[52]

There is some consistency between the conclusions of "Mitigation of Hydrogen Hazards in SA" and "Containment Integrity Research at SNL." "Containment Integrity Research at SNL" states that the failure pressure of Zion is 108 psig at the 5th percentile, approximately 135 psig at the 50th percentile, and 180 psig at the 95th percentile.[53] And "Containment Integrity Research at SNL" states that the failure pressure of Surry is 95 psig at the 5th percentile, approximately 130 psig at the 50th percentile, and 150 psig at the 95th percentile.[54]

Again, it is important to clarify that these analyses are for different PWRs, which have containments with different free volumes and different quantities of fuel cladding (active length) in their cores, and that their results do not directly apply to all PWRs. However, the results of these analyses can still be used to provide a general idea of the magnitude of the pressure loads that PWR containments might be expected to incur if a hydrogen deflagration or detonation were to occur in a the event of a severe accident, in which there was a quantity of hydrogen produced from a metal-water reaction of either 75 percent or 100 percent of the active fuel cladding length.

Unfortunately, PWRs (with large dry containments and sub-atmospheric containments) regulated by NRC are currently operating without either of the two possibilities for hydrogen management that are expected for future LWRs[55]: 1) the

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[51] IAEA, "Mitigation of Hydrogen Hazards in SA," p. 61.

[52] *Id.*

[53] M. F. Hessheimer, *et al.*, "Containment Integrity Research at SNL," NUREG/CR-6906, p. 28; the source of this information is NRC, NUREG-1150.

[54] *Id.*; the source of this information is NRC, NUREG-1150.

[55] Regarding the central goal of analyses of hydrogen distribution, combustion, and loads for future light water reactor ("LWR") design studies, "Report on FA and DDT" states that "[t]he central goal of the future plant hydrogen work is to derive hydrogen control systems that fulfill the safety requirements for future LWRs; namely, to show that the maximum amount of hydrogen that could be present during a severe accident can be confined without loss of containment integrity. In principle, there are two possibilities for hydrogen management in the future plants. The first one is to increase the strength of the containment design to the maximum possible

integrity of such PWRs' containments could fail from the maximum possible combustion load and 2) such PWRs are operating without any means to mitigate hydrogen in the event of a severe accident.

(It is noteworthy that NRC has concluded that "PWR facilities with large dry containments do not control hydrogen buildup inside the containment structure because the containment volume is sufficient to keep the pressure spike of potential hydrogen deflagrations within the design pressure of the structure."[56])

C. In the Event of a Severe Accident, the Potential Total Quantity of Hydrogen that could be Produced Exceeds the Quantity that would be Produced from a Metal-Water Reaction of 100 Percent of the Active Fuel Cladding Length

In the event of a severe accident, it would be possible for a total quantity of hydrogen to be produced which exceeded the quantity that would be produced from a metal-water reaction of 100 percent of the active fuel cladding length.

Regarding potential sources of hydrogen in the event of a severe accident, "Mitigation of Hydrogen Hazards in SA" states:

> Potential hydrogen sources during the development of a severe accident in a LWR come from:
>
> 1) In-vessel metal oxidation (Zr clads and grids and other metallic structures) or B_4C absorber material oxidation with steam or with water contained in the reactor pressure vessel lower plenum;
>
> 2) Ex-vessel oxidation of metallic material (Zr, Cr, Fe...) during direct containment heating ("DCH") or into the water eventually contained in the cavity pit (short term event occurring at vessel lower head failure);
>
> 3) Ex-vessel oxidation of metallic material (Zr, Cr, Fe...) during molten core concrete interaction ("MCCI") (complete and rapid energetic oxidation of Zr and Cr during the first hour, then partial and slow

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combustion load. The second, more evolutionary way, is to use an existing containment design and install hydrogen control systems for load reduction, so that the original design load (LOCA) will not be exceeded." See OECD Nuclear Energy Agency, "Report on FA and DDT," p. 6.37.

[56] Charles Miller, *et al.*, NRC, "Recommendations for Enhancing Reactor Safety in the 21st Century: The Near-Term Task Force Review of Insights from the Fukushima Dai-ichi Accident," SECY-11-0093, July 12, 2011, available at: www.nrc.gov, NRC Library, ADAMS Documents, Accession Number: ML111861807, p. 42 (hereinafter "Recommendations for Enhancing Reactor Safety").

> oxidation of Fe up to the time of the complete basemat penetration by the corium [the molten core]).[57]

(It is noteworthy that in the TMI-2 accident, the oxidation of steel accounted for approximately 10 percent to 15 percent to the total hydrogen production.[58])

Regarding different predicted percentages of Zircaloy fuel-cladding oxidation for different severe accident scenarios, "In-Vessel and Ex-Vessel Hydrogen Sources" states:

> Studies of different accident scenarios for a PWR[59] predicted a degree of Zircaloy oxidation of about 30% in a fast sequence [large break loss-of-coolant accident, about two hours to reactor pressure vessel ("RPV") failure], and of about 50% if core geometry failure occurs late [small break loss-of-coolant accident, station blackout, about five hours to RPV failure]. However, *estimates performed for a typical PWR show that the degree of cladding oxidation is in the range 25-70% in fast sequences and may increase to 90% if core geometry failure occurs late* [emphasis added].[60]

Regarding the fact that a great deal of additional oxidation could occur from the hot melt in the late core degradation phase, "In-Vessel and Ex-Vessel Hydrogen Sources" states:

> In the late core degradation phase, hot melt from the in-core area is relocated to the lower plenum, which may be filled with water. Injection of the melt into water, for instance in [the] form of a jet, and fragmentation of the melt would lead to an increase of the reaction surface and strong oxidation of not-yet-oxidized metals. Experiments with Zr/ZrO_2 and Zr/stainless steel, with oxidation degrees of up to 40%; *e.g.*, ZREX,[61] have indicated that typically 5 to 25% of the metals are oxidized if no steam explosion occurs, and *between 70 to 100% in the case of a triggered steam explosion.* Depending on the amount of participating masses and the

[57] IAEA, "Mitigation of Hydrogen Hazards in SA," p. 6.
[58] Report by Nuclear Energy Agency Groups of Experts, OECD Nuclear Energy Agency, "In-Vessel and Ex-Vessel Hydrogen Sources," NEA/CSNI/R(2001)15, October 1, 2001, Part I, B. Clément (IPSN), K. Trambauer (GRS), W. Scholtyssek (FZK), Working Group on the Analysis and Management of Accidents, "GAMA Perspective Statement on In-Vessel Hydrogen Sources," p. 15 (hereinafter: "In-Vessel and Ex-Vessel Hydrogen Sources," Part I).
[59] T. Krauss, "Sensitivity Studies of SB LOCA, LB LOCA, and SBO in a PWR of KONVOI Type with MELCOR 1.8.3," Forschungszentrum Karlsruhe, Internal Reports, 1997.
[60] Report by Nuclear Energy Agency Groups of Experts, "In-Vessel and Ex-Vessel Hydrogen Sources," Part I, p. 10.
[61] D. H. Cho, D. R. Armstrong, W. H. Gunther, "Experiments on Interactions Between Zirconium-Containing Melt and Water," NUREG/CR-5372, 1998.

> degree of pre-oxidation of the melt, significant hydrogen masses could be produced during a short period [emphasis added].[62]

Regarding hydrogen production during direct containment heating (or high pressure melt injection), "Mitigation of Hydrogen Hazards in SA" states:

> In case of a reactor vessel bottom breach when the reactor coolant system is pressurized (accident scenarios as loss of offsite power, small break LOCA), a DCH can happen. As observed in DCH experiments done in the Sandia National Laboratory in [the] USA, the Zr still present in the corium at the time of the vessel breach undergoes a very fast oxidation with the available oxygen and steam. This availability depends on the design of the cavity pit and surrounding compartments. If the corium is directed into an intermediate compartment before reaching the dome, as in some reactors like Zion NPP in [the] USA, it is correct, based on the USA tests, to consider that all remaining [the] Zr contained in the corium at the time of the vessel breach is oxidized in the intermediate compartment during the time duration of the DCH. If the corium is directed into the dome without going through an intermediate compartment, the Zr oxidation process may not be 100% complete. Nevertheless, *experts generally assume that 100% of the remaining Zr is oxidized during the DCH event (or very shortly after) in the containment or the cavity pit.*
>
> Assuming H_2 combustion in the containment at the same time as the arrival of the dispersed corium into the containment during a DCH adds to the pressure in the containment. The H_2 available for combustion comes from the H_2 present at the time of the vessel lower head failure and from the H_2 released from Zr oxidation during the DCH.
>
> Consequently, the mass of non-oxidized Zr and Cr at [the] time of vessel lower head failure is the main parameter to investigate the effect of this short term H_2 release during a DCH [emphasis added].[63]

Regarding hydrogen production during molten core-concrete interaction "Mitigation of Hydrogen Hazards in SA" states:

> In [a] case of a reactor vessel bottom breach when the reactor coolant system is depressurized, a gravitational corium drop occurs and in [a] case [when there is] a dry cavity pit, a MCCI starts.
>
> The Zr and Cr masses contained in the corium, coming from the remaining Zr and Cr masses in the corium at the time of the vessel lower head failure, undergo a fast oxidation [process] in the steam and CO_2

[62] Report by Nuclear Energy Agency Groups of Experts, "In-Vessel and Ex-Vessel Hydrogen Sources," Part I, p. 11.
[63] IAEA, "Mitigation of Hydrogen Hazards in SA," p. 17.

> environment, where the CO_2 is coming from the thermal decomposition of the basemat concrete. Due to the violent gas release from the concrete into the corium at the beginning of MCCI, the masses of H_2O and CO_2 are well in excess of those of Zr and Cr and are in close contact with these. *Experts generally assume that 100% of these remaining Zr and Cr masses will be oxidized by steam to [produce] H_2 and CO within the first hour ([or] even less) following the beginning of MCCI.* ...
>
> The main parameters controlling the amount of released H_2 during MCCI are the masses of Zr and Cr at the beginning of MCCI (at the beginning of MCCI, Fe mass is not a key parameter because of its very low oxidation potential compared to Zr and Cr) [emphasis added].[64]

The value for the potential total quantity of hydrogen that could be produced in the event of a severe accident is different for PWRs and BWRs. "Mitigation of Hydrogen Hazards in SA" states that "[the quantity] of hydrogen created by full Zr oxidation could be up to 1000 kg of H_2 for a typical PWR compared to at least 3 to 4 times more for a BWR with the same power (around 1000 MWe)."[65] (In both of these cases, the total quantity of zirconium in the core is greater than that of 100 percent of the active fuel cladding length.) In more detail, "Mitigation of Hydrogen Hazards in SA" states that for a typical PWR (3,600 MWt), with a total quantity of approximately 26,000 kg of zirconium in its core that a quantity of approximately 1,150 kg of hydrogen would be produced from a metal-water reaction of 100 percent of the zirconium; and that for a typical BWR (3,800 MWt), with a quantity of approximately 76,000 kg of zirconium in its core that a quantity of approximately 3,360 kg of hydrogen would be produced from a metal-water reaction of 100 percent of the zirconium.[66]

Additionally, "In-Vessel and Ex-Vessel Hydrogen Sources" states that "[s]teel oxidation may contribute about 10% to 15% to the total [in-vessel] hydrogen production."[67]

Furthermore, "Mitigation of Hydrogen Hazards in SA" states that for French PWRs the total quantity of hydrogen produced from the oxidation of boron carbide (B_4C) neutron absorber material would be between approximately 50 kg and 100 kg. It follows

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[64] *Id.*, pp. 17-18.
[65] *Id.*, p. 9.
[66] *Id.*, p. 10.
[67] Report by Nuclear Energy Agency Groups of Experts, "In-Vessel and Ex-Vessel Hydrogen Sources," Part I, p. 8.

that between 100 kg and 400 kg of hydrogen could be produced from the oxidation of boron carbide in a typical BWR, because a typical BWR has two to four times the quantity of boron carbide that French PWRs have.[68] "Mitigation of Hydrogen Hazards in SA" also states that "the strong linear kinetics of the oxidation of B_4C could contribute to local effects in the containment, such as hydrogen pockets."[69]

Clearly, the potential total quantity of hydrogen produced in a severe accident could exceed the total quantity of hydrogen produced from the oxidation of 100 percent of the active fuel cladding length. Therefore, the magnitude of the pressure loads that NPP containments could incur if a hydrogen deflagration or detonation were to occur in a the event of a severe accident, could exceed the pressure loads caused by a deflagration or detonation of the quantity of hydrogen produced from a metal-water reaction of 100 percent of the active fuel cladding length.

D. A Discussion of Analyses of a Loss of Offsite Power Accident for a Future Nuclear Power Plant Design

In an OECD Nuclear Energy Agency report, "Report on FA and DDT," there is an example of analyses of a loss of offsite power ("LOOP") accident for a future nuclear power plant design.[70] Of course, these analyses do not directly apply to the PWRs (with large dry containments and sub-atmospheric containments) regulated by NRC; however, these analyses should be instructive, in that they provide a general idea of the magnitude of the pressure loads that the containments of PWRs might be expected to incur if a hydrogen deflagration or detonation were to occur in a the event of a severe accident.

For one thing, the analyses model a containment with 90,000 m^3 (approximately 3.18×10^6 ft^3) of free volume[71] and the typical free volume of PWRs with large dry containments and PWRs with sub-atmospheric containments is approximately 2.2×10^6 ft^3 and 1.7×10^6 ft^3, respectively.[72]

[68] IAEA, "Mitigation of Hydrogen Hazards in SA," pp. 6, 15, 16.
[69] *Id.*, p. 15.
[70] OECD Nuclear Energy Agency, "Report on FA and DDT," pp. 6.37-6.45.
[71] *Id.*, p. 6.37.
[72] M. F. Hessheimer, *et al.*, "Containment Integrity Research at SNL," NUREG/CR-6906, p. 24.

These analyses are for a LOOP scenario in which there is a low overall concentration of steam in the containment and hydrogen concentrations in the containment that range from about 9 percent to 13 percent. There is a total of approximately 900 kg of hydrogen in the containment.[73] The source of the steam is the water that has evaporated from the internal refueling water storage tanks; and the hydrogen has been primarily generated from the oxidation of the Zircaloy fuel cladding.

In the base case analysis, there is not any hydrogen mitigation and in this case "a large detonation in the [containment] dome could not be excluded."[74]

In another analysis of the same LOOP scenario but including 44 PARs, designed by Siemens, "[t]he inclusion of [the PARs leads] to a decrease of the maximum H_2 inventory in the containment from previously [about] 900 kg to about 720 kg hydrogen."[75]

Regarding the simulated decrease of approximately 180 kg of hydrogen, "Report on FA and DDT" states:

> This relatively small decrease is due to the fact that the H_2 release during the first heatup of the core is much faster (10 min) than the recombiner removal time (1 to 2 hours). The relatively slow-acting recombiners, which [per unit] remove typically several grams of H_2 per second cannot significantly reduce the high initial release rate [of hydrogen] in the LOOP scenario (several kilograms per second).[76]

Regarding the rapid hydrogen production that "occurs in practically all severe accident scenarios," "Report on FA and DDT" states:

> A rapid initial H_2-source occurs in practically all severe accident scenarios because the large chemical heat release of the Zr-steam reaction causes a fast self-accelerating temperature excursion during which initially large surfaces and masses of reaction partners are available.[77]

In the analysis with the 44 PARs there was an accumulation of approximately 720 kg of hydrogen in the containment; and it could be "predict[ed] that the mixture

[73] OECD Nuclear Energy Agency, "Report on FA and DDT," p. 6.38.
[74] *Id.*, p. 6.37.
[75] *Id.*, p. 6.38.
[76] *Id.*
[77] *Id.*

present in the upper half of the containment (>11% H_2), would be able to support [flame acceleration]."[78]

"Report on FA and DDT" states that "[a] COM3D calculation was therefore performed using the stratified H_2 distribution from the GASFLOW calculation as initial conditions (9% to 13% H_2)"[79] and that "the results are quite surprising and are non-trivial."[80]

Describing the results, "Report on FA and DDT" states:

> The highest flame speeds (150 m/s) do not occur in regions of highest H_2 concentration; *e.g.*, the dome, but rather in regions with both sufficient hydrogen concentration and turbulence generation, which is below the operating deck, and along the staircases. The highest loads to the outer containment wall [to the left] (≤8.5 bar) [≤123.3 psi] develop on the containment side opposite to the ignition point because two propagating flame fronts meet [there], leading to pressure wave superposition (top part of Figure 6.4.5.2.2-2[81]). The right wall near the ignition point is loaded quite uniformly with pressures up to about 4 bar [58 psi] (bottom part of Figure 6.4.5.2.2-2[82]). Because this pressure rise time is much longer than the typical containment wall period, this represents a quasi-static load to the structure.[83]

The highest loads to containment are less than and equal to approximately 8.5 bar (123.3 psi); and the containment wall near the ignition point is loaded uniformly with pressures of up to approximately 4 bar (58 psi). Furthermore, the highest flame speeds are 150 m/s. According to "Report on FA and DDT," "[i]n current nuclear power plants, the load-bearing capacity of the main internal structures is jeopardized by flame speeds in excess of about 100 m/s."[84]

Continuing its description of the results, "Report on FA and DDT" states:

> The characteristic loading times of the left and right containment wall are quite different, about 50 [milliseconds ("ms")] and 300 ms, respectively. When compared to the typical natural response times T_{cont} of a dry PWR

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[78] *Id.*, p. 6.39.
[79] *Id.*
[80] *Id.*
[81] See Appendix A Figure 6.4.5.2.2-2 Containment Loads from Fast Turbulent Combustion in Future Plant.
[82] See Appendix A Figure 6.4.5.2.2-2 Containment Loads from Fast Turbulent Combustion in Future Plant.
[83] OECD Nuclear Energy Agency, "Report on FA and DDT," p. 6.39.
[84] *Id.*, p. i.

concrete containment,[85] the first case represents a dynamic load, ($T_{load}/T_{cont} << 1$), and the second case a load regime that is in the transition from dynamic to quasi-static ($T_{load} / T_{cont} \approx 1$). In the first domain, the deformation is proportional to the wave impulse, whereas in the quasi-static domain it is proportional to the peak pressure reached.[86]

The highest load of approximately 8.5 bar (123.3 psi) is a dynamic load; and the uniform load on the containment wall near the ignition point of approximately 4 bar (58 psi) is in a load regime that is in transition from dynamic to quasi-static.

"Report on FA and DDT" also discusses another analysis for the LOOP scenario with 44 recombiners in which there is a local detonation in the containment dome. In this analysis there is 690 kg of hydrogen in the containment and hydrogen concentrations between 7 percent and 13 percent.

Describing the results of the analysis with the local detonation, "Report on FA and DDT" states:

> This scenario should result in an upper limit for fast local combustion loads, which could be possible with the hydrogen inventory in the containment under the present conditions... A linear H_2 gradient from 7% to 13% was assumed, leading to a total H_2 mass of 690 kg in the containment. The initial temperature was 320 K [116.6°F], and the initial pressure 1.23 bar [17.8 psi]. Figure 6.4.5.2.3-2[87] shows the predicted pressure loads at different points along the upper edge of the containment cylinder (1 to 7). Ignition is initiated at point 1 [where the pressure reaches about 2.0 Mpa (290 psi)]. In points 2, 3, and 4 basically side-on pressures are generated [of about 1.25 Mpa (181.3 psi)], whereas in points 5, 6, and 7 higher reflected pressures appear [of about 2.0 Mpa (290 psi)]. Because of the short loading times of typically 10 ms, these loads clearly fall into the impulsive regime, where the building deformation is proportional to the wave impulse. The calculated impulses in the detonation wave range from about 5 to 20 kPa.[88]

In the analysis with the local detonation, the predicted pressure loads reach values as high as 290 psi; however, these loads have short loading times of typically 10 ms.

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[85] E. Studer, M. Petit, "Use of RUT Large Scale Combustion Test Results for Reactor Applications," SMIRT-14, Lyon, France, August 17-22, 1997.
[86] OECD Nuclear Energy Agency, "Report on FA and DDT," p. 6.41.
[87] See Appendix B Figure 6.4.5.2.3-2 Calculated Pressures from a Local Detonation in the Containment Dome.
[88] OECD Nuclear Energy Agency, "Report on FA and DDT," p. 6.42.

Concluding on what the analyses of the LOOP scenario with 44 recombiners have indicated, "Report on FA and DDT" states:

> The described calculations have shown that mitigation with recombiners alone still allows accumulation of up to roughly 700 kg H_2 in the containment and that combustion of this hydrogen mass could lead to significant dynamic loads. Although these loads may not endanger the containment integrity in the undisturbed areas, they would certainly require extensive analysis of containment integrity in regions around penetrations [hatches, pipe and cable penetrations[89]]. Moreover, these dynamic loads could have severe consequences for safety systems that are needed for further management of an accident. Especially vulnerable are the structurally weak recombiner boxes and the spray system.[90]

Again, these LOOP scenario analyses do not directly apply to PWRs (with large dry containments and sub-atmospheric containments) regulated by NRC; however, these analyses should be instructive, in that they provide a general idea of the magnitude of the pressure loads that PWR containments might be expected to incur if a hydrogen deflagration or detonation were to occur in a the event of a severe accident.

In the LOOP scenario—in which the highest flame speeds (150 m/s) occur below the operating deck and along the staircases—the highest dynamic load to the containment, approximately 123.3 psi, is well over the typical design pressures of PWR large dry containments and PWR sub-atmospheric containments, which are 53 psig and 52 psig, respectively,[91] and fairly close in value to the failure pressures NUREG-1150 estimates for Zion and Surry at the 50th percentile, which are approximately 135 psig and approximately 130 psig, respectively.[92] Additionally, the uniform loads (a load regime that is in the transition from dynamic to quasi-static) to the containment wall near the ignition point are approximately 58 psi and greater than the typical design pressures of PWR large dry containments and PWR sub-atmospheric containments.

"Report on FA and DDT" states that the magnitude of the calculated "loads *may* not endanger the containment integrity in the undisturbed areas" [emphasis added].[93] In other words, "Report on FA and DDT" does not definitively conclude that the

[89] IAEA, "Mitigation of Hydrogen Hazards in SA," p. 60.
[90] OECD Nuclear Energy Agency, "Report on FA and DDT," p. 6.44.
[91] M. F. Hessheimer, *et al.*, "Containment Integrity Research at SNL," NUREG/CR-6906, p. 24.
[92] *Id.*, p. 28; the source of this information is NRC, NUREG-1150.
[93] OECD Nuclear Energy Agency, "Report on FA and DDT," p. 6.44.

containment integrity would *not* be endangered. Furthermore, the magnitude of the calculated "loads may not endanger the containment integrity in the undisturbed areas;"[94] however, the magnitude of the calculated loads indicates that "extensive analysis of containment integrity in regions around penetrations [hatches, pipe and cable penetrations[95]]"[96] would be required. "Report on FA and DDT" also states that "these dynamic loads could have severe consequences for safety systems that are needed for further management of an accident."[97]

Clearly, it is not in the interest of public safety to have PWRs (with large dry containments and sub-atmospheric containments) operating without any means to mitigate hydrogen in the event of a severe accident.

E. The Damage Potential of Internally-Generated Missiles that could be Caused by Hydrogen Deflagrations or Detonations in the Event of a Severe Accident

According to a number of reports, in the event of a severe accident, the containment integrity and essential safety systems of a NPP could be compromised by internally-generated missiles, caused by a hydrogen deflagration or detonation.

An IAEA report, "Mitigation of Hydrogen Hazards in SA," published July 2011, states "no analysis ever has been made on the damage potential of flying objects, generated in an H_2-explosion"[98] that could occur in the event of a severe accident.

The same IAEA report states:

> [I]n the case that the containment has many sub-compartments, a local deflagration or detonation may occur that damages the sub-compartment and through this may generate missiles (concrete blocks from the disintegrated compartment walls) that can endanger the containment integrity. ... The resistance of a concrete containment to such objects is larger than that of a steel containment: upon impact, the missile may generate cracks rather than gross failure.[99]

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[94] *Id.*
[95] IAEA, "Mitigation of Hydrogen Hazards in SA," p. 60.
[96] OECD Nuclear Energy Agency, "Report on FA and DDT," p. 6.44.
[97] *Id.*
[98] IAEA, "Mitigation of Hydrogen Hazards in SA," p. 62.
[99] *Id.*, pp. 61-62.

If a large PWR dry containment, comprised of reinforced or post-tensioned concrete with a steel liner,[100] were impacted by an internally-generated missile, caused by a hydrogen deflagration or detonation, it seems more likely that the containment would incur cracks than gross failure. However, if a large PWR dry containment were to incur cracks it would be a serious problem. Additionally, essential safety systems could be seriously compromised by internally-generated missiles. Steel containments would clearly be susceptible to gross failure if impacted by an internally-generated missile, caused by a hydrogen deflagration or detonation.

Yet, as stated above, the damage potential of these flying objects still lacks sufficient analysis—at least, according to an IAEA report. In May 1980, the safety issue of the damage potential of internally-generated missiles, caused by hydrogen deflagrations or detonations, was addressed in a SNL slide presentation, titled "Hydrogen Behavior and Control." The SNL slide presentation states that one of the concerns of hydrogen combustion is that "detonations may produce missiles which could jeopardize equipment or breach [the] containment."[101]

Since "Hydrogen Behavior and Control" was presented over thirty years ago, NRC has not required licensees of NPPs to perform severe accident analyses on the damage potential of internally-generated missiles.

Furthermore, a SNL report, "Light Water Reactor Hydrogen Manual," published August 1983, states:

> Missiles may be generated when combustion (deflagration or detonation) occurs in a confined region or when a propagating combustion front produces dynamic pressure loads on equipment. Such missiles may pose a threat to the containment structure itself, as well as representing a potential threat to safety and control equipment.[102]

It is obvious that public safety would be enhanced by conducting analyses for NPPs, on the damage potential of internally-generated missiles, caused by hydrogen deflagrations or detonations. Until such analyses are conducted for NPPs, for the full

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[100] M. F. Hessheimer, *et al.*, "Containment Integrity Research at SNL," NUREG/CR-6906, p. 8.
[101] Marshall Berman, SNL, "Hydrogen Behavior and Control," Technology Exchange Meeting 3, Bethesda, Maryland, May 20, 1980, available at: www.nrc.gov, NRC Library, ADAMS Documents, Accession Number: ML093450113, p. 16.
[102] Allen L. Camp, *et al.*, "Light Water Reactor Hydrogen Manual," NUREG/CR-2726, p. 2-59.

range of possible scenarios of internally-generated missiles, caused by hydrogen deflagrations or detonations, it cannot be concluded that NPP containments would not fail in some severe accident scenarios.

(It is noteworthy that Appendix A to Part 50—"General Design Criteria for Nuclear Power Plants," Criterion 4, "Environmental and dynamic effects design bases," addresses the fact that a nuclear power plant's structures, systems, and components important to safety could be damaged by internally-generated missiles.

Appendix A to Part 50, Criterion 4 states:

> Structures, systems, and components important to safety shall be designed to accommodate the effects of and to be compatible with the environmental conditions associated with normal operation, maintenance, testing, and postulated accidents, including loss-of-coolant accidents. These structures, systems, and components shall be appropriately protected against dynamic effects, including the effects of missiles...that may result from equipment failures and from events and conditions outside the nuclear power unit. ...

Therefore, Appendix A to Part 50 makes reference to missiles yet issues no further requirement on assessing the damage potential of internally-generated missiles, caused by hydrogen deflagrations or detonations, in postulated severe accidents, in which there could up to 300 kg of hydrogen generated in one minute.[103])

1. Reports State that in the Event of a Severe Accident, Containment Integrity and Essential Safety Systems could be Compromised by Internally-Generated Missiles and that Containment Integrity could be Compromised by a Global Detonation

Some reports have stated that in the event of a severe accident, the containment integrity and essential safety systems of a nuclear power plant could be compromised by internally-generated missiles, caused by a hydrogen deflagration or detonation, and that containment integrity could also be compromised by a global detonation.

[103] E. Bachellerie, *et al.*, "Generic Approach for Designing and Implementing a Passive Autocatalytic Recombiner PAR-System in Nuclear Power Plant Containments," Nuclear Engineering and Design, 221, 2003, p. 158 (hereinafter "Designing and Implementing a PAR-System in NPP Containments").

Below are quotes from such reports:

1) An OECD Nuclear Energy Agency report, "Report on FA and DDT," states:

> Flame acceleration (FA) and deflagration-to-detonation transition (DDT) are important phenomena in severe accidents because they can largely influence the maximum loads from hydrogen combustion sequences and the consequential structural damage. ... In current nuclear power plants, the load-bearing capacity of the main internal structures is jeopardized by flame speeds in excess of about 100 m/s.[104]

2) The same OECD Nuclear Energy Agency report states:

> The significance of FA and DDT processes for reactor safety is due to the fact that *these fast combustion modes can be extremely destructive.* They have the highest damage potential for internal containment structures; for safety systems that are required for safe termination of the accident (sprays, recombiners); *and for the outer containment shell that is the last barrier against the release of radioactivity into the environment.*
>
> The concern about the outer containment shell is not only connected to its function as the ultimate barrier, but the concern is also due to its complicated structural behavior. All modern containment buildings are a complex composite of different structural elements, including an undisturbed shell, personal and material locks, and hatches of different sizes and design, as well as penetrations for electrical cables and pipes. This system has been qualified for a certain global and static design pressure, which is generally related to the maximum blowdown pressure from a break of the primary coolant line.
>
> However, in a severe accident, which is not part of the licensing process, in existing plants FA and DDT may become possible. In this case, new containment load classes would arise, namely high local or even global dynamic loads [emphasis added].[105]

3) Additionally, the same OECD Nuclear Energy Agency report states:

> [T]he way to jeopardize the containment may be different: possible missiles created by a local explosion compared to global pressure loading of the containment.[106]

4) A SNL report, "Containment Integrity Research at SNL," states:

> Containment failure probability is largely dependent on the individual containment design and the particular phenomena or load that challenges

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[104] OECD Nuclear Energy Agency, "Report on FA and DDT," p. i.
[105] *Id.*, p. 1.3.
[106] *Id.*, p. 6.2.

the integrity of the containment. Particular severe accident challenges to the containment include: 1) overpressure, 2) dynamic pressure (shock waves), 3) internal missiles, 4) external missiles, 5) melt-through, and 6) bypass.[107]

5) An IAEA report, "Mitigation of Hydrogen Hazards in SA," states:

Notably in the case that the containment has many sub-compartments, a local deflagration or detonation may occur that damages the sub-compartment and through this may generate missiles (concrete blocks from the disintegrated compartment walls) that can endanger the containment integrity. This is particularly a concern for a free standing steel containment, as it is vulnerable to such heavy, flying objects. The resistance of a concrete containment to such objects is larger than that of a steel containment: upon impact, the missile may generate cracks rather than gross failure. *To date* [July 2011], *however, no analysis ever has been made on the damage potential of flying objects, generated in an H_2-explosion* [emphasis added].[108]

6) The same IAEA report states:

[T]he containment may also suffer indirect damage. This can happen if a local explosion destroys a compartment, after which the missiles from this compartment penetrate the containment or damage lines that go through it.[109]

7) A paper, "Igniters to Mitigate the Risk of Hydrogen Explosions—A Critical Review," states:

The hydrogen concentrations averaged over the free volume of the containment may reach values between 7 and 16 percent or even more. Local concentrations may be much higher, in particular if steam condensation is realistically taken into account. It is concluded that within the large geometries of PWR-containments a slow laminar deflagration would be very unlikely. In most cases, highly efficient combustion modes must be expected. ...

Massive pre-stressed concrete containments or concrete containments which are equipped with a steel liner may be some what more favorable in forgiving the consequences of local detonations. According to the mass ratio of concrete to load bearing steel rebars, the internally generated missiles [which may result from a local detonation] may only damage the liner but not necessarily cause catastrophic failure of the steel rebars. In

[107] M. F. Hessheimer, *et al.*, "Containment Integrity Research at SNL," NUREG/CR-6906, pp. 25-26.
[108] IAEA, "Mitigation of Hydrogen Hazards in SA," pp. 61-62.
[109] *Id.*, p. 113.

general, it is anticipated that concrete containments are mainly challenged by global detonations involving the entire free volume.[110]

8) A SNL report, "Light Water Reactor Hydrogen Manual" states:

> Missiles may be generated when combustion (deflagration or detonation) occurs in a confined region or when a propagating combustion front produces dynamic pressure loads on equipment. Such missiles may pose a threat to the containment structure itself, as well as representing a potential threat to safety and control equipment. For instance, electrical cables may not be expected to withstand the impact of a door or metal box. The actual risk to plant safety posed by missiles generated from hydrogen combustion depends upon a number of independent factors.[111]

9) The same SNL report states:

> A typical Mark III BWR containment contains approximately 1.5 million cubic feet of free air volume. If one assumes a metal-water reaction similar to the one believed to have occurred at TMI-2, the resultant deflagration (or possible detonation) in a containment of this volume might challenge the containment integrity. Since the PWR ice condenser containment free air volume and design pressure (about 15 psig) are similar to those of the Mark III containment, the same type of concern exists for it.[112]

10) A different SNL report, "FLAME Facility: The Effect of Obstacles and Transverse Venting on Flame Acceleration and Transition to Detonation for Hydrogen-Air Mixtures at Large Scale," states:

> The pressure loads at TMI-2 did not threaten the strong containment structure. However, the pressure rise would have been higher and the combustion even more rapid if the hydrogen concentration had been higher. This might occur in smaller sized containments, if more hydrogen had been generated, or if the released hydrogen was more concentrated and not mixed throughout containment.[113]

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[110] Helmut Karwat, "Igniters to Mitigate the Risk of Hydrogen Explosions—A Critical Review," Nuclear Engineering and Design, 118, 1990, p. 267.
[111] Allen L. Camp, *et al.*, "Light Water Reactor Hydrogen Manual," NUREG/CR-2726, p. 2-59.
[112] *Id.*, p. 4-107.
[113] M. P. Sherman, S. R. Tieszen, W. B. Benedick, "FLAME Facility: The Effect of Obstacles and Transverse Venting on Flame Acceleration and Transition to Detonation for Hydrogen-Air Mixtures at Large Scale," NUREG/CR-5275, pp. 5-6.

11) An NRC letter to licensees, "Completion of Containment Performance Improvement Program, Etc.," states:

> Depending on the degree of compartmentalization and the release point of the hydrogen from the vessel, local detonable mixtures of hydrogen could be formed during a severe accident and important equipment, if any is nearby, could be damaged following a detonation. In addition, smaller [PWR] sub-atmospheric containments may develop detonable mixtures of hydrogen on a global basis.[114]

Clearly, in the event of a severe accident at a NPP, a hydrogen deflagration or detonation could cause a substantial amount of damage. The reports above also state that containment integrity and essential safety systems could be compromised by internally-generated missiles, caused by a hydrogen deflagration or detonation.

It is obvious that public safety would be enhanced by conducting analyses on the damage potential of internally-generated missiles, caused by hydrogen deflagrations or detonations, in postulated severe accidents. However, it is important to remember that computer analyses do not always provide realistic simulations and that there can be a great deal of uncertainty in their accuracy. Most likely it will be necessary to conduct experiments to figure out the extent of the damage NPP containments would incur from internally-generated missiles, caused by hydrogen deflagrations or detonations.

On the uncertainties of the accuracy of analyses of accident sequences and potential explosion hazards and the importance experimentation, "Report on FA and DDT" states:

> *The analysis of accident sequences and potential explosion hazards always involves evaluating complex phenomena in the face of considerable uncertainties.* Often because of these uncertainties, the results of analysis are not clear-cut. *In some cases, it may be necessary to use CFD or experimentation in order to sharpen the limits and provide sufficient as well as necessary conditions.* As an example, if detonation cannot be completely ruled out in a particular portion of a containment, CFD simulations can be used to estimate structural loads. Computation structural simulation can then be used to see whether these loads actually pose a threat to the integrity of the containment [emphasis added].[115]

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[114] NRC, letter to all licensees holding operating licenses and construction permits for NPPs, except licensees of BWR Mark Is, "Completion of Containment Performance Improvement Program, Etc.," July 6, 1990, available at: www.nrc.gov, NRC Library, ADAMS Documents, Accession Number: ML031210418, p. 1.

[115] OECD Nuclear Energy Agency, "Report on FA and DDT," p. 7.12.

On the difficulty of conducting accurate analyses of the hydrogen risk to containment sub-compartments, "Mitigation of Hydrogen Hazards in SA" states:

> In most plants, the walls of the containment sub-compartments have been designed for the pressure differences of [design basis accident] loads (large break LOCA, etc.). Often, it even is not known what other pressure differences these structures can bear, as the exact composition of the walls is unknown and, hence, a structural analysis cannot be done. Together with a potential accumulation of hydrogen in some compartments, the risk from indirect damage is difficult to estimate.[116]

This also suggests that it will be necessary to conduct experiments to figure out the extent of the damage NPP containments would incur from internally-generated missiles, caused by hydrogen deflagrations or detonations. Furthermore, analyses on the damage potential of local and global detonations in postulated severe accidents should be conducted. Until such analyses are conducted for NPPs, for the full range of possible local and global detonations, it cannot be concluded that NPP containments would not fail in some scenarios.

(It is noteworthy that the NRC Near-Term Task Force report, "Recommendations for Enhancing Reactor Safety in the 21st Century: The Near-Term Task Force Review of Insights from the Fukushima Dai-ichi Accident" states that "PWR facilities with large dry containments do not control hydrogen buildup inside the containment structure because the containment volume is sufficient to keep the pressure spike of potential hydrogen deflagrations within the design pressure of the structure."[117] The Task Force report does not mention that either a fast deflagration or a detonation could occur in the event of a severe accident—a fast deflagration or a detonation that could possibly compromise the integrity of a PWR large dry containment. The report also does not mention that an internally-generated missile, caused by a hydrogen detonation, could either compromise containment integrity or damage essential safety systems.

Given the fact that a number of hydrogen explosions occurred in the Fukushima Dai-ichi accident, it would have seemed appropriate for the Task Force report to discuss the possibility of having hydrogen detonations in the event of severe accidents.)

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[116] IAEA, "Mitigation of Hydrogen Hazards in SA," p. 62.
[117] Charles Miller, *et al.*, "Recommendations for Enhancing Reactor Safety," SECY-11-0093, p. 42.

F. Information on Hydrogen Combustion

1. Quotes from Two Reports that Provide Information on Hydrogen Combustion

Below are five quotes from two recent reports that provide information on hydrogen combustion. The quotes from the reports are as follows:

1) Regarding FA and DDT, "Report on FA and DDT" states:

> [I]n a severe accident, which is not part of the licensing process, in existing plants FA and DDT may become possible. In this case, new containment load classes would arise, namely high local or even global dynamic loads. The structural behavior of containment components under such dynamic pressure and impulse loads is complicated and difficult to evaluate. An effective way to protect the containment integrity even for the case of beyond-design accidents is therefore to control the hydrogen behavior in such a way that the possibility of FA and DDT occurring is decreased or even excluded. It is clear that this improvement of public and environmental protection against the consequences of severe accidents requires a detailed understanding of FA and DDT.[118]

2) Regarding different combustion modes that are possible in severe accidents, "Mitigation of Hydrogen Hazards in SA" states:

> All combustion modes are potentially possible in a severe accident scenario: 1) for low hydrogen concentration below about 8%, flame speed is expected to be slow and the deflagration produces...quasi-static pressure loads, 2) above about 8%, combustion is complete and combustion may accelerate leading to higher loads, 3) above 10%, acceleration up to sound velocity has been found in many experiments and 4) in an extreme case, flame acceleration, supported by turbulence, can reach detonation conditions, called [DDT]. Regarding reactor safety, flame acceleration and DDT can be extremely destructive and have high potential damage for internal containment structures and safety systems required for severe accident management. Direct initiation of a detonation is not possible within containment due to the high energy required.[119]

3) Regarding hydrogen combustion when the hydrogen concentration exceeds eight percent, "Mitigation of Hydrogen Hazards in SA" states:

> Above about 8% H_2 concentration, flames may accelerate and larger loads may result. A typical increase of loads is given in ["Hydrogen Behaviour

[118] OECD Nuclear Energy Agency, "Report on FA and DDT," p. 1.3.
[119] IAEA, "Mitigation of Hydrogen Hazards in SA," p. 33.

and Mitigation in Water-Cooled Nuclear Power Reactors"].[120] In addition, combustion is more complete, so that loads also increase due to the fact that more hydrogen is burned. Note that flame acceleration is a complex process, and does not depend just on the hydrogen concentration, but also on the amount of blockage, the degree of confinement, the presence of diluent gases (steam, CO_2), etc....

Accelerated flames produce pressure spikes, characterized by a high pressure which lasts a very short time. Where flames accelerate in a confined volume—typically a reactor containment or its sub-compartments—the pressure developed depends on the size of the H_2 gas region, the H_2 concentration, the size of the enclosure and the configuration of obstacles.

Flames may accelerate and transit to a detonation...or a direct detonation may occur. The latter one requires an adequate initiation energy. It varies from 4 kJ, as determined by stoichiometry in a dry atmosphere, to more than 10,000 kJ when the mixture contains 30% steam. Hence, direct initiation of a detonation is unlikely to occur in a reactor containment after a severe accident has occurred.[121]

4) Furthermore, regarding hydrogen combustion when the hydrogen concentration exceeds eight percent "Mitigation of Hydrogen Hazards in SA" states:

Hydrogen deflagration can pose various risks to the containment and other plant systems. Combustion can give large pressure spikes, varying from relatively low pressure loads, bound by the AICC loads, until large loads from accelerated flames and detonations. Such acceleration can already occur above about 8% H_2...so that above that value the AICC load may [no] longer be the bounding value.

AICC loads are quasi-static; *i.e.*, the structural response can be calculated assuming loads are static. Loads from accelerated flames or detonations require a dynamic analysis; *i.e.*, the dynamic characteristics of the structure need to be taken into account. A simplified approach is using an equivalent static load.

Apart from such direct damage, the containment may also suffer indirect damage. This can happen if a local explosion destroys a compartment, after which the missiles from this compartment penetrate the containment or damage lines that go through it. ...

[120] E. D. Loggia, "Hydrogen Behaviour and Mitigation in Water-Cooled Nuclear Power Reactors," European Commission, EUR 14039, 1992.
[121] IAEA, "Mitigation of Hydrogen Hazards in SA," pp. 58-59.

> Finally, combustion produces much heat, which can damage various structures, systems and components. ...
>
> Under unfavorable conditions, thermal stratification can occur that prevents the hydrogen from mixing with the steam. This can occur if mass releases from the primary system are widely apart; *e.g.*, in a small break LOCA, one may first see the steam and only much later the hydrogen. Hence, scenarios have to be included that can give rise to such phenomena. A typical risk is also if the containment initially is inert, due to the steam, so that hydrogen can accumulate considerably. Combustion will then first occur once the steam is largely condensed; *i.e.*, at a fairly large H_2 concentration, which then may result in large loads.[122]

5) Regarding hydrogen combustion when the hydrogen concentration exceeds 10 percent, "Mitigation of Hydrogen Hazards in SA" states:

> For higher hydrogen concentration, above 10%, experimental results have shown that flame acceleration could occur and reach the sound velocity. Fast hydrogen deflagration in an enclosure produces dynamic pressure with strong variation of time that, in some cases, may be high enough to threaten the integrity of the enclosure or its substructures. The peak pressure developed inside the enclosure depends on the size of the combustible gas region, the concentration of the combustible gas, the size of the enclosure and the arrangement of the obstacles.[123]

Clearly, in the event of a severe accident, a great deal of damage could occur as a consequence of the combustion of hydrogen in concentrations exceeding 8 and 10 volume percent. Therefore in a severe accident scenario it would be important to protect the containment integrity and essential safety systems by mitigating hydrogen in order to prevent FA and DDT from occurring.[124]

2. There are Different Conclusions as to What Constitutes the Most Severe Combustion Scenario for a Concrete Containment Building: Stable Detonations as Opposed to Fast Deflagrations

According to "Report on FA and DDT," reactor safety analyses and studies indicate that "hydrogen combustion can involve wide time scales (between milliseconds in [the] case of a detonation and several seconds in [the] case of a slow deflagration) and

[122] *Id.*, p. 113.
[123] *Id.*, p. 48.
[124] OECD Nuclear Energy Agency, "Report on FA and DDT," p. 1.3.

[cause] pressures (between 4 and 30 times the initial pressure or more, depending on the reflections of the shock waves)."[125]

If hydrogen combustion were to cause pressure increases of between 4 and 30 times the initial pressure, then that would mean that hydrogen combustion caused pressure increases of between approximately 4 and 30 atmospheres ("atm") (or between approximately 59 psi and 441 psi). However, high pressures resulting from detonations have a very rapid decay after the peak value, and "[h]igher peak loads do not necessarily result in higher structural loads: the peak pressure alone is insufficient to determine the vulnerability of a structure."[126] "Report on FA and DDT" states that "[i]mportant factors affecting the response of a structure to a transient pressure loading include the peak pressure and the length of the rise and decay times compared to the characteristic response time of the structure."[127]

Regarding the fact detonations are followed by a very rapid decay, "Mitigation of Hydrogen Hazards in SA" states:

> Detonations produce shock waves, resulting in high pressures, with a very rapid decay after the peak value. If the detonation results from a transition from deflagration to detonation, these loads can even be higher. Peak pressures of 250 bar [approximately 246.7 atm] have been observed in reflected shock waves, in an experiment initially at 1 bar [approximately 1 atm] pressure. ...
>
> In order to obtain the actual risk from these loads, the structural response of the containment (or other endangered structure), must be obtained. Higher peak loads do not necessarily result in higher structural loads: the peak pressure alone is insufficient to determine the vulnerability of a structure. Pressure records associated with DDT or a stable detonation display a sharp pressure rise followed by the decay, which is relatively rapid for DDT. Slow and fast deflagrations, on the other hand, display a more gradual pressure rise and decay. The details of the pressure histories can be very important in assessing the response of a particular structure.[128]

Two studies have different conclusions as to what constitutes the most severe combustion scenario for a concrete containment building. The findings of Breitung and

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[125] *Id.*, p. 6.1.
[126] IAEA, "Mitigation of Hydrogen Hazards in SA," p. 59.
[127] OECD Nuclear Energy Agency, "Report on FA and DDT," p. 2.22.
[128] IAEA, "Mitigation of Hydrogen Hazards in SA," p. 59.

Redlinger[129] indicate that a stable detonation is the most severe scenario for a concrete containment building. "Report on FA and DDT" states that "[i]n the range of 5 to 25 Hz, which is characteristic of the frequency response of concrete nuclear reactor containment buildings, [the findings of Breitung and Redlinger indicate that] stable detonation[s] and fast deflagrations display a similar response, whereas DDT and slow deflagrations exhibit a weaker response."[130]

"Report on FA and DDT" states that "Studer and Petit[131]...observe[d] significantly larger displacements for fast deflagrations with progressively lower responses for DDT and a stable detonation. [Studer and Petit] concluded that the fast deflagration is the most severe scenario for a concrete containment building.[132]

According to "Report on FA and DDT," "The different conclusions emerging from these [two] studies could be attributed to the different structural response models or to the different pressure histories used to characterize the various flame and detonation regimes. Assessment of the vulnerability of nuclear containment buildings and substructures will require more work in the analysis of experimental results and in the development of detailed models."[133]

It also seems that it will be necessary to conduct combined experimental and CFD modeling analysis (see section F.4, below) for specific containment structure properties in order to figure out the extent of the damage concrete containments would incur from either hydrogen fast deflagrations or detonations.

3. Information Regarding Plant Specific Analyses of the Quantity of Hydrogen Generated in the Event of a Severe Accident as well as the Hydrogen Distribution and Combustion

NPPs have certain plant-specific characteristics that would affect the quantity of hydrogen generated in the event of a severe accident as well as the hydrogen distribution

[129] W. Breitung, R. Redlinger, "A Model for Structural Response to Hydrogen Combustion Loads in Severe Accidents," Nuclear Technology, Vol. 111, 1995, pp. 420-425.
[130] OECD Nuclear Energy Agency, "Report on FA and DDT," p. 2.22.
[131] E. Studer, M. Petit, "Use of RUT Large Scale Combustion Test Results for Reactor Applications," International Association for Structural Mechanics in Reactor Technology, 14th International Conference on Structural Mechanics in Reactor Technology, Lyon, France, 1997.
[132] OECD Nuclear Energy Agency, "Report on FA and DDT," p. 2.22.
[133] *Id.*

and combustion: 1) the particular size of the NPP cores would affect the quantity of hydrogen generated; 2) the particular volume of the containment would affect hydrogen concentrations; and 3) the particular distribution of steel and concrete masses, as well as surfaces, would affect steam concentrations.

Regarding these three characteristics, "Report on FA and DDT" states:

> The starting point of any analysis is, of course, selection of the plant. This apparently trivial point is included explicitly into the general analysis procedure because the plant design has many important implications for later stages of the [computational fluid dynamics ("CFD")] analysis. For instance, the core size and type of reactor (PWR or BWR) will determine the maximum possible hydrogen source term, the free containment volume will influence hydrogen concentrations, and the distribution of steel and concrete masses, as well as surfaces, will affect the equally important steam concentrations.[134]

For a containment, the particular size and arrangement of obstacles (such as tubes, grid-irons, and doors[135]) would also affect hydrogen combustion.

Regarding this issue, "Report on FA and DDT" states:

> The geometry of a combustion volume is the most important and the most complex parameter for [flame acceleration]. Especially, in case of real situations, geometry of a single combustion compartment and arrangement of a multi-compartment combustion process are of main importance. The three main parameters can be summarized as size of obstacles, distance between [two] obstacles, and degree of confinement (all geometrical discontinuities on the combustion path). In actual NPP geometry, data such as blockage ratio or spacing of obstacles cannot always be defined because of their complexity.[136]

Different NPPs would also have different containment failure pressures, as discussed in section III.A.

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[134] OECD Nuclear Energy Agency, "Report on FA and DDT," p. 6.15.
[135] *Id.*, p. 5.36.
[136] *Id.*, p. 6.3.

4. According to a Recent IAEA Report, in the United States, Safety Analyses for Severe Accidents do not Use Advanced Computational Fluid Dynamics Codes to Enhance the Accuracy of Hydrogen Containment Distribution and Loads from Flame Acceleration, because it is been Assessed that Safety Margins are Sufficient to Account for Any Uncertainties

It is also pertinent to NPPs that "Mitigation of Hydrogen Hazards in SA" states:

> *In the USA* [as of July 2011], *the hydrogen risk during a severe accident is not considered an area for which further research is warranted*: it has been analyzed that containments of USA plants can either withstand the induced hydrogen combustion loads with enough safety margins (for the large dry PWR containments, for instance)... *The USA* [analyses do] *not include advanced methods such as the use of CFD codes to find a more refined hydrogen containment distribution, or loads from flame acceleration, as it was assessed that the safety margins were large enough to cover such uncertainties.* Moreover, a maximum of 75% [active cladding length] oxidation reacted [is] used for the hydrogen source[137] [emphasis added].[138]

Given the fact that hydrogen explosions occurred in the Fukushima Dai-ichi accident it seems that public safety would be enhanced by conducting further research on hydrogen risk in severe accidents and that analyses should be conducted using advanced CFD codes to predict hydrogen distribution and loads from flame acceleration in postulated severe accidents.

G. Information on Hydrogen Mitigation Systems

1. High Hydrogen Production Rates Must Be Taken into Account in the Design of Hydrogen Mitigation Systems

As quoted above in section III.D, "Report on FA and DDT" states that "[a] rapid initial H_2-source occurs *in practically all* severe accident scenarios because the large chemical heat release of the Zr-steam reaction causes a fast self-accelerating temperature excursion during which initially large surfaces and masses of reaction partners are

[137] The IAEA report, "Mitigation of Hydrogen Hazards in SA," states that "to identify the H_2 risk in France, containment calculations with 100% Zr active cladding length have to be performed. Calculations in the USA use often a maximum of 75% Zr ACL reacted." See IAEA, "Mitigation of Hydrogen Hazards in SA," p 16.

[138] IAEA, "Mitigation of Hydrogen Hazards in SA," pp. 105-106.

available" [emphasis added].[139] In a severe accident, during the reflooding of an overheated core up to 300 kg of hydrogen could be produced in one minute.[140] One report states that between 5 and 10 kg of hydrogen could be produced per second, during the reflooding of an overheated core;[141] this high rate of hydrogen production would not last long.

In the Three Mile Island accident, it is generally estimated that a total of 500 kg was produced.[142]

The fact that 300 kg of hydrogen could be produced in one minute is an important safety issue to consider for combustible gas control. Regarding the importance of this issue, "In-Vessel and Ex-Vessel Hydrogen Sources," Part I, "GAMA Perspective Statement on In-Vessel Hydrogen Sources," published in 2001, states:

> Reflooding and quenching of the uncovered core is the most important accident management measure to terminate a severe accident transient. If the core is overheated, this measure can lead to increased oxidation of the Zircaloy cladding which in turn can trigger a temperature escalation. Relatively short flooding and quenching times can thereby lead to high hydrogen source rates *which must be taken into account in risk analysis and in the design of hydrogen mitigation systems.*[143]

(It is noteworthy that the NRC Near-Term Task Force report, "Recommendations for Enhancing Reactor Safety in the 21st Century: The Near-Term Task Force Review of Insights from the Fukushima Dai-ichi Accident" does not discuss the fact that up to 300 kg of hydrogen could be produced in one minute, in a severe accident, during the reflooding of an overheated core, and that that "must be taken into account in risk analysis and in the design of hydrogen mitigation systems."[144])

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139 OECD Nuclear Energy Agency, "Report on FA and DDT," p. 6.38.
140 E. Bachellerie, *et al.*, "Designing and Implementing a PAR-System in NPP Containments," p. 158.
141 J. Starflinger, "Assessment of In-Vessel Hydrogen Sources," in "Projekt Nukleare Sicherheitsforschung: Jahresbericht 1999," Forschungszentrum Karlsruhe, FZKA-6480, 2000.
142 Jae Sik Yoo, Kune Yull Suh, "Analysis of TMI-2 Benchmark Problem Using MAAP4.03 Code," Nuclear Engineering and Technology, Vol. 41, No. 7, September 2009, p. 949.
143 Report by Nuclear Energy Agency Groups of Experts, "In-Vessel and Ex-Vessel Hydrogen Sources," Part I, p. 9.
144 *Id.*

2. Information on Hydrogen Igniter Systems

In the event of a severe accident, at either a PWR with an ice condenser containment or a BWR Mark III, it would be important to substantially reduce the quantity of hydrogen present in containment. Igniter systems have been installed in PWR ice condenser containments and BWR Mark III containments in order to reduce the quantity of hydrogen.

Regarding the importance of hydrogen igniter systems, "Mitigation of Hydrogen Hazards in SA" states:

> The phenomenon of incomplete burning of lean hydrogen-air mixtures is of fundamental importance in reactor safety. Combustion of lean mixtures, below 8% hydrogen, can be a method of consuming hydrogen without a significant increase of containment pressure. Because of the incomplete combustion process igniter devices [appear] to be...an efficient mitigation system.[145]

Describing two types of igniters (glow-plug and spark), "Report on FA and DDT" states:

> [An] important mitigation approach is deliberate ignition of flammable accident mixtures with igniters. The intention is to start a deflagration as early as possible before dangerous amounts of hydrogen have accumulated. Two types of devices have been developed; namely, glow-plug and spark igniters. Glow-plug igniters require a continuous power supply, which may not be available in severe accident sequences. Siemens developed an autark battery-powered spark igniter, which is activated by temperature or pressure set points... This module operates passively and does not require operator action. The reliable function was shown for a wide range of severe accident conditions.[146]
>
> The initial design used a spark interval of 10 sec. Large-scale experiments with dynamic H_2 injection and spark ignition[147] have shown, however, that a shorter spark interval would bring an additional safety margin. Ignition occurs only after the edge of the combustible gas cloud has arrived at the nearest igniter position, and the next spark is activated. The flame then

[145] IAEA, "Mitigation of Hydrogen Hazards in SA," p. 36.

[146] R. Heck, G. Keller, K. Schmidt, H. J. Zimmer, "Hydrogen Reduction Following Severe Accidents Using the Dual Recombiner-Igniter Concept," Nuclear Engineering and Design, Vol. 157, 1995, p. 311.

[147] W. Breitung, S. B. Dorofeev, V. P. Sidorov, "Large Scale Hydrogen-Air Combustion Experiments with Dynamic H_2-injection and Spark Ignition," Transact. of the 13th Int. Conf. on Structural Mechanics in Reactor Technology (SMiRT-13), Porto Allegre, Brazil, August 13-18, 1995, Vol. I, p. 199.

travels back to the source location. A short spark interval would minimize the H_2 content of the cloud at first ignition.[148]

Regarding the importance of conducting careful analyses before the installation of igniter systems, "Report on FA and DDT" states:

> The main question in the application of the igniter concept is its safety orientation. The use of igniters should *reduce* the overall risk to the containment and should not create new additional hazards such as a local detonation. A new methodology for safe igniter implementation in a 3D containment was recently developed and implemented into the GASFLOW code.[149] The method was applied to a bounding dry release scenario in a future PWR in which the steam from the core is condensed in a water pool. In the unmitigated case, significant DDT potential developed in the whole containment, including the possibility of global detonations. The analysis with igniters in different positions predicted deflagration or detonation in the break compartment, depending on the location of the igniter. Igniter positions were found that lead to early ignition, effective H_2 removal, and negligible pressure loads. This approach can be used to determine the number and position of igniters necessary to control different hydrogen-release scenarios in different plant designs.
>
> In summary, the installation of an igniter system for H_2 mitigation requires careful analysis regarding the number and location of igniters to exclude local detonations. The theoretical understanding and the numerical tools are sufficiently developed and verified to allow conclusive predictions with sufficient safety margins. The principal drawback of igniters is that they are not effective under inert conditions, which can arise from high steam concentrations or local oxygen burnout [emphasis not added].[150]

In the event of a severe accident, the number and location of the igniters of an igniter system is important for effective and safe hydrogen mitigation. Timing is also important because "[t]he concentration of hydrogen in the containment may be combustible for only a short time before detonation limits are reached."[151] Furthermore,

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[148] OECD Nuclear Energy Agency, "Report on FA and DDT," pp. 1.8, 1.10.

[149] W. Breitung, S. B. Dorofeev and J. R. Travis, "A Mechanistic Approach to Safe Igniter Implementation for Hydrogen Mitigation," Proc. of the OECD/NEA/CSNI Workshop on the Implementation of Hydrogen Mitigation Techniques, Winnipeg, Manitoba, Canada, May 13-15, 1996, AECL Report, AECL-11762; CSNI Report, NEA/CSNI/R(96)8; March 1997, pp. 199-218.

[150] OECD Nuclear Energy Agency, "Report on FA and DDT," p. 1.10.

[151] Peter Hofmann, "Current Knowledge on Core Degradation Phenomena, a Review," Journal of Nuclear Materials, Vol. 270, 1999, p. 208.

"the use of [water] sprays...can result in [a rapid condensation of steam and] a de-inertization of the containment atmosphere and, hence, provoke deflagrations."[152]

Clearly, the effective and safe use of igniters is a complex matter that needs to be thoroughly analyzed.

3. Recent Reports that have Questioned the Safety of Using Igniters to Mitigate Hydrogen at Certain Times in Severe Accidents and/or without having Conducted Thorough Safety Analyses with Computer Codes

Hydrogen igniter systems could help mitigate hydrogen in a severe accident; however, some recent reports have questioned the safety of using igniters to mitigate hydrogen at certain times in some severe accident scenarios and/or without having conducted thorough safety analyses with computer codes.

Below are quotes from recent reports that: 1) question the safety of using igniters in a severe accident; 2) emphasize that igniters are effective at hydrogen mitigation but that igniters must be used at precisely the correct time in order for them to not cause detonations in a severe accident; and 3) emphasize that igniters are effective at hydrogen mitigation but that igniters must be only used in cases where the affects of their use is entirely predictable and that "[a] prediction must show, that the integrity of the containment will not be challenged by any turbulent deflagration caused by the...deliberate ignition of a mixture of hydrogen, air and steam."[153]

The quotes from such recent reports pertaining to the use of igniters in severe accidents are as follows:

1) An OECD Nuclear Energy Agency report, "Report on FA and DDT," published in August 2000, states:

> The main question in the application of the igniter concept is its safety orientation. The use of igniters should *reduce* the overall risk to the containment and should not create new additional hazards such as a local detonation [emphasis not added].[154]

[152] IAEA, "Mitigation of Hydrogen Hazards in SA," p. 62.
[153] Helmut Karwat, "Igniters to Mitigate the Risk of Hydrogen Explosions—A Critical Review," Nuclear Engineering and Design, 118, 1990, p. 268.
[154] OECD Nuclear Energy Agency, "Report on FA and DDT," p. 1.10.

2) A paper, "Studies on Innovative Hydrogen Recombiners as Safety Devices in the Containments of Light Water Reactors," published in 2004, states:

> The introduction of igniters as discussed in the past still seems to be very questionable as the prediction of hydrogen distribution and combustion in the containment is at present not reliable enough to ensure the safe application of this measure.[155]

3) A paper, "Current Knowledge on Core Degradation Phenomena, a Review," published in 1999, states:

> The concentration of hydrogen in the containment may be combustible for only a short time before detonation limits are reached. This limits the period during which igniters can be used.[156]

4) A paper, "Safety Implementation of Hydrogen Igniters and Recombiners for Nuclear Power Plant Severe Accident Management," published in 2006, states:

> For a postulated accident, hydrogen will accumulate in the upper region of the room because of buoyancy. Reasonable location of the igniter system and selection of the initial ignition time are critical to effective hydrogen removal and control of the hydrogen concentration and the high local thermal and pressure loads. Hydrogen can be removed by a slow diffusion flame, with flame acceleration and DDT excluded. With early ignition, the hydrogen will be eliminated by slow combustion without high thermal and temperature loads, but with late ignition, hydrogen detonation transition will quickly occur with high local thermal and pressure loads which will threaten the integrity of the containment.
>
> Using igniters only [without the support of hydrogen recombiners] does not remove the hydrogen effectively when hydrogen concentration is less than the flammability limit or when the steam concentration is too high.[157]

5) A paper, "Igniters to Mitigate the Risk of Hydrogen Explosions—A Critical Review," published in 1990, states:

> Within the USA two types of containments have been equipped with systems for controlled ignition. These are [BWR] pressure suppression system containments of the MARK III type and some [PWR]

[155] Ernst-Arndt Reinecke, Inga Maren Tragsdorf, Kerstin Gierling, "Studies on Innovative Hydrogen Recombiners as Safety Devices in the Containments of Light Water Reactors," Nuclear Engineering and Design, 230, 2004, p. 59.

[156] Peter Hofmann, "Current Knowledge on Core Degradation Phenomena, a Review," p. 208.

[157] Xiao Jianjun, Zhou Zhiwei, Jing Xingqing, "Safety Implementation of Hydrogen Igniters and Recombiners for Nuclear Power Plant Severe Accident Management," Tsinghua Science and Technology, Vol. 11, Number 5, October 2006, p. 557.

containments provided with ice condensers to reduce the global pressure built-up. ...

In case of the release of large amounts of hydrogen during a severe accident sequence the hydrogen initially will accumulate inside the steam inerted area. It can reach the air-enriched areas only via a predetermined flow path.

[I]gniters which have been installed downstream the ice condensers...are efficiently protected from the immediate mechanical impact of the local pipe rupture. They may ignite reliably if inflammable concentrations have been reached. ...

Under such conditions the implementation of the controlled ignition appears to be acceptable *even if the predictability of the activated combustion processes is less than vague* [emphasis added].[158]

6) A SNL report, "Hydrogen-Steam Jet-Flame Facility and Experiments," states:

[A] serious problem may be the formation of diffusion flames at the point-of-release of the hydrogen-steam mixture into the containment. The jet of steam and hydrogen will entrain and mix with the containment atmosphere, and possibly burn as a turbulent diffusion flame. The ignition source could be accidental (arcing switch contacts) or deliberate (glow plug [igniters]), and, if the jet mixture is hot enough, spontaneous ignition could occur (auto-ignition). The primary threat from diffusion flame combustion will be the high thermal loads imposed by the flame on safety-related equipment.[159]

7) An NRC letter to licensees, "Completion of Containment Performance Improvement Program, Etc.," states:

A potential vulnerability for Mark III [BWRs] involves station blackout, during which the hydrogen igniters would be inoperable. Under these conditions, a detonable mixture of hydrogen could develop which could be ignited upon restoration of power. ...

[158] Helmut Karwat, "Igniters to Mitigate the Risk of Hydrogen Explosions—A Critical Review," p. 270.

[159] Joseph E. Shepherd, "Hydrogen-Steam Jet-Flame Facility and Experiments," NUREG/CR-3638, October 1984, available at: www.nrc.gov, NRC Library, ADAMS Documents, Accession Number: ML071650392, p. 3.

> The same situation could occur in [PWR] ice condenser containments as in Mark III containments relative to hydrogen detonations following restoration of power.[160]

8) On the importance of predicting the affects of the controlled ignition of hydrogen in a severe accident, "Igniters to Mitigate the Risk of Hydrogen Explosions—A Critical Review" states:

> The application of controlled ignition requires that the combustion process must be predictable for any case of its activation. A prediction must show, that the integrity of the containment will not be challenged by any turbulent deflagration caused by the incidental or deliberate ignition of a mixture of hydrogen, air and steam. Moreover, also highly energetic local deflagrations must not damage internal structures of steel containments leading to the formation of internal missiles.[161]

As quoted in section III.F.4, an IAEA report claims that in the USA, "[analyses do] not include advanced methods such as the use of CFD codes to find a more refined hydrogen containment distribution, or loads from flame acceleration."[162] Clearly, there must be a review of how igniters would perform in different severe accident scenarios. It must be demonstrated that under no circumstances would igniters cause detonations in the event of severe accidents at PWRs with ice condenser containments or at BWR Mark IIIs.

(It is noteworthy that Westinghouse's probabilistic risk assessment for the AP1000 claims that "[c]ontainment failure from a directly initiated detonation wave is not considered to be a credible event for the AP1000 containment. There are no ignition sources of sufficient energy to directly initiate a detonation in the AP1000 containment."[163]

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[160] NRC, letter to all licensees holding operating licenses and construction permits for NPPs, except licensees of BWR Mark Is, "Completion of Containment Performance Improvement Program, Etc.," July 6, 1990, p. 1.
[161] Helmut Karwat, "Igniters to Mitigate the Risk of Hydrogen Explosions—A Critical Review," p. 268.
[162] IAEA, "Mitigation of Hydrogen Hazards in SA," p. 106.
[163] Westinghouse, "AP1000 Design Control Document," Rev. 19, Tier 2 Material, Chapter 19, "Probabilistic Risk Assessment," Sections 19.34 to 19.35, June 13, 2011, available at: www.nrc.gov, NRC Library, ADAMS Documents, Accession Number: ML11171A405, p. 19.34-4.

Westinghouse does not consider that the AP1000 containment's hydrogen igniter system would be able to provide enough energy to directly initiate a detonation. In the event of a severe accident there would always be the possibility of plant operator error and the AP1000 containment's "*hydrogen igniters are actuated by manual action* when [the] core-exit temperature exceeds a predetermined temperature as directed by the emergency response guidelines (ERG)" [emphasis added].[164] As quoted above, "[t]he concentration of hydrogen in the containment may be combustible for only a short time before detonation limits are reached."[165]

Westinghouse's probabilistic risk assessment does not consider that plant operator error—actuating the hydrogen igniter system after detonation limits were reached—could directly initiate a detonation, which could, in turn, compromise the containment.)

IV. THE RATIONALE FOR THE PROPOSED REGULATIONS

A. The Request that PWRs and BWR Mark IIIs Operate with Systems for Combustible Gas Control that would Effectively and Safely Control the Potential Total Quantity of Hydrogen that could be Generated in Different Severe Accident Scenarios

Petitioner requests that NRC revise 10 C.F.R. § 50.44 to require that all PWRs (with large dry containments, sub-atmospheric containments, and ice condenser containments) and BWR Mark IIIs operate with systems for combustible gas control that would effectively and safely control the potential *total* quantity of hydrogen that could be generated in different severe accident scenarios (this value is different for PWRs and BWRs), which could exceed the quantity of hydrogen generated from a metal-water reaction of 100 percent of the fuel cladding active length. Systems for combustible gas control also must effectively and safely control the potential *total* quantity of hydrogen that could be generated *at all times* throughout different severe accident scenarios, taking into account the potential *rates* of hydrogen production.

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164 Westinghouse, "AP1000 Design Control Document," Rev. 19, Tier 2 Material, Chapter 19, "Probabilistic Risk Assessment," Sections 19.41 to 19.54, June 13, 2011, available at: www.nrc.gov, NRC Library, ADAMS Documents, Accession Number: ML11171A409, p. 19.41-4.

165 Peter Hofmann, "Current Knowledge on Core Degradation Phenomena, a Review," p. 208.

1. The Rationale for the Proposed Regulations Cited in Section IV.A

The results of the calculations and analyses discussed in sections III.B and III.D as well as the information discussed in sections III.C, III.E, and III.E.1, indicates that NRC needs to require PWRs with large dry containments and PWRs with sub-atmospheric containments to effectively mitigate the hydrogen that would be generated in the event of a severe accident and to require such PWRs to operate with systems for combustible gas control that would effectively and safely control the potential total quantity of hydrogen that could be generated in different severe accident scenarios, which could exceed the quantity of hydrogen generated from a metal-water reaction of 100 percent of the fuel cladding active length.. If there were a severe accident at a PWR with a large dry containment or sub-atmospheric containment, it is highly likely that there would be hydrogen combustion in the form of a deflagration or a detonation.

The results of the calculations and analyses discussed in sections III.B and III.D as well as the information discussed in sections III.C, III.E, and III.E.1, also applies to PWRs with ice condenser containments and BWR Mark IIIs. As stated in section III.A.3, the design pressures and estimated failure pressures of PWRs with ice condenser containments and BWR Mark III containments are lower than those of PWRs with large dry containments or sub-atmospheric containments, so NRC needs to require PWRs with ice condenser containments and BWR Mark IIIs to operate with systems for combustible gas control that would effectively and safely control the potential total quantity of hydrogen that could be generated in different severe accident scenarios, which could exceed the quantity of hydrogen generated from a metal-water reaction of 100 percent of the fuel cladding active length.

The information discussed in sections III.C and III.G.1 also indicates that NRC needs to require PWRs and BWR Mark IIIs to operate with systems for combustible gas control that effectively and safely control the potential total quantity of hydrogen that could be generated at all times throughout different severe accident scenarios, taking into account the potential rates of hydrogen production.

B. The Request that BWR MARK Is and IIs Operate with Systems for Combustible Gas Control or Inerted Containments that would Effectively and Safely Control the Potential Total Quantity of Hydrogen that could be Generated in Different Severe Accident Scenarios

Petitioner requests that NRC revise 10 C.F.R. § 50.44 to require that BWR Mark Is and BWR Mark IIs operate with systems for combustible gas control or inerted containments that would effectively and safely control the potential *total* quantity of hydrogen that could be generated in different severe accident scenarios, which could exceed the quantity of hydrogen generated from a metal-water reaction of 100 percent of the fuel cladding active length. Systems for combustible gas control or inerted containments also must effectively and safely control the potential *total* quantity of hydrogen that could be generated *at all times* throughout different severe accident scenarios, taking into account the potential *rates* of hydrogen production.

1. The Rationale for the Proposed Regulations Cited in Section IV.B

Given the fact that hydrogen explosions damaged primary and secondary BWR Mark I containment structures in the Fukushima Dai-ichi accident, it would seem appropriate to enhance hydrogen mitigation at BWR Mark Is and BWR Mark IIs regulated by NRC.

The information discussed in section III.C indicates that NRC needs to require that BWR Mark Is and BWR Mark IIs operate with systems for combustible gas control or inerted containments that would effectively and safely control the potential total quantity of hydrogen that could be generated in different severe accident scenarios, which could exceed the quantity of hydrogen generated from a metal-water reaction of 100 percent of the fuel cladding active length. Additionally, the information discussed in sections III.C and III.G.1 indicates that NRC needs to require BWR Mark Is and BWR Mark IIs to operate with systems for combustible gas control that effectively and safely control the potential total quantity of hydrogen that could be generated at all times throughout different severe accident scenarios, taking into account the potential rates of hydrogen production.

C. The Request that PWRs and BWR Mark IIIs Operate with Systems for Combustible Gas Control Capable of Precluding Local Concentrations of Hydrogen in the Containment from Exceeding Concentrations that would Support Fast Deflagrations or Detonations

Petitioner requests that NRC revise 10 C.F.R. § 50.44 to require that PWRs and BWR Mark IIIs operate with systems for combustible gas control that would be capable of precluding local concentrations of hydrogen in the containment from exceeding concentrations that would support combustions, fast deflagrations, or detonations that could cause a loss of containment integrity or loss of necessary accident mitigating features.

1. The Rationale for the Proposed Regulations Cited in Section IV.C

The results of the calculations and analyses discussed in sections III.B and III.D as well as the information discussed in sections III.C, III.E, and III.E.1, indicates that NRC needs to require that PWRs and BWR Mark IIIs operate with systems for combustible gas control that would be capable of precluding local concentrations of hydrogen in the containment from exceeding concentrations that would support combustions, fast deflagrations, or detonations that could cause a loss of containment integrity or loss of necessary accident mitigating features.

D. The Request that PWRs and BWR Mark IIIs Operate with Combustible Gas and Oxygen Monitoring Systems that are Qualified in Accordance with 10 C.F.R. § 50.49

Petitioner requests that NRC revise 10 C.F.R. § 50.44 to require that PWRs and BWR Mark IIIs operate with combustible gas and oxygen monitoring systems that are qualified in accordance with 10 C.F.R. § 50.49. Petitioner also requests that NRC revise 10 C.F.R. § 50.44 to require that after the onset of a severe accident, combustible gas monitoring systems be functional within a timeframe that enables the proper monitoring of quantities of hydrogen indicative of core damage and indicative of a potential threat to the containment integrity. The current requirement that hydrogen monitors be functional within 90-minutes after the initiation of safety injection is inadequate for protecting public and plant worker safety.

1. The Rationale for the Proposed Regulations Cited in Section IV.D

Given the fact that hydrogen explosions damaged primary and secondary BWR Mark I containment structures in the Fukushima Dai-ichi accident, it would seem appropriate to enhance combustible gas and oxygen monitoring systems at PWRs and BWR Mark IIIs.

The information discussed in sections III.C and III.G.1 indicates that NRC needs to require that PWRs and BWR Mark IIIs operate with combustible gas and oxygen monitoring systems that are qualified in accordance with 10 C.F.R. § 50.49. Furthermore, the information regarding hydrogen igniter systems discussed in sections III.G.2 and III.G.3 indicates that NRC needs to require that PWRs with ice condenser containments and BWR Mark IIIs (and any other NPPs that would operate with hydrogen igniter systems) operate with combustible gas and oxygen monitoring systems that are qualified in accordance with 10 C.F.R. § 50.49.

The information discussed in sections III.C and III.G.1 indicates that NRC needs to require that PWRs and BWR Mark IIIs operate with combustible gas monitoring systems that would be functional within a timeframe that enables the proper monitoring of quantities of hydrogen indicative of core damage and indicative of a potential threat to the containment integrity. Furthermore, the information regarding hydrogen igniter systems discussed in sections III.G.2 and III.G.3 indicates that NRC needs to require that PWRs with ice condenser containments and BWR Mark IIIs (and any other NPPs that would operate with hydrogen igniter systems) operate with combustible gas monitoring systems that would be functional within a timeframe that enables the proper monitoring of quantities of hydrogen indicative of core damage and indicative of a potential threat to the containment integrity.

E. The Request that Licensees of NPPs Perform Analyses with the Most Advanced Codes to Demonstrate that Containment Structural Integrity would be Retained in the Event of a Severe Accident

Petitioner requests that NRC revise 10 C.F.R. § 50.44 to require that licensees of PWRs and BWR Mark IIIs perform analyses that demonstrate containment structural integrity would be retained in the event of a severe accident. Such analyses must use the most advanced codes, such as CFD codes, to model hydrogen distribution in the containment and loads from flame acceleration as well as include sufficient supporting justification to show that the simulation realistically models the containment response to the structural loads involved. Petitioner also requests that NRC revise 10 C.F.R. § 50.44 to require that licensees of BWR Mark Is and BWR Mark IIs perform analyses (*e.g.*, modeling the performance of inerted containments), using the most advanced codes, which demonstrate containment structural integrity would be retained in the event of a severe accident. Such analyses must address severe accidents that release the potential *total* quantity of hydrogen that could be generated in different scenarios (this value is different for PWRs and BWRs), which could exceed the quantity of hydrogen generated from a metal-water reaction of 100 percent of the fuel cladding active length. Such analyses must also consider the potential *total* quantity of hydrogen that could be generated *at all times* throughout different severe accident scenarios, taking into account the potential *rates* of hydrogen production. Systems necessary to ensure containment integrity must also be demonstrated to perform their function under these conditions.

1. The Rationale for the Proposed Regulations Cited in Section IV.E

The information discussed in section III.F.4 indicates that NRC needs to require that licensees of NPPs perform analyses that demonstrate containment structural integrity would be retained in the event of a severe accident, using the most advanced codes. The results of the calculations and analyses discussed in sections III.B and III.D as well as the information discussed in sections III.C, III.E, and III.E.1, indicates that NRC needs to require that licensees of NPPs perform analyses using the most advanced codes, and that such analyses must consider the potential total quantity of hydrogen that could be generated at all times throughout different severe accident scenarios, taking into account the potential rates of hydrogen production.

F. The Request that Licensees of NPPs Perform Analyses with the Most Advanced Codes to Demonstrate that Hydrogen Igniter Systems would Operate Safely in Different Severe Accident Scenarios

Petitioner requests that NRC revise 10 C.F.R. § 50.44 to require that licensees of PWRs with ice condenser containments and BWR Mark IIIs (and any other NPPs that would operate with hydrogen igniter systems) perform analyses that demonstrate hydrogen igniter systems would effectively and *safely* mitigate hydrogen in different severe accident scenarios.

1. The Rationale for the Proposed Regulations Cited in Section IV.F

The information regarding hydrogen igniter systems discussed in sections III.G.2 and III.G.3 indicates that NRC needs to require that licensees of PWRs with ice condenser containments and BWR Mark IIIs (and any other NPPs that would operate with hydrogen igniter systems) perform analyses that demonstrate that hydrogen igniter systems would effectively and safely mitigate hydrogen in different severe accident scenarios.

V. CONCLUSION

If implemented, the regulations proposed in this petition for rulemaking would help improve public and plant-worker safety.

Respectfully submitted,

/s/

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Dated: October 14, 2011

Appendix A Figure 6.4.5.2.2-2 Containment Loads from Fast Turbulent Combustion in Future Plant[1]

[1] OECD Nuclear Energy Agency, "Report on FA and DDT," p. 6.41.

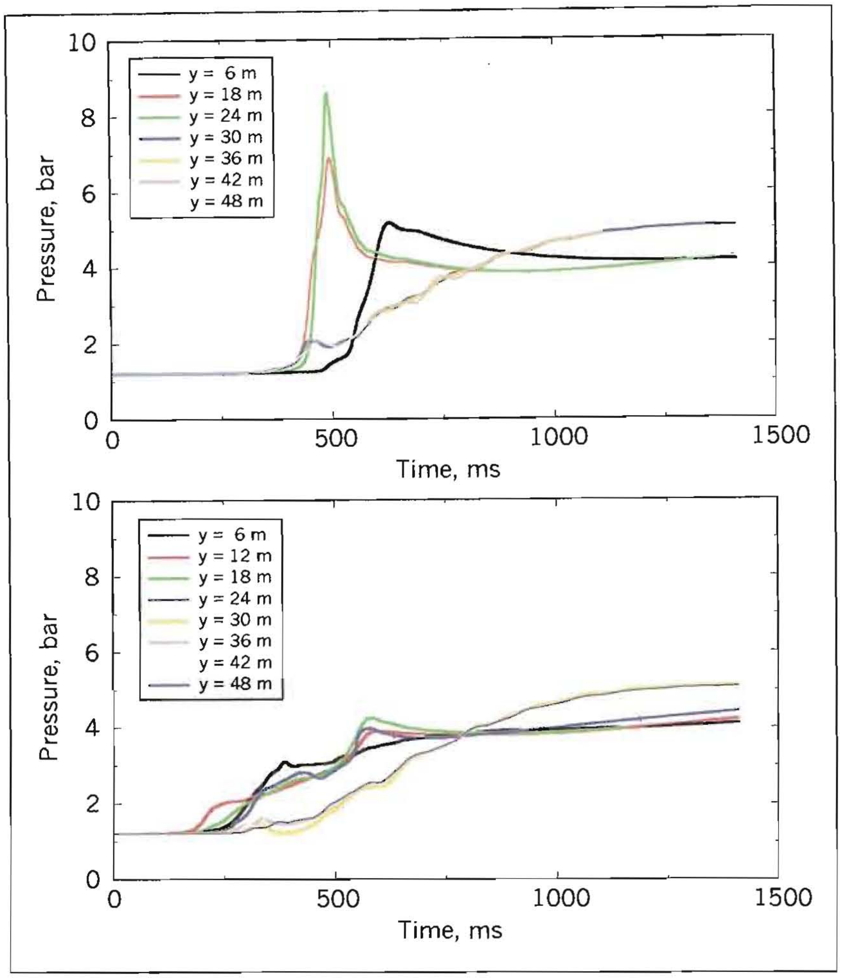

Figure 6.4.5.2.2-2 Containment loads from fast turbulent combustion in future plant, 3D COM3D calculation, initial gas distribution from GASFLOW, LOOP scenario, 44 recombiners installed. Top: pressure on the left containment wall, opposite from ignition point. Bottom: pressures on right containment wall near ignition point.

The characteristic loading times of the left and right containment wall are quite different, about 50 ms and 300 ms, respectively. When compared to the typical natural response times T_{cont} of a dry PWR concrete containment [6.18], the first case represents a dynamic load, ($T_{load}/T_{cont} << 1$), and the second case a load regime that is in the transition from dynamic to quasi-static ($T_{load} / T_{cont} \approx 1$). In the first domain, the deformation is proportional to the wave impulse, whereas in the quasi-static domain it is proportional to the peak pressure reached.

Appendix B Figure 6.4.5.2.3-2 Calculated Pressures from a Local Detonation in the Containment Dome[2]

[2] OECD Nuclear Energy Agency, "Report on FA and DDT," p. 6.44.

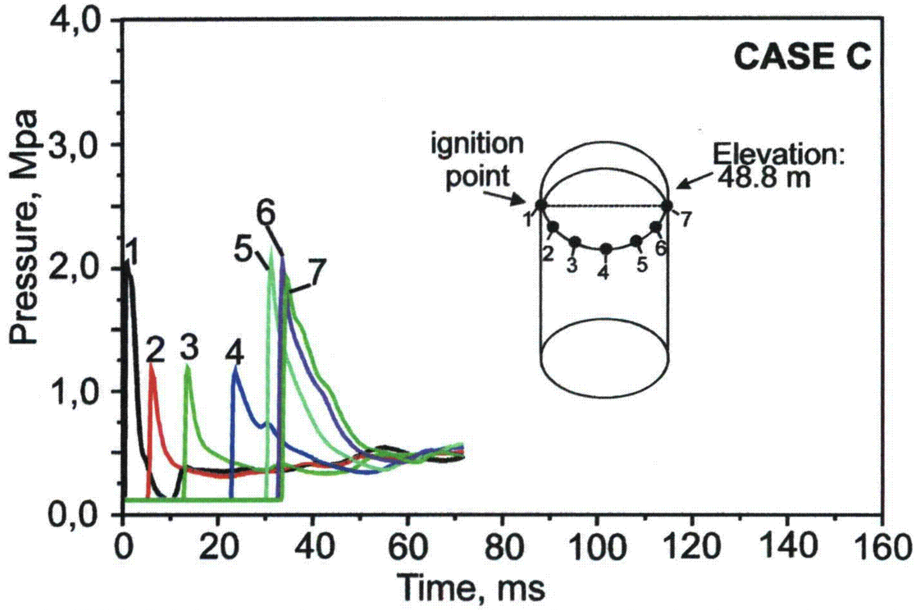

Figure 6.4.5.2.3.-2 Calculated pressures from a local detonation in the containment dome. Total H_2 inventory in the building 690 kg H_2, vertical H_2 gradient from 7% to 13% H_2, initial pressure 1.23 bar, initial temperature 47°C, LOOP scenario with 44 recombiners .

6.4.5.2.4 Results

The described calculations have shown that mitigation with recombiners alone still allows accumulation of up to roughly 700 kg H_2 in the containment and that combustion of this hydrogen mass could lead to significant dynamic loads. Although these loads may not endanger the containment integrity in the undisturbed areas, they would certainly require extensive analysis of containment integrity in regions around penetrations. Moreover, these dynamic loads could have severe consequences for safety systems that are needed for further management of an accident. Especially vulnerable are the structurally weak recombiner boxes and the spray system.

A general conclusion from these investigations is that early deliberate ignition in severe accidents, e.g., by igniters, appears necessary for further reduction of the maximum possible hydrogen inventory and of the corresponding pressure loads. Recombiner systems alone will not allow one to fulfil the new safety recommendations for future plants at least for dry LOOP scenarios. Therefore, an analysis with recombiners and igniters was performed.

6.4.5.3 Mitigation with recombiners and igniters

In addition to the 44 recombiners, one igniter was installed at each of the four IRWST exits from which the hydrogen-steam mixture would emerge in dry scenarios. Again, the MAAP sources for the LOOP scenario with reflood were used as input to the GASFLOW code.

In the simulation, the first ignition occurred at a hydrogen inventory of 110 kg in the building. Thereafter a continuous burn was predicted, with one large standing flame at each IRWST exit (Figure 6.4.5.3-1). The evaluation of the 7λ-criterion, as it is implemented in GASFLOW, showed that at no time was there a possibility of a DDT occurring and that a safe implementation of igniters is possible for the LOOP scenario. The early ignition, with most of the hydrogen still in the IRWST as a non-flammable mixture, reduced the maximum combustion pressure effectively to insignificant values.

Rulemaking Comments

From: Weaver, Jordan [jweaver@nrdc.org]
Sent: Friday, October 14, 2011 4:10 PM
To: Rulemaking Comments
Cc: Nuclear; Mark Leyse
Subject: Attn: Rulemakings and Adjudications Staff
Attachments: NRDC_Rulemaking50-44_FINAL_141011.pdf

Rulemaking and Adjudications Staff,

Please see the enclosed PDF which includes a cover letter and the associated "2.802 Petition for Rulemaking to revise 10 C.F.R. 50.44." The enclosed petition is being submitted by the Natural Resources Defense Council (NRDC) and was researched and written by NRDC consultant Mark Leyse.

Please do not hesitate to contact me if you have any further questions. NRDC appreciates your prompt consideration of this matter.

Sincerely,

--
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