Tier 3 – NTTF Recommendation 6

Purpose

The purpose of this project plan is to assess the current state of knowledge regarding hydrogen generation, transport, distribution, and combustion in light of the Fukushima Dai-ichi accident, and determine whether any new safety issues arise that result in the need for additional regulatory action (e.g., rulemaking, orders).

NTTF Recommendation and Other Direction

The Task Force recommended:

> as part of the longer term review, that the NRC identify insights about hydrogen control and mitigation inside containment or in other buildings as additional information is revealed through further study of the Fukushima Dai-ichi accident.

This recommendation was prioritized as Tier 3 in SECY-11-0137 because longer term staff evaluation was required to support a decision on the need for regulatory action. In the SRM to SECY-11-0317, the Commission agreed with the Tier 3 prioritization of Recommendation 6.

Regulations and Guidance

1. General Design Criterion 41, "Containment Atmosphere Cleanup" of Appendix A, "General Design Criteria for Nuclear Power Plants," to Title 10 of the Code of Federal Regulations (10 CFR) Part 50, "Domestic Licensing of Production and Utilization Facilities," requires, in part, systems to control hydrogen which may be released into the reactor containment be provided as necessary to control the concentration of hydrogen or oxygen and other substances in the containment atmosphere following postulated accidents to assure that containment integrity is maintained.

2. General Design Criterion 50, "Containment Design Basis" of Appendix A, "General Design Criteria for Nuclear Power Plants," to Title 10 of the Code of Federal Regulations (10 CFR) Part 50, "Domestic Licensing of Production and Utilization Facilities," requires, in part, the reactor containment structure to be designed to accommodate, without exceeding the design leakage rate and with sufficient margin, the calculated pressure and temperature conditions resulting from any loss-of-coolant accident. This margin is to reflect consideration of the effects of potential energy sources which have not been included in the determination of the peak conditions, such as energy in steam generators and as required by 10 CFR 50.44 energy from metal-water and other chemical reactions that may result from degradation but not total failure of emergency core cooling.

3. 10 CFR 50.44, "Combustible Gas Control for Nuclear Power Reactors," provides requirements applicable to the different containment designs (e.g., Mark I/II/III, Ice

Condenser, Large Dry). These requirements include: ensuring a mixed containment atmosphere, ensuring an inerted containment atmosphere, controlling combustible gas generated from a metal-water reaction involving a percentage of the fuel cladding surrounding the active fuel region, and monitoring oxygen and hydrogen concentrations in containment.

4. 10 CFR 52.47(a)(23), "Contents of Applications; Technical Information," and 10 CFR 52.79(a)(38), "Contents of Applications; Technical Information in Safety Analysis Report," both require that design certification and combined license applicants provide a description and analysis of design features for the prevention and mitigation of severe accidents including challenges to containment integrity caused by core-concrete interaction, steam explosion, high-pressure core melt ejection, hydrogen combustion, and containment bypass in their applications.

5. RG 1.7, "Control of Combustible Gas Concentrations in Containment" issued March 1971, and updated September 1976, November 1978, and March 2007, describes methods for implementing the requirements in 10 CFR 50.44.

6. NUREG-0800, "Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants: LWR [Light-Water Reactor] Edition," Section 6.2.5, "Combustible Gas Control in Containment," Revision 3, March 2007, describes methods that are acceptable to the NRC staff for implementing 10 CFR 50.44 and Section 19.0, "Probabilistic Risk Assessment and Severe Accident Evaluation for New Reactors" describes acceptance criteria for determining whether an applicant has adequately demonstrated that their design properly balances preventive and mitigative (e.g., hydrogen generation and control) features..

Staff Assessment

The NRC has long recognized the potential impact on nuclear safety and risk from the production and combustion of hydrogen gas from severe accidents. In addition to the accident at Fukushima Dai-ichi, hydrogen was also produced and burned during the Three Mile Island accident (TMI) in 1979. Following the TMI accident, the NRC strengthened the hydrogen control safety requirements, and initiated numerous broad multi-year research programs to evaluate core melt progression and a range of severe accident issues, including hydrogen production and control. As a result, the NRC has a significant knowledge base regarding hydrogen production, transport, distribution, and combustion, and has incorporated that knowledge base into our analytical tools, and deterministic and probabilistic models to assess the safety and risk implications of hydrogen generation and combustion. Also, over the years, the NRC has identified numerous Generic Safety Issues and Generic Issues (e.g., A-48, B-14, 106, 121, 167, 189, 195, 198) involving hydrogen and evaluated their impact on nuclear safety. Given the significance of the events that occurred at Fukushima Dai-ichi, the staff concludes that it is appropriate to assess the existing state of knowledge regarding hydrogen generation and combustion in light of the Fukushima Dai-ichi accident, and the potential impact on reactor safety and risk to determine whether any additional regulatory action is needed.

The production and combustion of hydrogen gas during a severe accident is dependent upon many variables, such as the nuclear power plant design, particular severe accident sequence underway, and the plant's emergency response to any hydrogen produced. The NTTF recognized such, and identified some of the interrelationships between Recommendation 6 and the other NTTF Recommendations. In particular, the NTTF noted that:

> Implementation of Task Force Recommendation 4, associated with prolonged SBO, would reduce the likelihood of core damage and hydrogen production. In addition, implementation of Recommendation 5 to enhance the containment venting capabilities for Mark I and Mark II containments, while primarily intended for overpressure protection, would also provide for the reliable venting of hydrogen to the atmosphere. These two steps would greatly reduce the likelihood of hydrogen explosions from a severe accident.

As a result, in addressing Recommendation 6, the staff concludes that it is important to coordinate efforts in addressing and resolving this recommendation with the other NTTF recommendations and to recognize the synergy in the integrated plant's safety response. Specifically, the direction from the Commission on the forthcoming SECY Paper describing potential options for venting strategies and requirements (Recommendation 5) will have a definitive impact on the path forward and level of effort associated with Recommendation 6.

<u>Hydrogen Control for Different Containment Designs</u>

In 2003, the NRC revised the hydrogen control requirements in 10 CFR 50.44, "Combustible Gas Control for Nuclear Power Reactors." This rule eliminated the requirements for hydrogen recombiners and hydrogen purge systems in currently licensed light water reactors, and relaxed the requirements for hydrogen and oxygen monitoring equipment to make them commensurate with their risk significance. However, the rule retained existing requirements for ensuring a mixed atmosphere, inerting Mark I and II containments, and providing a hydrogen control systems capable of accommodating an amount of hydrogen generated from a metal-water involving 75 percent of the fuel cladding surrounding the active fuel region in Mark III and ice condenser containments. The technical bases for the regulations were established from experience at TMI along with bounding estimates for the amount of hydrogen likely to be generated by a severe core damage accident.

This rule also specifies requirements for combustible gas control in future water-cooled reactors which are similar to the requirements specified for existing plants. However, a key difference is the need to accommodate an equivalent amount of hydrogen as would be generated from a 100 percent fuel clad-coolant reaction. Particularly, if a containment does not have an inerted atmosphere, it must limit hydrogen concentrations in containment during and following an accident that releases hydrogen (equivalent to 100 percent fuel-coolant reaction) when uniformly distributed to less than 10 percent (by volume); and maintain containment structural integrity and appropriate accident mitigating features.

Boiling water reactors with Mark I or Mark II type containments must have an inerted atmosphere. This concept reduces oxygen enough in order to suppress combustion; thereby a hydrogen generation limit is not specified. The result of a hydrogen combustion event is characterized as a relatively sharp pressure pulse and thus the intent of the hydrogen rule precludes this occurrence inside containment; but, it does not recognize the slow build-up of containment pressure as a result of the hydrogen gas generated by postulated severe core damage accidents. Therefore, containment pressure control is addressed in the severe accident management guidelines. Essentially, pressure control for severe accidents in Mark I and II containments is also related to hydrogen control for the containment and now, based on the experience from the Fukushima Dai-ichi accident, can have an impact on the reactor building.

The key attributes of Mark I and Mark II containments designs are: (1) the containment free gas volumes are relatively small compared to other light water reactors, so the hydrogen gas (and other non-condensable gases produced) and steam buildup in containment will affect the pressure rise more dramatically, and (2) BWR reactor cores have about three times the zirconium inventory compared to comparable PWR power levels, so there is a greater potential to generate significant amounts of hydrogen gas which also will affect adversely the containment pressures. Consequently, a reliable containment venting strategy is needed and must be properly integrated in the severe accident management guidelines. Thus, Mark I and II containments are more strongly coupled to control hydrogen, than other containment designs.

To determine whether additional regulatory action is needed to resolve Recommendation 6, the staff has developed this project plan to address the following key questions:

1. Did the accident reveal new information on the manner in which hydrogen gas is generated, transported, distributed, and combusts?

2. Was the manner in which the containment and the reactor buildings failed in the accident consistent with our understanding?

3. Did the accident reveal important gaps in our deterministic and probabilistic risk assessment modeling of the threat from hydrogen generation, distributed, and combustion?

4. Did the accident reveal new information that conflicts with the technical basis for the existing hydrogen generation and control requirements?

5. Did the accident reveal new technical information, not previously considered, to pursue regulatory action?

Staff Plan for Addressing NTTF Recommendation 6

1. Evaluate the Fukushima Dai-ichi accident sequences with particular emphasis on hydrogen generation from all sources and timing. Compare the accident timing and amount of hydrogen generated both in-vessel and ex-vessel, to that predicted in comparable severe accident scenarios for U.S. nuclear power plants. This assessment will include a review of information from sources such as the Government of Japan, TEPCO, INPO, and international organizations, along with any analytical modeling predictions such as the DOE/NRC MELCOR forensics analysis.

    a. Approach – Review existing reports and studies, and analytical modeling results. Assess implications of any new information on the existing state of knowledge.
    b. Product – Document results of assessment in final report.

2. As information becomes available in the near term, follow the efforts to assess the potential containment release pathways (e.g., upper drywell head, equipment/personnel hatches, instrument penetrations, bellows, seals) for hydrogen ingress into the reactor building. Also, follow the hydrogen combustion assessments on the reactor building and the safety related equipment. This assessment will include a review of information from sources such as the Government of Japan, TEPCO, INPO, and international organizations, along with any analytical modeling predictions such as the DOE/NRC MELCOR forensics analysis. This task also includes the potential need for new analytical modeling and experimental evaluation of possible containment release pathways. The staff notes that the transport, distribution, and migration of hydrogen gas following a severe accident contains a fair amount of uncertainty due to limitations in analytical modeling capabilities and the complex layout of nuclear power plants. Also, the RCS gas/steam release locations are speculative in a variety of severe accident sequences.

    a. Approach – Review existing reports and studies, and analytical modeling results. Conduct best estimate analytical modeling and evaluate containment release pathways. Assess implications of any new information on existing state of knowledge.
    b. Product – Document results of assessment in final report.

3. Assess additional hydrogen control measures and potential hydrogen ingress into adjacent buildings– including the feasibility, safety significance, and risk implications of providing additional hydrogen control measures for the primary containment and connected structures, e.g., reactor buildings and auxiliary buildings.

    a. Approach – Evaluate additional mitigative measures to improve the capability of reactor and auxiliary buildings to deal with hydrogen released during a severe accident. Quantify the impact on safety and risk of the mitigative measures and address uncertainty in performance. Conduct stakeholders meetings.
    b. Product – Document results of assessment in final report.

4. Technical Basis for 50.44 Regulatory Requirements – Assess the technical basis for NRC's existing hydrogen generation and control requirements in 10 CFR 50.44 against the results of Tasks 1-3 above. The focus of the assessment is to confirm the validity of the existing technical basis or identify gaps, and characterize the safety and risk significance of any identified gaps.

    a. Approach – Review the existing technical basis for 10CFR 50.44 and evaluate the results of Tasks 1-3 to determine the significance of any new technical information.
    b. Product – Document results of assessment in final report.

The staff will integrate the results of the above tasks into a final report that will be used to determine whether any additional regulatory action is needed to address Recommendation 6. In carrying out the above assessments, the staff is limited by the extent of information available and the validity of that information in determining the plant's response to the Fukushima Dai-ichi accident. The July 2011 NTTF report noted that sufficient information was not yet available for the Task Force to reasonably formulate any further specific recommendations related to combustible gas control based on insights from the Fukushima Dai-ichi accident. While a year has gone by since the Task Force issued their report, in actuality, very little additional empirical information has been reported regarding hydrogen generation and control from the accident. Recent efforts and information released over the past year have been focused on analytical modeling and predictions that provide some insights into the plant's response. However, the actual data and conclusive evidence on the timing and amount of hydrogen production, including contributions from both in-vessel and potential ex-vessel reactions, and the physical mechanisms and pathways for the hydrogen release from the containment to the reactor building may not be able for many years (more than 10). Past experience with the TMI-2 accident indicates that a thorough accident investigation, including physical investigation and deconstruction of the reactor building, containment, and reactor pressure vessel is necessary to fully understand and learn from a severe accident.

The staff also notes that hydrogen generation and control following a severe accident and the resulting impacts on a nuclear power plant is a highly specialized technical discipline. While the NRC and international organizations had considerable hydrogen research and regulatory programs in place in the 1980 and 1990s, those resources and many of the experts working in that discipline are no longer available. As such, the staff will be challenged in its ability to carry out this project plan in the 5-year time frame established by the Commission.

<u>Staff Recommendation</u>
The staff recommends that the Commission approve this project plan for addressing NTTF Recommendation 6. The staff will provide a recommendation to the Commission on the need for additional regulatory action based on the results of this plan.