STAFF REVIEW OF THE EXPERT PANEL RECOMMENDATIONS ON CONTAINMENT LINER CORROSION

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Mr. Darrell Dunn, RES/Division of Engineering,
Mr. Paul Klein, NRR/Division of Engineering
Dr. Allen Hiser, NRR/Division of License Renewal
Dr. Abdul Sheikh, NRR/Division of License Renewal
Dr. George Thomas, NRR/Division of Engineering

The following are the conclusions of the working group assembled to review the expert panel report on containment liner corrosion. The working group reviewed the panel's recommendations for follow-on research on:

1. Detailed liner corrosion modeling and experiments
2. Advancements in non-destructive examination methods
3. Effects of nuclear plant design and operation
4. Concrete aging and degradation and
5. Concrete repair and corrosion mitigation.

For each area, the working group summarized background information and the panel's recommendations for follow-on research. The working group also provided an evaluation that contained options and identified the optimal path forward under each topic.

Path Forward – Liner Corrosion Modeling and Experiments

1. **Background** – The expert panel report included initial back-of-the envelope calculations of containment liner corrosion which showed that the governing mechanism, macrocell accelerated localized corrosion, could result in penetration of the containment liner in a time period consistent with plant operating experience. In order to conduct these calculations, several rough, simplifying assumptions were necessary for physical properties and electrochemical parameters.

2. **Expert Panel Recommendations** – Detailed modeling of corrosion initiation and propagation was recommended to better capture the complexity of the system. The model should include refined electrochemical parameters, the effects of oxygen transport and availability, concrete quality, water content, wall dimensions, rebar placement, temperature and other variables. Subsequent or concurrent experimental investigation aimed at replicating the observed damage conditions could be conducted to determine or confirm under which conditions a sustained corrosion regime can be supported at the debris/steel interface, including required factors such as debris size, composition, transport properties, temperature, moisture content and native chloride content of the concrete.

3. **NRC Working Group Evaluation –** The back-of-the-envelope calculations support the assertion that macrocell accelerated localized corrosion is the governing corrosion mechanism for containment liner corrosion that initiated at the liner/concrete interface. Although the staff does not view liner corrosion as an issue of immediate safety significance, refined calculations will provide additional information such as the minimum time necessary for containment liner degradation that can lead to loss of function, and the morphology of the expected area of the liner plate degradation as a function of time. For example, the model should be used to predict the extent of liner corrosion that may occur in an operating cycle assuming a preexisting defect of maximum size that cannot be identified through visual inspection. The damage accrued over an operating cycle can then be compared to the required inspection frequency. Improved model calculations may also provide insight to determine whether increased corrosion rates are possible at locations where the liner is not in contact with the concrete (i.e., liner bulges and concrete voids). Bench-top experiments to determine parameter values or ranges may be necessary to develop improved models. The working group, however, does not recommend experiments to replicate damage observed in operating experience. Such experiments would be time consuming and would not likely provide additional useful information since replicating actual containment structure configurations, aged concrete, liner interface conditions, and thermal cycle history may not be possible.

4. **Path Forward Options**
    1. No additional modeling of corrosion rates or supporting experiments.
    2. Limited additional modeling to determine degradation time scales and the effects of time on the morphology of the containment liner degradation. Companion

bench-top experiments to determine values and ranges for the most important model parameters.

3. Detailed modeling of macrocell accelerated localized corrosion, with bench-top experiments to determine key parameters and prototypical confirmatory testing.

5. **Working Group Recommendations** – The working group recommends Option 2: limited additional modeling of containment liner corrosion at the liner/concrete interface. Efforts will be focused on obtaining the following information:

   - time scale for containment liner degradation,
   - morphology of expected area of containment liner degradation
   - corrosion rates and morphology at liner bulges and concrete voids

   To complement the additional modeling work, the working group also recommends using existing information to assess containment leakage as a function of area and depth of containment liner degradation. This will provide the technical basis for interpreting the liner corrosion modeling results.

<u>Path Forward – Non-destructive examination (NDE)</u>

1. **Background** – Current ASME Section XI Code requires a general visual exam of 100% of accessible liner surfaces three times in a ten year period. Areas that are suspect or identified as susceptible to accelerated degradation are subjected to VT-1 visual examination. Visual examination can be effective for detecting corrosion initiating from inside the plant but can only detect corrosion initiating from the concrete-liner interface after through-wall penetration has occurred. Per the ASME Code, local volumetric NDE is performed after corrosion is detected or wall thinning is suspected with a subsequent inspection of the same area after additional plant operation. Ultrasonic Testing (UT) is used for local liner wall thickness measurements but large scale screening is not feasible with current technology.

   After identification of through-wall containment corrosion at Beaver Valley Unit 1, the licensee committed to UT examinations of the containment liner at both Units 1 and 2 both prior to entering and during the period of extended operation.

2. **Expert Panel Recommendations** – Limited research indicates that several NDE techniques exhibit potential to detect liner corrosion propagating from the concrete-liner interface. Further investigation could be pursued with respect to detection capability and signal processing.

3. **NRC Working Group Evaluation –** The working group supports an evaluation of developing NDE technology to determine if recent advancements would permit large scale inspection for containment liner corrosion occurring at the concrete-liner interface. EPRI has proposed a program to evaluate NDE inspection methods for this application. The working group also considers that liner corrosion may occur as a function of plant age. Therefore, some volumetric inspection of the liner beyond the currently required visual examination is warranted during an extended period of operation for plants that have previously experienced liner corrosion and for all plants operating beyond 60 years.

4. **Path Forward Options**
   1. Interact with EPRI representatives to stay informed about the status of a potential program to evaluate new NDE techniques for inspection of containment liners.
   2. Continue to interact with licensees that experience liner corrosion on a plant-by-plant basis.
   3. Consider liner sampling using volumetric exams for: (a) plants that have experienced liner corrosion at the concrete interface and (b) plants that want to continue to operate beyond 60 years.

5. **Working Group Recommendations** – The working group recommends Options 1, 2, and 3 to evaluate the application of developing NDE methods to evaluate containment liner corrosion. Accordingly, the staff will:
   - Interact with EPRI representatives to stay abreast of their proposed program to evaluate new NDE techniques for liner inspection.
   - Consider development of Interim Staff Guidance to revise the Generic Aging Lessons Learned (GALL) aging management program for containment liners to include enhanced inspections for plants that have experienced liner degradation at the concrete interface.
   - Consider incorporation of liner sampling using volumetric exams as a part of renewing plant licenses for plant operation beyond 60 years.

Path Forward – Nuclear Plant Design and Operation

1. **Background** – The expert panel concluded that reinforced concrete containments may have a higher probability for liner corrosion initiating from foreign materials embedded in the concrete. This is consistent with the assumption that a greater rebar density increases the probability of foreign objects being left behind during construction and, thus, remaining in contact with the steel liner. The same logic applies to plants that are post-tensioned but include additional reinforcement for seismic considerations.

2. **Expert Panel Recommendations** – Since the probability for liner corrosion as a result of embedded foreign material may be greater in concrete containments with a higher rebar density, focusing on those containments for further study may be appropriate. Also, a more detailed study could be conducted on the cases of embedded foreign material to-date. This study could include an examination of the construction practices and procedures with respect to the locations of the embedded material to look for trends. Foreign materials may be more likely to be located at higher density rebar locations (e.g., around penetrations) or at cold joints (e.g., concrete lift layers).

3. **NRC Working Group Evaluation –** Three U.S. plants have uncovered liner corrosion propagating through-wall from foreign objects at the concrete-liner interface during inservice inspections. Although the majority of the plants in the U.S. use post-tensioned concrete construction, through-wall corrosion initiating at the concrete-liner interface has only been observed in containments with reinforced concrete construction. The plant age (since commercial operation) at the time through-wall corrosion was detected ranges from 19 to 33 years. Additional information may be useful if it confirms whether this mechanism occurs at specific concrete structure features, such as cold joints, since some plants (e.g., Beaver Valley 1) are performing follow-on ultrasonic spot tests of liner plate.

   Some locations such as concrete cold joints or regions of high reinforcing bar density may have a higher probability of containing a foreign object. However, a review of containment construction practices indicates that, within a reinforced containment, it is possible for foreign material to be introduced throughout the reinforced concrete. Therefore, the working group does not think that significant resources should be expended investigating further details from previous cases of liner corrosion from the concrete interface.

4. **Paths Forward Options**
   1. Take no additional action related to searching for additional details from those plants that have experienced corrosion from the liner-concrete interface.
   2. NRC staff contact the few licensees that experienced through-wall liner corrosion from the concrete interface requesting their voluntary assistance with a more detailed study considering the expert panel's recommendations.

3. Ask the nuclear industry to take the initiative with respect to developing detailed information from the plants that experienced through wall corrosion to see if there is any information able to predict higher susceptibility locations.
4. NRC staffs review of plant drawings to determine if they contain sufficient information to compare containment structure features with locations where foreign materials have caused liner corrosion.

5. **Working Group Recommendations** – The working group recommends Options 2 and 4 to evaluate the relationship between containment design and construction practices and the probable locations for foreign materials that may lead to corrosion at the concrete–liner interface.

   The working group performed a more detailed examination of available information for incidents of containment liner corrosion due to foreign objects at the concrete interface to determine if the locations where foreign materials were positioned are associated with specific containment structure features, (e.g., penetrations) where higher reinforcement bar density may be used. For D.C. Cook, it appeared that the corrosion occurring at the liner concrete interface was approximately 1.5 feet above a concrete construction joint. It was also apparent that there are many construction joints in the containment structure. In other cases, there was not sufficient detail in the drawings reviewed by the NRC to identify any relationship between structural features and the locations were corrosion was observed.

   Additional information about specific incidents may be requested from licensees only if the information is readily available.

Path Forward – Concrete Aging and Degradation

1. **Background** – As stated in the expert panel report, factors that influence concrete durability are related to constituent materials, construction processes, physical properties of the hardened concrete, nature of exposure conditions, and loading types and frequencies. The expert panel concluded that one potential long-term concrete degradation mechanism could be a concern and have effects on corrosion occurring at the liner interface. Specifically, reduced ettringite stability and release of sulfate at locations with embedded foreign materials and resultant reduced concrete pH values. Other concrete degradation mechanisms such as chloride ingress and carbonation were determined to be neither critical, nor likely, or would be visible at locations other than the liner-concrete interface.

2. **Expert Panel Recommendations** – Investigation of the possibility of sulfate induced corrosion of the steel liner from delayed ettringite formation and dissolution may be warranted. Potentially as part of the testing and analysis work for liner corrosion, additional work on steel plate exposed to similar concretes could be conducted to determine the severity of both temperature and the other possible concrete degradation reactions on steel corrosion in the absence of chlorides or carbonation.

3. **NRC Working Group Evaluation –** The dissolution of ettringite would result in $CaSO_4$ formation. $CaSO_4$ is not very soluble at high pH, but could become soluble if the pH is reduced. Therefore, the presence of sulfate from delayed ettringite formation and dissolution may increase corrosion rates especially in the presence of a foreign material at the concrete-liner interface. Modeling may provide insights on the magnitude of possible changes in corrosion rates with and without the presence of a foreign material. The effect of concrete degradation mechanisms are also being explored in other materials degradation related activities associated with the extended periods of operation beyond 60 years. Concrete sampling of operating or decommissioned facilities may provide material to determine if delayed ettringite formation and dissolution has actually occurred during the service life of U.S. nuclear plants.

4. **Path Forward Options**
    1. No additional testing and analysis of concrete aging and degradation. Coordinate with RES staff evaluating concrete aging and degradation related activities associated with extended (60 to 80 years) periods of operation.
    2. Explore the feasibility of limited additional corrosion modeling to determine the magnitude of effects from sulfate released as a result of delayed ettringite formation and dissolution.
    3. Sample and analyze concrete from operating or decommissioned reactor containment structures to evaluate for delayed ettringite formation and dissolution.

5. **Working Group Recommendations** – The working group recommends Options 1 and 3 to evaluate sulfate the possible effects of delayed ettringite formation and dissolution on containment liner corrosion. The staff have coordinated with ongoing efforts for evaluating materials degradation during extended periods of operation to determine the scope of these concrete degradation evaluations. In addition the staff are investigating the feasibility of obtaining concrete samples from a nuclear plant (e.g., Zion, Ginna) and determining if the samples can be evaluated for delayed ettringite formation and dissolution

Path Forward – Concrete Repair and Corrosion Mitigation

1. **Background** – Concrete repairs are used to mitigate aging related effects such as cracks and spalls, however, these repairs typically encompass small areas and are not through the containment concrete thickness. Repairs associated with temporary openings in containment affect much larger areas and result in the formation of cold joints that extend from the outside concrete surface to the liner plate. It is unclear if these repairs will result in increased corrosion susceptibility containment liner.

2. **Expert Panel Recommendations** – Procedures are available for repair of containment liners and concrete. The overall effectiveness of remedial measures for reinforced concrete materials is one area where additional information would be useful. Very little data and information are available relative to the durability and effectiveness of repairs that have been made to nuclear power plant concrete structures.

3. **NRC Working Group Evaluation** – Inspections of concrete containments are required every 5 years as part of the Section XI Article IWL of the ASME B&PV code. The required IWL inspections include visual examination of all accessible concrete surfaces. In addition, plants are required to conduct inspections of the concrete and the containment liner 2 times between Appendix J integrated leak rate tests. Repair techniques for concrete containments are well established and repair locations are documented. Small repairs for cracks and spalls are not likely to have an impact on containment liner corrosion. Repairs of temporary openings in containment for steam generator and/or reactor pressure vessel head replacement are through the containment concrete thickness and may result in cold joints that could affect containment liner corrosion susceptibility. However, repairs of temporary openings are in accessible locations and the concrete and the liner plate are inspected per requirements of ASME Section XI Articles IWL and IWE.

   Currently used repair techniques are well established and inspection requirements are sufficient to identify potential increased susceptibility of the liner to corrosion as a result of repairs to temporary openings in containments.

4. **Potential Paths Forward**
   1. No additional action or analysis of concrete repairs.
   2. Continue to monitor licensee results from ASME Section XI Articles IWE and IWL inspections of containment liners and concrete containment structures documented in in-service inspection reports.

5. **Working Group Recommendations –** The working group recommends Option 2 to evaluate the effectiveness of concrete repairs on containment liner corrosion. The NRC has a mature regulatory program in place for ongoing inspection of concrete repairs. Therefore, the staff will continue to monitor the performance of concrete repairs using the

currently required inspections of containment concrete structures and metal containment liners.