OVERVIEW OF U. S. NUCLEAR REGULATORY COMMISSION RESEARCH TO ADDRESS ISSUES RELATED TO DEGRADATION OF CONTROL ROD DRIVE MECHANISMS IN U. S. NUCLEAR POWER PLANTS

Introduction:

Since the late 1990s, the Materials Engineering Branch (RES/DET/MEB) has been conducting research to address regulatory issues in the area of vessel head penetration (VHP). Interest in this area gained momentum with the observations of indications of control rod drive mechanism (CRDM) housing cracking at Oconee Unit 2 in 1994, and the focus has been sharpened by additional discoveries at many of the B&W PWRs, together with the recent cracking discovered at the North Anna Unit 2 (Westinghouse-designed) plant. In particular, RES/DET/MEB programs have evaluated inspection technology for VHPs, stress analysis of CRDMs and closure welds, and crack growth rate studies of the nickel-base alloys used in CRDM construction. These individual focal points are integrated through probabilistic modeling of degradation processes to predict times to leakage, times to failure, and inspection criteria. The overarching thrust of these programs is to provide the technical bases for evaluating potential pressure boundary degradation, and to produce results for use in integrated risk assessments and risk-informed regulatory decisions.

Against the background of these on-going and generically-oriented programs in the critical area of VHP cracking, MEB was well-positioned to respond quickly with appropriate expertise to assess the specific issues raised by the event at the Davis-Besse NPS early last year. Toward that end, MEB redirected several contractors to varying degrees to assist in increasing the staff's understanding of the corrosion processes and to develop structural integrity models specifically for the Davis-Besse reactor pressure vessel (RPV) head, VHPs and corrosion cavity. This research summary reviews the activities directly related to the degradation of materials in the VHPs and the staff's assessment of the Davis-Besse event. The Office of Nuclear Regulatory Research (RES) has also evaluated systems performance and the potential for collateral damage that might be experienced if a CRDM housing were ejected.

This summary describes the short-term efforts to evaluate the Davis-Besse event, together with the generic and longer-term research related to VHP degradation of vessel head penetrations. It should be noted that RES has coordinated this research with other national and international activities addressing the degradation of pressure boundary materials; these efforts are an important aspect of the overall program.

Support for Davis-Besse Review:

Since the licensee discovered the cavity in the Davis-Besse RPV head on March 8, 2002, RES has drawn from the ongoing research related to Alloy 600 cracking to provide staff expertise, and has redirected contractor efforts to provide NRR with the support requested during the disposition of the event and the ensuing interactions with the licensee. Simultaneously, MEB has interacted with the relevant Materials Reliability Project task groups, sponsored by the Electric Power Research Institute (EPRI), which are also dealing with the Alloy 600 issue. RES staff participated on both the Augmented Inspection Team (AIT) and the Lessons Learned Task Force (LLTF). We

also have worked with NRR in reviewing the licensee's root cause report, and with industry to plan follow-on research and testing to understand better the mechanics of the degradation process described in the root cause report.

Staff analyses evaluating the risk implications of the Davis-Besse event - the Significance Determination Process (SDP) and the Accident Sequence Precursor (ASP) evaluation - require a variety of inputs related to the specific event, systems performance, and the nature of the degradation and its progression. The materials research program contributed to the SDP, and will contribute to the ASP, key information, including: (1) predictions of cladding failure probability as they relate to induced pressure (fragility curves) for the as-found cavity configuration, (2) the wastage rate of continued low-alloy steel corrosion from the as-found condition, (3) the calculation of the remaining time before cladding rupture would have occurred under continued cavity growth, and (4) the probability of CRDM nozzle failure leading to a LOCA event. The RES staff drew from ongoing efforts to provide this important information as follows.

Cladding Capacity Analysis: RES performed detailed finite element analyses of the as-found cavity to evaluate the failure probability of the cladding and the anticipated failure time in the event of continued cavity growth. RES provided the resulting data to NRR for the SDP. Using the best data available at the time (about October, 2002), ORNL computed that the unflawed cladding, as found, could have supported more than twice the normal operating pressure. Secondly, if (somehow) the plant had continued to operate without discovery of the cavity, and assuming the cavity was actively growing at the maximum wastage rate of 7 inches per year, it would have required a minimum of 12 months of operation, with continued corrosion and cavity enlargement before a rupture would have occurred. Note that these analyses have several uncertainties, including the effects of cracks in the cladding. It should be pointed out that the licensee has continued analysis of the sizing and dimensions of the cavity, and the integrity of the cladding over the last few months. The licensee discovered that the exposed surface of the clad contained a network of cracks. The depth of cracks will be determined in the next couple of months. The more accurate data on the morphology and depth of the clad cracks is necessitating a revision of these calculations, and a possible reduction in the amount of margin that was originally calculated is a likely outcome.

RES is also considering an experimental program of limited scope to confirm the cladding failure mode. The licensee's forthcoming metallographic examination of the clad and cracks will provide important data for these analyses. In addition, our analyses will explicitly address uncertainties and provide fragility curves for the ASP evaluation being conducted by RES.

Boric Acid Corrosion Rates: The staff completed a review of foreign and domestic nuclear plant corrosion incidents that bear some resemblance to the corrosion at Davis-Besse. This review was coupled with a review of those laboratory experiments that bear reasonable similitude with the expected Davis-Besse corrosion process. Based on the accumulated data, corrosion rates of up to 5 to 7 linear inches per year are considered reasonable for low-alloy steel in an aqueous solution of concentrated boric acid. Coupled with the ORNL failure probability analyses of unflawed cladding discussed above, these corrosion rates suggest that the Davis-Besse reactor was still at least a year away from a small-to-medium LOCA rupture. RES provided this information to NRR for the SDP, and it will also be considered in the ASP analysis.

CRDM Nozzle Failure Probability Analysis: A preliminary probabilistic model was developed at

Argonne National Laboratory (ANL) to estimate nozzle failure probability when circumferential cracks were discovered at Oconee Nuclear Station Unit 3, in 2001. This model has been further refined based on the ongoing CRDM stress analysis and additional crack growth data, both of which are part of the staff's generic CRDM research effort. RES provided the resulting model to NRR for use in the SDP and it will also be used in the ASP evaluation.

The short-term response required for Davis-Besse is a natural outgrowth from MEB's ongoing suite of longer-term programs that address the broader issues of reactor pressure boundary degradation and VHP cracking. Programs have been in place for several years in the following topical areas.

Broad-Scope Generic Programs:

Non-Destructive Examination: The RES program at Pacific Northwest National Laboratory (PNNL) is evaluating enhanced methods of ultrasonic testing (UT) and eddy current (ET) inspection, and better analysis of UT and ET signatures to identify reliably the modes of degradation of VHPs, closure welds, and corrosion damage. A cut-out from an RPV head of a canceled plant is currently being used to interrogate the volume in and around the J-groove weld and nozzle, which are the locations where cracking has been observed and which are particularly difficult to inspect. These studies will assess the probability of flaw detection, estimate defect sizing uncertainties, and develop inspector qualification procedures leading to more reliable interpretation of inspection results. This is an area where the RES program is well-coordinated with the industry efforts. The staff routinely makes use of inspection sample sets developed by the industry.

CRDM Structural Integrity and Leakage: RES is already conducting research to improve the probabilistic model for determining the failure probability of CRDM nozzles attributable to circumferential cracking. The program has produced an improved assessment of residual stresses in VHPs and their symbiosis with resulting crack growth rate analyses to provide more accurate failure times, which are key to evaluating inspection intervals that can effectively preclude leakage. This program also seeks to develop leak rate models applicable to the CRDM geometry, and probabilistic assessments of leakage rates from the time of through-wall cracking to support assessments of the potential consequences of leaks that might develop. The industry is engaged in parallel efforts, and comparisons of the predictions to the staff's analyses have improved both models. The models are being applied in conjunction with corrosion data to assess the conditions that could lead to rapid degradation of the RPV head.

Crack Initiation and Growth Rates of Alloys 600 and 182 (and Alloys 690 and 152/52): For many years, RES has had an aggressive program to evaluate the effects of the water coolant on the degradation of pressure boundary materials. As degradation of Alloy 600 and the associated weld materials has become an increasingly important issue over the past several years, RES has adjusted it's research program to emphasize degradation of these materials and potential degradation of the replacement materials, Alloy 690 and the 152/52 welds. The objective of this ongoing research is to continue stress-corrosion crack initiation and crack growth rate testing of CRDM and J-weld alloys in simulated PWR environments. This will include testing CRDM and J-weld alloys removed from the RPV head of the Davis-Besse plant. The initiation tests will show whether cracks can form with little or no incubation period, and will provide crack shape information as a function of the material constitutive properties, residual stress and grain size. The

crack growth rate tests will demonstrate how the materials used in constructing the original Davis-Besse head perform in comparison with other alloys. This program also includes testing of Alloy 690 and 152/52 because they are the industry's preferred replacements for Alloys 600 and 182, respectively. RES participates in an EPRI-managed international program addressing these issues, and the broader RES corrosion-induced cracking program is structured to coordinate with these national and international activities.

Corrosion and Corrosion Potential of Reactor Steels in Concentrated Boric Acid Solutions: In evaluating the corrosion processes that resulted in the degradation of the Davis-Besse RPV head, the RES staff discovered that basic corrosion data had not been developed for the types of steels used in RPV and other pressure boundary components exposed to boric acid solutions. This basic information is key to assessing unanticipated sets of circumstances that could result in rapid degradation of the pressure boundary and to implementing appropriate inspection and maintenance procedures. The objective of this new program is to measure the wastage rates of reactor RPV steel and cladding steel in boric acid solutions of varying concentrations and at various temperatures. One program requirement is to complete measurements of the corrosion rates and electrochemical potential of RPV steel, 308SS cladding, and Alloys 600 and 182 in flowing and quiescent boric acid solutions over a range of applicable temperatures and solution concentrations.

The objective of this task is to determine the set of circumstances that is needed to promote the rapid and extensive degradation of the pressure boundary observed at Davis-Besse. For example, this task will examine whether a slow leak from a VHP nozzle results in this rapid corrosion without the significant boric acid deposit that was present at Davis-Besse. The approach to addressing this issue will be to develop and test a simulated leak into a crevice and monitor the degree of plugging of the annulus openings, as well as the progress of the corrosion of the low-alloy steel.

Integrated Plan: The overall objective of the RES program is to derive and verify an integrated, probabilistic calculational model that can support evaluation of inspection techniques and intervals for vessel penetrations for long-term management of VHP degradation and incorporation in overall risk assessments. The model will incorporate uncertainties in critical factors such as: (1) sizing of cracks as determined through nondestructive examinations; (2) probability of detection; (3) variation in crack growth rates, as a result of microstructural and environmental conditions; (4) variations in stress intensity factor, primarily as a result of residual stresses; (5) variations in leakage rates; and (6) structural integrity evaluations. This integrated program plan already addresses several recommendations made by the Davis-Besse Lessons Learned Task Force, particularly in the area of stress corrosion cracking. Some other recommendations (e.g., online leakage detection system) may require some redirection or additional development of RES programs.

Industry Cooperation and Other Supporting Activities: As noted previously, there has been and continues to be strong cooperation among RES, the industry, and the international community involved in the issue of pressure boundary material degradation. The cooperation is structured to avoid potential conflicts of interest by focusing on the development of data, test samples, and comparison of analysis results. This permits a continuing dialogue and sharing of information, without permitting inappropriate influence by the regulated industry. The most appropriate research area identified for cooperation is the development of relevant boric acid corrosion data.

Additionally, the NRC and the industry are investigating the use of the materials from other discarded components, such as the North Anna 2 RPV head, in both NRC and industry research programs to provide ideal surrogate materials that are representative of those used in operating PWRs.

The international community has also expressed significant interest in the broader issue of primary water stress corrosion cracking of nickel-based alloys, which are used in several components of the pressure boundary including VHPs, lower head penetrations, and pressurizer heater sleeves (the Alloy 600 penetration that was the first to exhibit cracking and leakage). RES is organizing a conference on March 24-26, 2003, to provide an open forum to discuss worldwide experiences and latest findings in the area of PWSCC, inspections, materials degradation, and repair techniques. Representatives of the NRC and its international peers, the industry, and researchers are all expected to participate in this conference. Additionally, an international activity to develop a database on the nickel-based alloys is also being discussed.

The research program incorporates operating experience in adjusting priorities to make certain key information is available to support regulatory assessments of immediate issues and future inspection programs, to preclude recurrence of those events and to identify other potential types of degradation. Overall, the RES effort to address the recent Davis-Besse event provides an excellent example of the staff's ability to bring staff and contractor expertise to bear - rapidly and effectively - on an emergent problem.

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