1. Introduction, Purpose and Scope

In March 2002, during a refueling outage inspection, a large wastage cavity was discovered in the reactor pressure vessel (RPV) head at the Davis-Besse nuclear plant in Ohio. The wastage cavity was adjacent to the control rod drive mechanism (CRDM) Nozzle 3 near the top of the RPV head. The discovery of this cavity eventually resulted in the RPV head being replaced with a new head refurbished from the canceled Midland nuclear plant in Michigan. As a result of the event, the Davis-Besse plant was shut down until March 2004.

Exponent Failure Analysis Associates (Exponent) and Altran Solutions (Altran) were contracted to prepare this analysis by FirstEnergy Nuclear Operating Company (FENOC) in an arbitration against Nuclear Electric Insurance Limited (NEIL), the industry insurance organization that provides insurance to nuclear plant owners and operators and against which FENOC has a pending claim that is the subject of this arbitration.

Exponent and Altran addressed a number of issues that are involved in the arbitration claim. These issues relate to whether the event that caused the damage to the Davis-Besse RPV head was:

- A “sudden, event of the moment”;
- A “condition which developed, progressed or changed over time or which was inevitable”;
- An “event that happened by chance, was unexpected and unforeseeable”;
- Caused by “any ordinary form of deterioration or wear and tear”.

Also related to these key issues was whether or not the wastage cavity that developed at CRDM Nozzle 3 could have been detected in April-May 2000 when the Davis-Besse plant was shut down for its twelfth refueling outage (12RFO).

In Section 2 that follows we summarize the principal conclusions and opinions that we have reached that are relevant to the issues in the arbitration. These conclusions and opinions are based upon the review and analysis set forth in Sections 4 through 10. In Section 3 we provide a brief description of the Davis-Besse plant, the RPV and the CRDMs.

In Section 4, we first describe the plant UT inspections that led to the discovery of the wastage cavity at CRDM Nozzle 3, and the subsequent laboratory inspections and metallurgical examinations that were performed on the CRDM nozzles and the wastage cavity at Nozzle 3. We also describe in Section 4 the wide-ranging analysis and investigation effort that was undertaken by FENOC, by industry organizations such as the Electric Power Research Institute (EPRI), and by the US Nuclear Regulatory Commission (NRC), which is ongoing today almost four years after the event. This extensive industry effort is an indication that this was not just an unanticipated event, but one that still remains largely unexplained.

In Section 5, we review and analyze the industry history of CRDM nozzle cracking and leakage between 1991 and 2002, and the industry and regulatory responses to this ongoing issue during that time period. With almost 10,700 CRDM nozzles in 155 operating PWR plants around the world, cracks have been found in only 414. Other than the Davis-Besse Nozzle 2 and 3 cracks, none of these axial cracks extended more than 0.6 inches above the nozzle weld, and none caused significant leakage. Moreover, other than the Davis-Besse event, there was no reported significant wastage of the RPV head as a result of any of these leaks. In contrast, the long axial crack discovered in Nozzle 3 in February 2002, which extended 1.23 inches above the weld was unprecedented. While much work has been undertaken to investigate and understand the reasons for this long crack at Davis-Besse Nozzle 3, it remains a unique, singular, and in many ways an unexplained “event of the moment” that can not, be considered the result of any expected or foreseeable ordinary, “wear and tear” process.

In Section 6, we present the results of our review and analysis of the industry history of boric acid leakage and corrosion of carbon steel components that occurred beginning in

1980 to 2002, the industry and regulatory responses to this ongoing issue during that time period, and the large body of relevant corrosion research that is available.

It is clear from our review of this thirty year history that the large wastage cavity discovered at Davis-Besse CRDM Nozzle 3 in March 2002 was again a unique and singular event that was totally unexpected and unanticipated either from the prior three decades of operating experience, or from the large body of boric acid corrosion research that had been conducted over that same time period.

Out of the approximately 155 operating PWR plants worldwide, and prior to the Davis-Besse event, only minor boric acid wastage of the RPV head had been reported in three isolated events over a 32-year time period from 1970 through 2002. In those three events, despite the fact that considerable quantities of boric acid had been deposited on the RPV head, no significant boric acid wastage of the RPV head was found under the deposits, all three RPV heads were returned to service, and are still in service today. At these three plants, the boric acid leakage occurred from leaking components (flanges) above the RPV head.

Similarly, leakage from the CRDM flanges in B&W-designed plants resulted in boric acid deposits on the RPV head on numerous occasions over the 30 or so years these plants have been operating, none of which caused any significant or reported wastage of the head. Therefore, boric acid deposits on the RPV head were not expected to, nor had they proved to, cause any significant wastage of the RPV head material.

The large wastage cavity at Davis-Besse CRDM Nozzle 3, as well as the smaller sub-surface cavity at CRDM Nozzle 2, remain the only reported instances of significant RPV head wastage caused by boric acid leakage from cracked CRDM nozzles.

In Section 7, we first summarize the response by FENOC to the industry experience with CRDM nozzle cracking and boric acid corrosion in the years leading up to 2002. We reviewed and formed opinions concerning the refueling outage and other operational activities at the Davis-Besse plant between 1983 and 2002, leading up to the March 2002 discovery of the corrosion cavity. This effort included a review of the RCS leakage program and the history of CRDM flange leakage during all relevant RFOs to document the efforts of Davis-Besse staff and management to address the boric acid leakage issue.

The severe wastage discovered during the RPV head inspection at 13RFO was completely unanticipated and unexpected. No individual or organization in the nuclear utility industry, ranging from the reactor vendors, owner's groups, operators, or regulators, anticipated that such severe RPV head wastage due to boric acid deposits was possible.

None of these organizations identified the potential for cracking of the CRDM nozzles to lead to significant RCS leakage and resulting head wastage. The unexpected nature of this event is further emphasized by the accidental discovery of the wastage cavity due to an unexpected tool movement during the nozzle repair process, as noted in Section 4 of this report.

In Section 8, we describe the results of our finite element stress analysis (FEA) of Davis-Besse Nozzle 3, and our predicted crack growth for the long crack at that nozzle. In this work, recently available experimental measurements developed by an NRC research program at Argonne National Laboratory (ANL) has provided new data for the crack growth rates for Alloy 600 material specifically taken from Davis-Besse Nozzle 3. While the very high crack growth rates measured for this material still remain unexplained, they allowed us to develop an accurate timeline for the growth of the long axial crack at Nozzle 3, which we have concluded occurred over a much shorter time frame than previously reported.

In Section 9 we describe the results of the detailed computational fluid dynamics (CFD) modeling effort that we undertook to develop a better understanding of the thermal hydraulic conditions in the Nozzle 3 annulus and developing wastage cavity. To our knowledge, there is no published work on this subject, and the initial phase of this effort has provided considerable insights into the development of thermal hydraulic environments in the CRDM annular crevice and developing wastage cavity. In turn, this has allowed us to relate these conditions to the potential metal removal rates by mechanical jet cutting, jet impingement, molten metaboric acid corrosion, flow assisted corrosion, and possibly concentrated aqueous boric acid corrosion/erosion.

Finally, in Section 10, we integrate the data and analysis from the preceding sections to develop a chronology of the crack growth and wastage cavity development at Davis-Besse CRDM Nozzles 2 and 3. We conclude that at 12RFO in April-May 2001, the incipient forming sub-surface wastage cavity at Nozzle 3 would not have been found even if the RPV head had been completely cleaned of boric acid deposits, because at that time boric acid accumulation from the very low leak rate would have been miniscule. Moreover, even had there been no pre-existing boric acid deposits on the RPV head from CRDM flange leakage at 12RFO, the sub-surface cavity that was present would not been detectable from the very small enlargement of the nozzle annulus that we believe to have been present at that time. The crack growth, CFD modeling, and analysis of the potential metal removal and wastage mechanisms lead us to conclude that a critical point was reached around October-November 2001 when the upward growing nozzle crack and the rapidly downward growing wastage cavity intersected. After that critical point in time, rapid metal removal of the remaining one inch of steel occurred, uncovering the large pre-existing weld crack. The leak rate increased by a factor of eight, the growth of the wastage cavity accelerated further, with most of the cavity formation between October-November 2001 and February 2002.

The Davis-Besse RPV head wastage event was therefore not the result of ordinary "wear and tear". It was an unanticipated, unforeseeable, and extraordinary "event of the moment" that was brought about by a unique combination of a large, rapidly growing crack in CRDM Nozzle 3, leakage from that crack at a rate and at a location that caused a unique thermal hydraulic environment to develop in the nozzle annulus, that in turn caused the wastage cavity to develop at not just an unusual, but at an unprecedented rate.