August 26, 2003

MEMORANDUM TO: R. William Borchardt, Acting Director
Office of Nuclear Reactor Regulation

FROM: Ashok Thadani, Director **/RA/ by Jack Strosnider for:**
Office of Nuclear Regulatory Research

SUBJECT: RESEARCH INFORMATION LETTER RIL-0301, THE LOWER HEAD FAILURE PROGRAM SPONSORED BY THE NUCLEAR ENERGY AGENCY OF THE ORGANIZATION FOR ECONOMIC COOPERATION AND DEVELOPMENT

The purpose of this research information letter (RIL) is to present insights developed from an Organization for Economic Cooperation and Development/Nuclear Energy Agency (OECD-NEA) study of failure of the lower head of a reactor pressure vessel (RPV) following a core melt accident. These insights can be used broadly to assess the adequacy of severe accident management strategies in preventing vessel failure. The failure of the lower head defines the initial conditions for ex-vessel events that threaten the integrity of the containment with potential release of radioactivity to the atmosphere. While core melt accidents are low-probability events, they can have potentially high consequences. Thus, it is important to understand the progression of severe accidents, including the potential of lower head failure in order to estimate plant risk or assess accident management strategies to ameliorate their consequences.

Risk analyses indicate that severe accident scenarios that do not proceed to vessel failure (i.e., molten core is retained in the lower head of the RPV similar to TMI-2 accident) pose no risk to public health and safety. Accordingly lower head integrity constitutes an important barrier in the late phase of severe accident progression and was the subject of significant international research. During this late phase of severe accidents, molten core materials impose thermal loads in addition to mechanical loads due to pressure on the lower head of the RPV. A memorandum to Sam Collins dated June 11, 2001, RIL-0008, described the RASPLAV project that provided data on the natural convection behavior of molten core materials and resulting thermal loads on the RPV lower head. This RIL expands on the RASPLAV project to address the RPV lower head material response as a result of the imposed thermal load and the prevailing pressure load that might be expected in the late phase of severe accidents. Results from these programs are used to validate and improve models for RPV lower head failure, specifically with regard to time history and location of the failure. These improved models are being implemented in the USNRC MELCOR severe accident code. With this improvement, the MELCOR code can be used to assess lower head failure of the RPV for various accident sequences, reactor designs, and vessel boundary conditions (e.g., ex-vessel flooding). The Office of Nuclear Regulatory Research (RES) recommends that appropriate staff be cognizant of the insights contained in this RIL, and the detailed information in the attachment, when assessing accident management strategies or plant designs.

Attachment: Summary of the OECD Lower Head Failure Program

CONTACT: Ali Reza Behbahani (axb), RES:DSARE:SMSAB
415-6768

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THE LOWER HEAD FAILURE PROGRAMS SPONSORED BY THE NUCLEAR ENERGY AGENCY OF THE ORGANIZATION FOR ECONOMIC COOPERATION AND DEVELOPMENT

The OECD-sponsored lower head failure (OLHF) program showed that, in the absence of a pressure transient, initiation of failures in the lower head of the RPV is localized. The Larson-Miller parameter (LMP) correlation, based on vessel material property data obtained from both the OLHF and NRC-initiated lower head failure project (LHF), was assessed against the OLHF integral experiment. This assessment showed that vessel failure time can be predicted adequately. It should be noted that the prediction of time to vessel failure dictates how long radionuclides are confined to the RPV, and therefore are not easily available for release to the containment. This in turn affects source term estimates in severe accident analysis.

The OLHF program also yielded a unique and well-qualified data set for code validation. To better predict RPV behavior in the late phase of severe accidents, knowledge gained in both the OECD RASPLAV and OLHF programs is presently being implemented in the USNRC MELCOR severe accident code.

The mechanical behavior of the reactor vessel lower head is important to both severe accident assessment and assessment of accident mitigation strategies. For severe accident assessment, the failure of the lower head defines the initial conditions for all ex-vessel events that threaten the integrity of the containment with potential release of radioactivity to the atmosphere. Phenomena that threaten containment integrity include direct containment heating, core-concrete interactions, and fuel-coolant interactions. Moreover, for accident mitigation, the knowledge of mechanical behavior of the reactor vessel can be useful in developing possible mitigation actions.

The accident at Three Mile Island Unit 2 (TMI-II) involved relocation of about 20 tons of molten core material into the lower head of the RPV, which was largely flooded with water at that time. Although water was present, the lower head reached temperatures of approximately 1,300 K for 30 minutes in a 1-m diameter local hot spot when the reactor coolant system (RCS) pressure was 10 MPa. The TMI-II vessel did not fail; however, code analysis generally predicted creep rupture failure for the given conditions. Following the Three Mile Island Reactor Pressure Vessel Investigation Project (TMI-II VIP), methodologies were developed to analyze existing and next-generation reactors from the perspectives of accident assessment, accident mitigation, and accident management. However, there was still a fundamental need for a validated understanding of the lower head deformation and failure phenomena.

In 1994, the NRC initiated experimental and analytical work at Sandia National Laboratories (SNL) to investigate the mechanical behavior of the lower head under postulated severe accident conditions. This program ended in 1998. Although a number of other reactor safety programs have addressed creep rupture, the NRC-initiated LHF experiments (Chu et al., 1999) were the only experiments performed with prototypical RPV geometry. These LHF experiments were performed mainly at high RCS pressures and with low temperature differential (ΔT_W) across the vessel wall (typically on the order of 25 K). In 1998, OECD sponsored the OLHF program at SNL to address some of the issues that remained unresolved following the LHF experiments. These issues included RCS pressures of interest to accident mitigation

applications (i.e., low to moderate RCS pressure) and prototypic ΔT_W (200 K – 400 K) where stress redistribution effects are important. The OLHF program consisted of three elements, including (1) integral experiments, (2) material characterization, and (3) model development and validation. Among these elements, material characterization formed the key link between integral experiments and modeling development.

The OLHF program has shown that (1) in the absence of a pressure transient, the RPV lower head failure site is likely to be localized, (2) with proper implementation of the RPV material property data, a simplified model, such as LMP, can predict vessel failure time adequately, (3) the effect of ferrite-to-austenite phase transition of the OLHF vessel material appears to play a less significant role on the RPV vessel failure characteristics, and (4) penetration failure was found to occur as a result of global deformation.

The OLHF program benefitted greatly from contributions from Belgium, the Czech Republic, Finland, France, Germany, Spain, Sweden, and the United States. Partner contributions included test matrix development, test design calculations, material property studies, model development, post-test analysis, and the benchmark study. The OLHF program ended in October 2002, and its final report will be published and distributed among OECD participating countries in the near future.

BACKGROUND

The lower head of the RPV can be subjected to significant thermal and pressure loads in the event of a core meltdown accident. The mechanical behavior of the reactor vessel lower head is important to both severe accident assessment and assessment of accident mitigation strategies. For severe accident assessment, the failure of the lower head defines the initial conditions for all ex-vessel events, and in accident mitigation, the knowledge of mechanical behavior of the reactor vessel defines the possible mitigation actions.

The objective of the OLHF program was to provide data and insights to characterize the mode, timing, and size of RPV lower head failure for conditions of (1) low to moderate RCS pressure (2–5 MPa), including both constant and transient pressurization and (2) prototypical differential temperatures (ΔT_W = 200 K – 400 K) across the lower head wall. Prototypic ΔT_W is important because material strength decreases with increasing temperature resulting in stress redistribution in the vessel wall. Pressure transient information is useful in assessing the effect of water injection as part of an accident management strategy. The OLHF program complements the earlier SNL/NRC LHF program, which focused mainly on the high RCS pressures (10 MPa) that are associated with TMI-like severe accidents and a small through-wall temperature differential (ΔT_W) of approximately 25 K.

OVERVIEW OF THE OLHF PROGRAM

The OLHF integral experiments were performed using 1 to 4.85 linear scale models of a typical PWR lower head. The test vessel consisted of a 91.4-cm inner diameter, nominally 70-mm-thick SA533B1 steel (the prototypical material for U.S. PWRs) hemisphere welded to a 45-cm upright cylinder assembly closed off on top by a blank flange. The vessel was heated from within with a unique induction-heated graphite-radiating cavity. Large ΔT_W was achieved by increasing the wall thickness and leaving the wall uninsulated. The membrane stress was

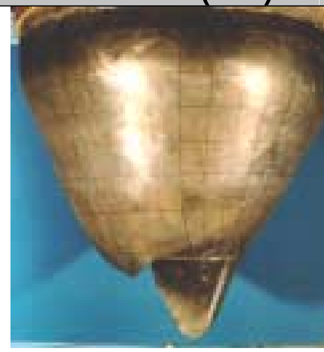
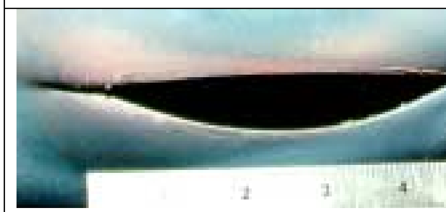
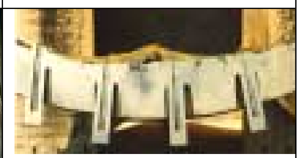
preserved by increasing the test pressure by a factor corresponding to the wall thickness distortion. The tests were extensively instrumented to provide temperature, pressure, and displacement data. The vessel surfaces were mapped both before and after the test to provide measurements of pre-test thickness, post-test thickness, and cumulative vessel deformation. Data was assessed and qualified in supplemental data reports for each test.

Four integral tests were performed as part of the OLHF project (see Table 1). Specifically, OLHF-1 and OLHF-2 were performed at RCS pressures of 5 MPa and 2 MPa, respectively. OLHF-3 examined the effect of pressure transients as the vessel wall passed through the ferrite-austenite phase transition region while the RCS pressure increased from an initial pressure of 2 MPa to a transient upper plateau of 5 MPa. The final test, OLHF-4, examined the effect of penetrations on vessel failure and was also performed at an RCS pressure of 2 MPa (similar to OLHF-2). The bottom of the test vessel was uniformly heated with a heatup rate of 12 K/min for all tests. Figure 1 shows a pictorial summary of the four experiments.

Table 1. Summary of OLHF testing

	OLHF-1	OLHF-2	OLHF-3	OLHF-4
Objectives	Mid-pressure test (tieback to previous LHF test)	Accident management (depressurization)	Pressure transient at phase transition temperatures	Global deformation vs local weld failure
Equivalent RCS pressure	5 MPa	2 MPa	Pressure transient 2 MPa to 5 MPa	2 MPa
Heatup rate	12 K/min	12 K/min	12 K/min	12 K/min
Test Features				Penetrations

Two extra vessels were fabricated from the SA533B1 steel from which samples were prepared for material property testing. This material underwent essentially the same heat treatment and work history as actual test vessels to minimize variability in material properties. Five tensile tests and 21 creep tests (at about 75 percent and 95 percent of yield stress) were performed at high temperatures between 925 K and 1,275 K. Two replicate creep tests were performed to provide a means of assessing the reproducibility of test results. Additional mechanical property testing was carried out at Commissariat à l'Energie Atomique (CEA) of France (Mongabure 2001). SA533B1 steel undergoes a transition from ferrite to austenite at approximately 1,000 K. In the OLHF tests, vessel failure occurs at inside surface temperatures well above the phase transition temperature. Therefore, dilatometry experiments were performed to define the phase transition region of the test vessel material. These experiments determined the ferrite-to-austenite phase transition region for the OLHF material to be between 1,005 K and 1,133 K.

OLHF-1	OLHF-2	OLHF-3	OLHF-4
4.7 MPa (RCS)	**2.02 MPa (RCS)**	**Transient: 2.02 MPa (RCS) to 4. 7 MPa (RCS)**	**2.02 MPa (RCS)**
			
			 *Separation of the penetration welds from the base material.*
T_{inside} = 1450 K Area of failure = 17.1 cm^2 (0.22 m FSE diameter) $t_{failure}$ - t_{800} = 56 min	T_{inside} = 1750 K Area of failure = 36.5 cm^2 (0.33 m FSE diameter) $t_{failure}$ - t_{800} = 96 min	T_{inside} = 1380 K Area of failure =1180 cm^2 (1.9 m FSE diameter) $t_{failure}$ - t_{800} = 52 min	T_{inside} = 1650 K Area of failure ~ 1 cm^2 $t_{failure}$ - t_{800} = 73 min

$t_{failure}$ = time at failure; t_{800} = time at 800 K

Figure 1. Pictorial summary of the OLHF integral experiments

The results of material characterization tests are used to construct a constitutive model for implementation into structural analysis models to assess the ability of the models and codes to capture the response of the pressure vessel in the integral experiments. Independent numerical simulations were performed for the OLHF-1 test by all OECD partners in an international benchmark activity (Nicolas, 2002a and 2002b). Simple “engineering” methodologies utilized in severe accident codes were also assessed against the OLHF and LHF experimental data.

KEY OBSERVATIONS FROM INTEGRAL EXPERIMENTS

Large Temperature Differential

Comparison of the results of OLHF-1 and earlier tests (i.e., LHF-7) demonstrated the importance of stress redistribution on vessel deformation. Because large ΔT_W can occur during

severe accidents, tests were performed with large through-wall temperature differentials (OLHF-1 and OLHF-2). The results showed signs of nonlinear deformation at higher temperatures than similar tests with small through wall-temperature differentials (LHF). For the conditions of the OLHF tests, the onset of nonlinear deformation occurs as more than 10 percent of the vessel wall exceeds the yield stress. Failure for the OLHF tests occurred at higher temperatures than in corresponding LHF tests (small temperature differential). Since penetration failure was governed by global vessel deformation, this was also true of the penetration test. Therefore, large temperature differentials lead to failure at higher inside vessel wall temperatures.

Failure Location

Both the LHF and OLHF experiments and the Swedish FOREVER (Sehgal et al. 1998) experiments revealed that initiation of failures is typically localized. Specifically, failure was found to initiate at the location of the maximum membrane-to-yield stress ratio. For the OLHF experiments, because the load was carried by the cooler outer region of the wall, the stress ratio was evaluated at the external wall temperature. For the case of uniform temperature distribution, the crack initiates in the thinnest region because that location corresponds to the maximum membrane stress. By contrast for the case of non-uniform temperature distribution, the crack initiates at the highest temperature regions because yield stress is minimum in this region.

Most of the tests exhibited localized propagation afterward. Nevertheless, repressurization at elevated temperature can lead to rapid onset of nonlinear deformation and failure and may result in larger failure sites.

It is important to note that the test results cannot be directly used to assess failure size for reactor cases because the rate of depressurization depends on the gas volume in the system, which was not scaled in the OLHF or LHF tests. Moreover, in reactors, molten corium ejection could enlarge the failure site through ablation.

In reactor cases ablation of the failure site must be taken into account for ex-vessel severe accident phenomena evaluation.

Global Failure Strain

The critical effective strain is often used as a failure criterion in modeling vessel deformation in the severe accident codes. The critical effective failure strain for a uniformly heated vessel without penetration was found to be approximately 30 percent at the time of test vessel failure. This value was consistent among the first three OLHF tests and uniformly heated LHF tests.

Penetration failure was found to occur as a result of global deformation of the lower head leading to failure at the weld-vessel interface. Penetration failure occurs at a much lower effective strain (i.e., 10 percent for OLHF-4 and 7 percent for LHF-4). In both experiments, failure initiated at the weld-vessel interface, which resulted in depressurization and termination of experiments.

Caution should be taken in applying the results to reactors because the scaling effect of weld failure is not currently well understood; furthermore, the OLHF experiments did not simulate the effects of molten corium. Metallurgical and material weld properties are important topics that should be addressed in order to develop a predictive model of penetration failure.

Provisionally, one can assume that initiation of penetration failure caused by global deformation occurs at a critical effective strain of approximately 10 percent. Experimental and numerical simulations of penetrations that would be beneficial in developing simplified models for use in severe accident codes (SACs) may be undertaken in the future.

Material Characterization

The tensile and creep properties were measured for temperatures up to approximately 1,300 K for LHF and OLHF steel. The data from SNL and CEA are generally consistent with the external database established in the LHF program. The data fits developed in the LHF program were also used in OLHF analyses and numerical simulations. A close examination of the data indicates that, for future analysis of OLHF integral experiments, it might be advisable to refit the data with more weight given to measured OLHF material properties. To analyze RPV lower head creep failure, actual RPV material property data should be utilized.

CEA also performed metallurgical characterization of failure sites of LHF and OLHF material. At high temperatures (~1260 K), LHF material exhibits intergranular ductile fracture, while OLHF material exhibited transgranular ductile fracture. Both materials revealed similar time-to-failure and high ductility. The LHF material exhibited 44% elongation while OLHF exhibited 55 to 60% elongation at failure. CEA concluded that the difference could be attributable to the fact that sulfur content in the LHF material is nearly 10 times that of the OLHF material, although both materials conform to the specifications of SA533B1 steel. The higher sulfur content (0.010 weight percent) resulted in weakened grain boundaries at higher temperature.

The ferrite-to-austenite phase transition region for the OLHF material has been determined to be between 1,005 K and 1,133 K using dilatometry. The rate of vessel deformation diminished or reversed as the vessel wall passed through the phase transition from ferritic to austenitic steel.

The effect of phase transition appears to be less significant than once considered, probably because only a portion of the wall is in the transition region at any point in time and the induced stresses due to phase transition are of the second order.

Severe Accident Codes and Numerical Simulations

The OLHF project has produced a unique and well-qualified data set for code validation.

The OLHF participants have conducted a benchmark exercise based on the OLHF-1 test data. Participants have used different failure criteria (damage or strain) with no consensus or convincing argument for any preference. The predicted failure times calculated by participants agree reasonably well with the test data. All the models, irrespective of their complexity, gave reasonable predictions of the failure time. It should be noted, however, that failure time is not a rigorous measure of model predictability because the time to nonlinear deformation is long

compared to the time interval between the initiation of nonlinear deformation and vessel failure. When referenced to the onset of nonlinear deformation, there is still considerable spread in the predicted time to failure.

Test conditions for OLHF-2 and OLHF-4 are nearly identical, the key difference between the two is that OLHF-4 has penetrations. However, OLHF-4 was terminated prior to vessel failure due to penetration weld failure and consequent depressurization. Therefore, the OLHF-4 test vessel provides a snapshot of the deformed vessel head prior to failure. Since the OLHF-4 vessel appears to be nearly symmetric, this provides some evidence that early deformation in the vessel head is axisymmetric. Calculations performed by Finnish participants showed that the penetration behavior in OLHF-4 could be adequately represented by a two-dimensional simulation, but the location and extent of the failure site must be determined by three-dimensional modeling. The OLHF tests and LHF tests demonstrated that rather small asymmetries in temperature or wall thickness could lead to large asymmetries in the overall vessel deformation. Therefore, a three-dimensional model would be needed to completely characterize the vessel deformation and to predict the location and extent of the failure site. The propagation and final size of the failure are still issues; however, three-dimensional calculations by CEA, presented at the OLHF Seminar 2002, show promising results.

The simple SAC models evaluated in this report proved quite adequate in predicting vessel failure time in the OLHF tests. Various failure criteria, damage functions, and strain rate equations were assessed. For the conditions of these tests, the accuracy of the various models in predicting the test failure times appears to lie within the spread of results obtained by the finite element analysis benchmark analysis. This finding supports the use of such simple models for severe accident analysis.

SACs such as MELCOR use creep-based methodologies, (i.e., LMP correlation to predict time to failure of the RPV.) The LMP correlation is dependent upon both the stress and temperature histories of a given RPV material. There is significant scatter in available data in literature for SA533B1 steel material properties on which the LMP correlations are based. This scatter in data translates to a variation of the estimated RPV lower head failure time by at least a factor of two. This variation is attributed to material composition, work history of the material, and differences in testing procedures. A first attempt at fitting LMP correlation through OLHF material test data appears to be in general agreement with the previously obtained correlation of LMP as a part of the LHF program. However, it appears that refitting the LMP correlation by including OLHF test data leads to reduction in the error in estimated time to failure of the RPV. This LMP correlation model would then be implemented in severe accident codes such as MELCOR. With this improvement, the MELCOR code would then be used to assess lower head failure of the RPV for various accident sequences, reactor designs, and vessel boundary conditions (e.g., ex-vessel flooding). This refitting will be performed and will be implemented in the MELCOR code in the future.

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