1.5 Overview of Severe Accident Research at the USNRC

Sudhamay Basu and Charles E. Ader
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Mail Stop T-10K8, 11545 Rockville Pike
Rockville, Maryland 20850, USA

ABSTRACT

This paper summarizes the U.S. Nuclear Regulatory Commission's (USNRC) severe accident research activities, in particular, progress made in the past year toward the resolution and/or improved understanding of a number of severe accident issues. The direct containment heating (DCH) is nearing resolution for Combustion Engineering and Babcock & Wilcox type pressurized water reactors (PWRs) as well as for ice condensers. Additionally, two lower pressure DCH tests were conducted recently at the Sandia National Laboratories (SNL) under the NRC/IPSN/FzK sponsorship to provide data regarding intentional depressurization as an accident management strategy to mitigate DCH loads. In the area of lower head integrity, the experimental program to investigate boiling heat transfer on downward facing curved surfaces with insulation was completed. Finally, the SNL program investigating the creep rupture behavior of the lower head under the combined thermo-mechanical loading was completed recently. Additional lower head experiments at SNL are being planned as an OECD project.

During the past year, the USNRC participated in two programs aimed at extending the data base on hydrogen combustion into more prototypic situations. Testing was performed at the Brookhaven National Laboratory (BNL) to investigate detonation transmission at elevated temperatures. In a cooperative program under the sponsorship of NRC/IPSN/FzK, Russian Research Center (RRC) investigated hydrogen combustion issues at large scale at the RUT facility. The experimental program at the SNL to examine the performance of Passive Autocatalytic Recombiners (PARs) was completed also this year. In the fuel-coolant interaction (FCI) area, the experimental work at the Argonne National Laboratory (ANL) to investigate chemical augmentation of FCI energetics was completed as was the experimental work at the University of Wisconsin (UW) involving one-dimensional propagation experiments (similar to KROTOS). The USNRC is continuing to participate in the current framework of the cooperative FARO/KROTOS program at the Joint Research Center (JRC-Ispra) and in the cooperative MACE program managed by EPRI. Finally, in the fission product research area, the USNRC continued to be involved in the PHEBUS program which is addressing accident progression and fission product behavior in the reactor coolant system and containment.

With the completion or near-completion of many of the experimental programs, the focus of NRC's severe accident research is currently on the development of those severe accident codes that provide the analytical capability necessary to support the agency's risk-informed initiatives. The severe accident codes are intended to provide analytical tools to resolve safety issues, assess accident management strategies, and support risk-informed regulatory activities. Toward these goals, NRC has recently undertaken an initiative to streamline code development activities and is considering consolidation of various severe accident code activities.

PRESENTATION OUTLINE

- Introductory Remarks
- Current Severe Accident Research Activities
- Future Direction of Severe Accident Research

INTRODUCTORY REMARKS

- Severe accident research has focused on understanding and quantifying phenomena and issues that can challenge reactor vessel and containment integrity
- Research has provided data and analytical tools to support risk assessment, resolve severe accident issues, and evaluate accident management strategies; some issues resolved, others nearing resolution
- Research program currently in transition; consistent with risk-informed initiatives, increased emphasis on prioritization of risk significant issues
- Need to maintain core capabilities and expertise recognized; increased emphasis on international cooperative efforts

CURRENT SEVERE ACCIDENT RESEARCH ACTIVITIES

- Direct Containment Heating
- Lower Head Integrity
- Fuel-Coolant Interactions and Debris Coolability
- Hydrogen Combustion
- Fission Products Behavior
- Severe Accident Codes

Page 4

DIRECT CONTAINMENT HEATING (DCH)

ISSUE

- Likelihood of early containment failure as a consequence of high pressure melt ejection and direct containment heating (DCH); identified in NUREG-1150 and subsequent IPE as an important contributor to early failure of PWR containments

STATUS

- Issue resolved with finding of no significant failure probability for Westinghouse plants with large dry or subatmospheric containments. Reports (NUREG/CR-6075, NUREG/CR-6109 and NUREG/CR-6338) published
- Resolution based on integral and separate effects tests of Zion and Surry geometries and evaluation of containment fragility

Page 5

DIRECT CONTAINMENT HEATING (DCH)
(Continued)

STATUS

- Issue also resolved for Combustion Engineering (CE) and Babcock & Wilcox (B&W) type plants, based on integral effects tests and extrapolation of Zion and Surry issue resolution methodology to these plants; results documented in NUREG/CR-6475

- Completed two additional tests for CE like geometry at lower reactor system pressure under a cooperative program with FzK and IPSN to investigate the effect of intentional depressurization as an accident management strategy

- DCH issue for ice condenser plants nearing resolution; NUREG/CR-6423 report documenting the findings will be published early next year

Page 6

LOWER HEAD INTEGRITY

ISSUES

- Assessment of conditions for retaining molten core in the reactor pressure vessel (RPV) through internal and/or external cooling (i.e., ex-vessel flooding)

- If the RPV were to fail, assessment of likely failure mode, location and timing of vessel failure

- Issues raised by TMI-2 margin to failure analysis and prospect of reducing containment challenges by retaining core in-vessel

RESEARCH PROGRAMS

- Critical heat flux experiments (Penn State) - completed
- Lower head failure experiments (SNL) - completed
- In-vessel debris coolability experiments (FAI) - ongoing
- OECD RASPLAV Project (RRC-KI) - ongoing

Page 7

LOWER HEAD INTEGRITY
(Continued)

STATUS

CRITICAL HEAT FLUX (CHF) EXPERIMENTS

- CHF experiments on downward facing curved surfaces (with and without insulation) performed to assess capability of removing decay heat via boiling on outside surface of vessel
- Report (NUREG/CR-6507) documenting CHF phenomena and modeling published earlier. Another report (NUREG/CR-5534) on the effect of insulation on CHF published September 1998
- Findings indicate downward heat fluxes with insulation (AP600 type) is higher than without insulation; with insulation, minimum CHF occurs at minimum gap spacing

Page 8

LOWER HEAD INTEGRITY
(Continued)

STATUS
LOWER HEAD FAILURE EXPERIMENTS

- Conducted experiments to measure strain, failure time, size and location under combined effects of thermal and pressure loads; NUREG/CR-5582 documenting results to be published shortly
- Results provide data base for creep rupture failure of lower head with and without penetrations for different thermal loadings; failure occurs at minimum thickness and/or high temperature locations
- Results useful for development and/or assessment of analytical models; Larson-Miller formulation predicts failure time but axisymmetric formulation inadequate to predict failure location
- Additional experiments planned under proposed OECD project

Page 9

LOWER HEAD INTEGRITY
(Continued)

STATUS

IN-VESSEL DEBRIS COOLABILITY EXPERIMENTS

- **Participating in cooperative program (NRC, EPRI, and three international organizations) to investigate inherent heat transfer mechanisms that may promote in-vessel cooling of core debris and RPV lower head in the presence of water**

OECD RASPLAV PROJECT

- **Participating in OECD cooperative program to perform integral tests with prototypic materials to assess the possibility of retaining molten core material in the RPV lower head**

FUEL-COOLANT INTERACTIONS (FCI) AND DEBRIS COOLABILITY

ISSUES

- **Potential challenges to lower head integrity from shock loading generated by energetic FCI; also, potential challenges to containment integrity from ex-vessel energetic FCI**

- **Assessment of potential for ex-vessel quenching of core debris by an overlying water pool**

RESEARCH PROGRAMS

- **Simulant FCI experiments (U. Wisconsin) - completed**
- **Chemical augmentation (ZREX) experiments (ANL) - completed**
- **FARO/KROTOS FCI experiments (JRC/Ispra) - ongoing**
- **MACE ex-vessel debris coolability experiments (ANL) - ongoing**

FUEL-COOLANT INTERACTIONS (FCI) AND DEBRIS COOLABILITY (Continued)

STATUS
U. WISCONSIN SIMULANT FCI EXPERIMENTS

- Completed one-dimensional steam explosion experiments with metallic (tin) and oxidic (iron oxide) simulants to determine the effects of various fuel/coolant parameters on energetics
- Large data base accumulated for tin simulant; results indicate low energetic yield (typically 0.3 to 0.7 percent) - somewhat lower than that from KROTOS tin experiments
- Very limited data base on iron oxide simulant; results indicate even lower energetic yield, however, results not conclusive
- Experimental data base useful for assessment of analytical models in FCI codes; data base also useful to determine conditions for occurrence of steam explosions

Page 12

FUEL-COOLANT INTERACTIONS (FCI) AND DEBRIS COOLABILITY (Continued)

STATUS
CHEMICAL AUGMENTATION (ZREX) EXPERIMENTS

- Completed ZREX experiments to determine the chemical augmentation of FCI energetics in zirconium containing melts; results documented in NUREG/CR-5372
- Extent of chemical augmentation proportional to zirconium content in the melt; however, there is a dilution effect when oxide or other metal present in zirconium containing melt
- No evidence that chemical energy is converted into mechanical energy any more efficiently than stored thermal energy
- Impact of chemical augmentation of FCI energetics on reactor safety assessment should be examined on a case-by-case basis for individual accident situations

Page 13

FUEL-COOLANT INTERACTIONS (FCI) AND DEBRIS COOLABILITY (Continued)

STATUS

FARO/KROTOS FCI EXPERIMENTS

- Participating in cooperative FARO/KROTOS program at JRC/Ispra to experimentally investigate non-explosive and explosive melt coolant interactions involving prototypic and simulant melts

MACE EX-VESSEL DEBRIS COOLABILITY EXPERIMENTS

- Participating in cooperative program to examine the mechanisms for ex-vessel quenching of core debris using prototypic materials

HYDROGEN COMBUSTION RESEARCH

ISSUES

- Potential challenges to containment integrity resulting from various modes of hydrogen combustion during severe accidents
- Hydrogen control using passive autocatalytic recombiners (PARs)

RESEARCH PROGRAMS

- Large-scale deflagration-to-detonation transition (DDT) experiments (RRC-KI) - completed
- PARs performance testing (SNL) - completed
- High-temperature detonation transmission experiments (BNL) - nearing completion
- Low speed hydrogen combustion experiments (CalTech) - nearing completion

HYDROGEN COMBUSTION RESEARCH
(Continued)

STATUS
LARGE-SCALE DDT EXPERIMENTS AT RRC-KI

- Performed large-scale DDT experiments in RUT facility with hydrogen-air and hydrogen-air-steam mixtures
- Results provide data base for validation of analytical models and for evaluation of criteria for placement of igniters

PASSIVE AUTOCATALYTIC RECOMBINERS (PARS) PERFORMANCE

- Completed confirmatory tests to verify PARs performance as part of AP600 design review process; results documented in NUREG/CR-6580
- Provide data base on PARs performance in steam, low oxygen and well-mixed environment, scale effect, ignition potential, etc.

Page 16

HYDROGEN COMBUSTION RESEARCH
(Continued)

STATUS
HIGH TEMPERATURE DETONATION TRANSMISSION EXPERIMENTS

- Performed experiments to predict conditions that may result in detonation and detonation transmission at high temperatures
- Results, documented NUREG/CR-6391 and NUREG/CR-6509, provide data base to predict likelihood of detonation in containment and transmission between subcompartments.

LOW SPEED HYDROGEN COMBUSTION EXPERIMENTS

- Experiments to investigate diffusion flame stability and ignition of lean hydrogen, air, nitrogen mixtures by hot jets
- Data base to predict likelihood of stable diffusion flames and ignition potential of combustible gases by hot jets

Page 17

FISSION PRODUCT BEHAVIOR RESEARCH

ISSUE

- **Assessment of the magnitude and timing of release of fission products during a severe accident, transport of the same in the RCS and in the containment, and ultimately offsite release; assessment essential to understanding risk**

STATUS

- **Participating in PHEBUS experimental program to confirm and, if needed, to improve current understanding of fission product release and transport; data will be used to improve and/or assess models in severe accident codes**

- **Completed the "rebaselining" activity dealing with potential impact of implementing revised source terms (NUREG-1465) for operating plants**

Page 18

SEVERE ACCIDENT CODES

ISSUE

- **Need to embody phenomenological understanding gained from several years of experimental research into codes which provide analytical tools to evaluate and resolve severe accident issues, and to support risk assessment**

STATUS

- **Followed a two-tier approach to code development; currently maintaining a suite of codes: *MELCOR, CONTAIN, SCDAP/RELAP5, VICTORIA, GASFLOW,* and *IFCI***

- **Reviewing long-term strategy for consolidating severe accident codes; future emphasis on improvement and maintenance of integral system level code**

Page 19

SEVERE ACCIDENT CODES
(Continued)

MELCOR: System level code to analyze severe accidents in nuclear power plants from core uncovery through reactor vessel failure, containment response, and fission product release and transport

Status

- MELCOR 1.8.4 version released June 1997
- Model improvement in FP and other areas continuing
- Current thrust on assessment and plant calculations
- MCAP continuing and providing an application data base

SCDAP/RELAP5: Detailed mechanistic code for analysis of in-vessel severe accident phenomena including primary system thermal hydraulics, core degradation, and reactor vessel failure

Status

- SCDAP/RELAP5 3.2 version released June 1998
- Code maintenance continuing

SEVERE ACCIDENT CODES
(Continued)

CONTAIN: Detailed code for analysis of containment transient response (i.e., pressure and temperature conditions) during severe and design basis accidents for a variety of containment types

Status

- CONTAIN 2.0 released; manual published December 1997
- Code assessment in progress
- Qualification of CONTAIN to replace old DBA codes planned

VICTORIA: Detailed code to analyze fission product (FP) release and transport in the reactor coolant system during a severe accident including FP deposition, resuspension and revaporization

Status

- Code improvement based on peer review recommendations in progress; VICTORIA 2.0 to be released December 1998
- Offsite release calculations for risk dominant sequences

SEVERE ACCIDENT CODES
(Continued)

IFCI: Integrated fuel-coolant interactions code to model in-vessel and ex-vessel explosive and non-explosive FCI phenomena

Status

- IFCI 7.0 version nearing release; improved models and numerics incorporating peer review comments
- Assessment against experimental data base and code-to-code comparison planned

GASFLOW: Best estimate 3D finite difference code to predict transport, mixing, and combustion of hydrogen and other gases in the containment

Status

- GASFLOW 2.1 version completed August 1998
- No further development planned; limited assessment under consideration

FUTURE DIRECTION OF SEVERE ACCIDENT RESEARCH

- Focusing severe accident research consistent with risk-informed regulatory initiatives
- Priority on maintenance of core capabilities and expertise in risk significant areas
  - Maintenance and improvement of severe accident codes will be primary means
  - Involvement in international cooperative experimental programs will also be important
- Cooperative programs such as CSARP important in providing a forum for sharing research findings and promoting cooperative initiatives in severe accident code development and applications