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ADAM: AN ACCIDENT DIAGNOSTIC, ANALYSIS AND MANAGEMENT SYSTEM – APPLICATIONS TO SEVERE ACCIDENT SIMULATION AND MANAGEMENT

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ABSTRACT

The Accident Diagnostic, Analysis and Management (ADAM) computer code has been developed as a tool for on-line applications to accident diagnostics, simulation, management and training. ADAM's severe accident simulation capabilities incorporate a balance of mechanistic, phenomenologically based models with simple parametric approaches for elements including (but not limited to) thermal hydraulics; heat transfer; fuel heatup, meltdown, and relocation; fission product release and transport; combustible gas generation and combustion; and core-concrete interaction. The overall model is defined by a relatively coarse spatial nodalization of the reactor coolant and containment systems and is advanced explicitly in time. The result is to enable much faster than real time (i.e., 100 to 1000 times faster than real time on a personal computer) applications to on-line investigations and/or accident management training. Other features of the simulation module include provision for activation of water injection, including the Engineered Safety Features, as well as other mechanisms for the assessment of accident management and recovery strategies and the evaluation of PSA success criteria. The accident diagnostics module of ADAM uses on-line access to selected plant parameters (as measured by plant sensors) to compute the thermodynamic state of the plant, and to predict various margins to safety (e.g., times to pressure vessel saturation and steam generator dryout). Rule-based logic is employed to classify the measured data as belonging to one of a number of likely scenarios based on symptoms, and a number of "alarms" are generated to signal the state of the reactor and containment. This paper will address the features and limitations of ADAM with particular focus on accident simulation and management. *Keywords: simulation, severe accidents, recombiners*

INTRODUCTION

There are a variety of potential severe accident scenarios and sequences for light water reactors. In general, accidents start from different initiating events that may lead directly or through additional failures to severe core degradation. The range of the potential plant states include operation at power, plant heat-up, plant cool-down, and plant shutdown conditions. Once an accident starts, loss of coolant inventory is followed by oxidation of the Zircaloy cladding, and eventually core damage, reactor pressure vessel failure, and a multitude of physical phenomena potentially challenging the containment integrity. The further the accident progresses into the severe accident regime, the more difficult it becomes to manage the accident by the Emergency Operating Procedures (EOPs). Therefore, many utilities tend to develop or have already developed Severe Accident Management Guidelines (SAMG) with a structure that is more appropriate for severe accident situations.

The actual implementation of SAMGs requires sufficient understanding of the plant condition and the availability of systems or components needed to limit core damage, mitigate radiological impacts, and eventually achieve a stable configuration for the plant. In general, since the sequences of events that could result in a severe accident are not unique and can involve a multitude of accident pathways, it is desirable to have an understanding of the impact of the particular SAMGs on accident progression, and ultimately, on the potential challenges to containment integrity and/or radiological releases.

The management of severe accidents is expected to be under the direction of the plant/utility through the utility technical support organization and accident response team. However, important utility actions may require interaction and/or approval by cognizant regulatory authority; thus, requiring appropriate technical information on the actual plant condition, the observed symptoms, and the potential impact of implementing selected accident management actions. The implementation effectiveness of the SAMGs during an accident is strongly impacted by the level of training of the emergency response team. Furthermore, during an accident, close collaboration and interaction between the plant emergency response organization and the national emergency response centers is essential. Finally, communication with the general public needs to be based on accurate and reliable information.

The Windows ^{TM}-based ADAM system has been developed by ERI to provide a comprehensive accident analysis platform that uses the available plant data, supplemented by computer simulation. The initial version of ADAM was developed in 1997, and since that time versions have been developed that are applicable to BWRs with Mark I and III containments, U.S. and German-type PWRs with large dry containment, and VVER-440/213 type plants. In general, the ADAM system for a particular plant includes a Diagnostics Module (ADAM-D), in which selected plant parameters (as measured by plant instrumentation and transmitted to plant computers) are used to assess safety margins and perform some low-level rule-based diagnostics of the state of the system; and a severe accident Simulation Module (ADAM-SIM), which consists of a user interface and a Fortran-based computer code used to simulate the evolution in time of a severe accident using parametric, mechanistic models for various aspects of the physics, and provide output to the user on the time-dependent state of the plant, fission product releases, etc.

The ADAM system is designed to meet the objectives of the analysts at an accident response center and/or a regulatory emergency response team who only have limited on-line information about the plant status. Therefore, implementation of complicated models is avoided as part of the ADAM development philosophy. ADAM is designed to run several orders of magnitude faster than real time on a Personal Computer (PC) platform.

APPROACH AND MODELS

The accident management and analysis module includes extensive mathematical models for simulation of a large spectrum of accidents, including severe accidents leading to reactor pressure vessel failure, molten core-concrete interactions (MCCI), and containment pressurization and failure. In keeping with the philosophy that guided the development of ADAM, the various mechanistic models have a sufficient level of detail to provide accurate and useful results, while remaining simple enough to be fast-running.

Among the aspects of severe accident phenomenology treated in ADAM's models are:

(1) *Hydrodynamic and Thermodynamic Models* - Mass and energy transport of liquid water, steam, and various species of noncondensible gases is modeled through the use of a control volume and flow path nodalization. The nodalization is kept very coarse in order to speed up the hydrodynamic calculations as much as possible. Typically, six to eight control volumes are used, including a single volume for the vessel and RCS, several volumes for the containment, and, in the case of PWRs, one volume for the pressurizer and two for the steam generators (in pressurizer and combined loops). A non-equilibrium, separated-flow model is used, with provision for critical and non-critical flows. A special model for heat and mass transfer between liquid and the atmosphere is employed in the control volume containing the sump, where heatup and evaporation is important to long-term containment pressurization. The resulting equations are discretized explicitly with respect to time in order to further save on resources; in the future, work is planned on experimenting with a semi-implicit discretization.

(2) *Heat and Mass Transfer to Structures* - A number of one-dimensional heat conduction models, coarsely nodalized, are used to model the heat removal and condensation by solid structures in the containment of various sizes, thicknesses, materials, and locations. Structures that are similar in terms of thermal behavior are typically lumped together in order to save on computation. Correlations for natural-convection heat and mass transfer at the structure surfaces are used. As with the hydrodynamic model, the equations are solved explicitly with respect to time.

(3) *Steam Generator Model* - A version of the one-dimensional heat conduction model is specialized for use in modeling heat transfer between the primary and secondary sides of a PWR. Heat transfer from the tubes is modeled in the forced convection and pool boiling regimes for the liquid phase only. Due to focus on particular regimes of heat transfer, the current steam generator model is specialized for most severe accidents, and does not perform as well after dryout or at full-power operation. Future plans include extending the range of applicability of the steam generator heat transfer model.

(4) *Fuel Heatup and Relocation* - The reactor core is coarsely nodalized into a number of axial segments, typically five. A specially developed heatup approach is used for each core node employing a two-lumped-parameter model for the fuel and cladding, respectively. The resulting equations can be solved analytically with a minimum of computation at each timestep. Cladding oxidation at elevated temperatures is also modeled and integrated into the heatup routine. Core node relocation is performed when the intact fuel reaches a user-defined maximum temperature. Following fuel relocation, heatup and creep-

rupture of the lower core plate and vessel lower head are calculated.

(5) *In-Vessel Fission Product Release and Transport* - During heatup of the reactor core following loss of heat removal, fission products discretized into seven classes are released from the fuel into the RCS in accordance with the CORSOR-M and CORSOR-Booth correlations [1,2]. Fission product aerosol removal by gravitational deposition, Brownian diffusion, thermophoresis, and diffusiophoresis is modeled through the use of a special in-vessel deposition heat structure, the dimensions of which are changed according to the type of accident being simulated (since the retention areas differ, for example, for high-pressure transients and large LOCAs). Since a single control volume is typically used to represent the RCS, ADAM cannot model impaction as a fission product removal mechanism. Heatup of the in-vessel deposition structure is calculated, along with the consequent revaporization of volatiles fission products.

(6) *MCCI and Basemat Erosion* - Following vessel failure and relocation of the molten core to the reactor cavity, the corium's attack on the concrete basemat and the resulting release of gases and fission product aerosols is calculated, modeling the molten debris as a hemisphere. Input parameters and the concrete composition determine the rate of concrete erosion, the composition of the gases released from concrete decomposition, and the rate and amount of ex-vessel fission product aerosol generation.

(7) *Combustion* - Deflagrations in the containment involving hydrogen and/or carbon monoxide can be calculated in ADAM, with input parameters modeling the flammable concentrations and flame speed. The conditions immediately following combustion are computed to determine whether resulting failure of the containment is possible. Detonation events are not modeled in ADAM.

(8) *Fission Product Transport, Scrubbing, and Release in Containment* - As in the in-vessel model, the transport and removal of fission product aerosols in the containment control volumes is modeled for various mechanisms, including also removal by sprays. Release to the environment is calculated following containment failure or controlled venting.

(9) *Radionuclide Decay* - The decay and transmutation of radioactive fission products is modeled using sixty risk-dominant nuclides on the basis of ORIGEN calculations [3] in order to estimate the time behavior of decay heat and for purposes of calculating the activity of release to the environment following containment failure.

(10) *ECCS and Containment Safeguard Models* - A number of safety systems common to BWRs and PWRs are modeled through the use of logical controls and mass and energy sources to the appropriate control volumes. Among the systems included in ADAM are accumulators, ECCS systems, containment sprays and fans, containment venting systems, feed water, and controls intended to simulate manual feed and bleed operation.

TESTS AND VALIDATION

Since its initial development, ADAM's approach has been validated through assessments of its pre-core damage and severe accident models benchmarked against experiments [4,5]. These experiments included the GE Large Vessel Blowdown tests [6], FIST experiments [7], Severe Fuel Damage (SFD) tests [8], and DF-4 BWR Damaged Fuel experiment [9]. The assessments generally validated the calculations performed with ADAM, with some differences explainable by limitations of the simplified models employed in the code, including lack of detail in in-vessel two-phase hydrodynamics and limitations of the parametric core heatup and relocation model. Differences between ADAM and experimental results drive some future intended modifications of the code.

Results obtained for various accident scenarios from ADAM have also been compared to calculations performed using the MELCOR severe accident simulation code [10], which employs many similar models with a higher level of detail and higher computational requirements. Figures 1 and 2 show the containment pressure and level of concrete basemat erosion obtained in one such study for a large LOCA in a typical PWR with large dry containment, where it can be seen that the results are similar. Compared to MELCOR, ADAM generally under-predicts in-vessel release and zirconium oxidation due to the different models in MELCOR that sustain the core at high temperatures longer before relocation. The composition of the ex-vessel gas release is calculated to be somewhat different due to the parametric nature of the MCCI model. Also, due to some aspects of the methodology for fission product transport in MELCOR versions 1.8.4 and earlier, environmental releases are high due to resuspension of aerosols from pools late in the accident. Table 1 compares timing and releases predicted by the two codes, which are comparable except for discrepancies explained by the above methodological differences.

APPLICATION TO LATE HYDROGEN COMBUSTION

As an example of the applicability of ADAM to severe accident simulation and management, several calculations were performed to examine the issue of late combustion of hydrogen and carbon monoxide and its impact on the containment. The base case calculation consisted of an ADAM simulation of a transient scenario with operating containment sprays and heat removal at a typical PWR with large dry containment. Some of the main results of this calculation are shown in Figures 3 and 4 and Table 2, where it can be seen that the containment fails at around 32 hours as the result of overpressure following a large combustion event in the containment when the equivalent concentration of combustible gases (hydrogen and carbon monoxide) reaches about 10%. Because the failure of containment occurs very late, the release to the environment of aerosols is less than 10^{-5} of initial core inventory in general, although nearly all of the noble gases are released. The activity of release at this time is about 7.3 x 10^{12} Bq from aerosols and 1.8 x 10^{18} from noble gases.

One possible approach to the issue of late combustion in large dry PWR containments is the installation of passive autocatalytic recombiners (PARs) to remove hydrogen. ADAM includes a system based on the Fischer model [11] for NIS type PARs. Using this system, it is a simple matter in ADAM to observe the effects on the accident progression of installing PARs, as well as to explore parameters such as how many units would be required to achieve the goal of preventing large late combustion events. ADAM results using 12 PAR units in the containment show in Figure 4 that the hydrogen concentration is kept to about 2-3%, low enough to prevent combustion, and containment failure is averted. The total releases are very low and correspond to normal containment design leakage.

Another procedural approach to the late combustion issue is to allow for late controlled venting of the containment. Examination of this alternative using ADAM can be easily done, since a controlled venting system is included that can be turned on or off or altered with respect to various parameters. For this case, a filtered controlled venting system was activated in ADAM at about 10 hours time and intermittently thereafter. As a result, Figure 4 shows that the hydrogen concentration in containment is kept below 7%, low enough to prevent combustion. Although the releases to the environment are filtered, they are higher than in the base case due to the much earlier release. The activities of release are likewise more than an order of magnitude higher for aerosols.

As the above studies demonstrate, ADAM can be used by planners to quickly and easily obtain information useful for severe accident management, in this case data useful for estimating the requirements and benefit of recombiners and the requirements and costs in terms of environmental release for late controlled containment venting.

CONCLUSION

The ability of ADAM to simulate the evolution of severe accidents faster than real time, and with an easy-to-use graphical user interface, has been useful in a number of applications including training, accident planning, and assisting in severe accident management. ADAM's parametric, mechanistic models, although necessarily simple for performance reasons, are able to generate accurate and useful results. Application has been made using ADAM to examination of accident management options for control of late hydrogen combustion in the containment, with results easily obtained regarding the impacts on hydrogen concentration, containment failure time, and the amounts and activities of release.

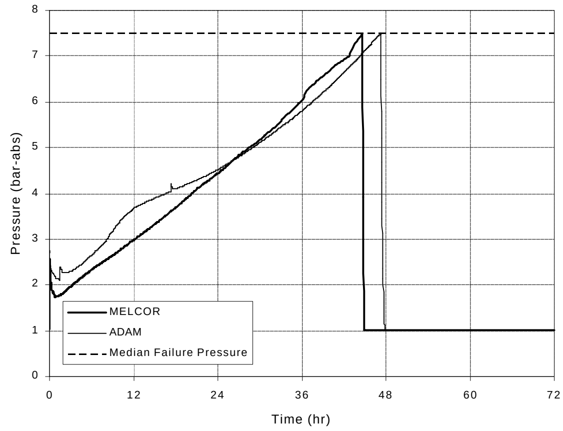

Figure 1: Containment Pressure, Comparison between ADAM and MELCOR for Large LOCA in a PWR with Large Dry Containment

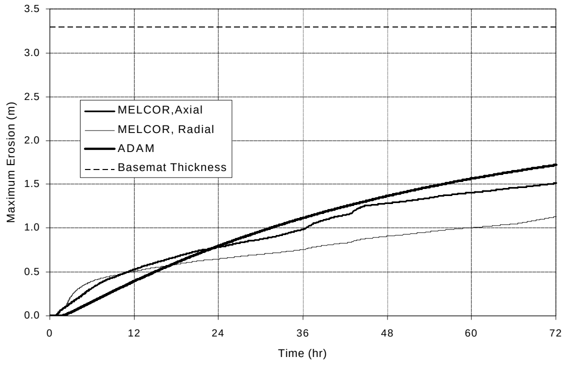

Figure 2: Concrete Basemat Erosion, Comparison between ADAM and MELCOR for Large LOCA in a PWR with Large Dry Containment

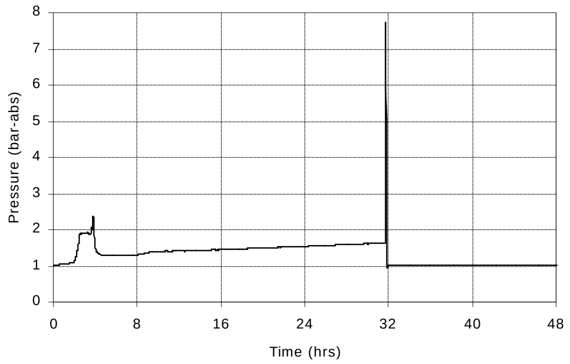

Figure 3: Containment Pressure, ADAM Transient with Sprays for PWR with Large Dry Containment

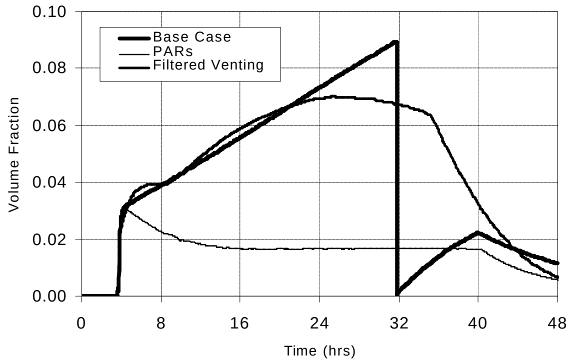

Figure 4: Containment Hydrogen Concentrations, ADAM Transient with Sprays for PWR with Large Dry Containment and Management Options

Result		ADAM	MELCOR
Time of Start of Core Uncovery (hr)		0.21	0.01
Time of Start of Core Damage (hr)		0.23	0.10
Time of RPV Failure (hr)		1.67	0.87
Time of Containment Failure (hr)		46.57	44.69
In-Vessel Releases (fraction of initial core inventory)	Xe	0.60	0.95
	Cs	0.64	0.95
	Te	0.33	0.87
	Ba	0.02	0.08
RCS Retention (fraction of in-vessel release)	Cs	0.95	0.53
	Te	0.62	0.61
	Ba	0.62	0.70
Releases to Environment (fraction of initial core inventory)	Xe	1.00	0.91
	Cs	2.3e-3	0.07
	Te	4.1e-3	0.07
	Ba	1.2e-5	0.01

Table 1: Accident Timing and Radionuclide Releases, Comparison between ADAM and MELCOR for Large LOCA in a PWR with Large Dry Containment

Result		Base Case	With PARs	With Controlled Venting
Time of Release (hr)		31.75	--	9.70
Release to Environment (fraction of initial core inventory)	Xe	0.87	<1e-12	0.99
	Cs	2.7e-6	<1e-12	3.4e-5
	Te	2.4e-6	<1e-12	3.2e-5
	Ba	3.3e-7	<1e-12	4.6e-6
	La	5.5e-8	<1e-12	2.0e-7
Noble Gas Activity of Release (Bq)		1.84e18	<1e-12	2.09e18
Aerosol Activity of Release (Bq)		7.30e12	<1e-12	2.81e14

Table 2: Fission Product Releases to the Environment, ADAM Transient with Sprays for PWR with Large Dry Containment and Management Options

ACKNOWLEDGMENTS

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