Reprint of Paper Presented at the OECD/NEA Severe Accident Management (SAM) Workshop on Operator Training and Instrumentation Capabilities, Lyon, France, 12-14 March 2001

Accident Diagnostic, Analysis and Management (ADAM) System Applications to Severe Accident Management*

M. Khatib-Rahbar, M. Zavisca, H. Esmaili
ERI, Rockville, Maryland USA

E. G. Cazzoli
ERI, Rotkreuz, Switzerland

U. Schmocker, G. Schoen, R. Schulz
HSK, Villigen, Switzerland

Abstract

Accident Diagnostic, Analysis and Management (ADAM) system has been developed as a tool for on-line applications to accident diagnostics, accident simulation and accident management applications and training. The fundamental philosophy behind ADAM is to model a full spectrum of severe accidents using a "balanced" mechanistic approach, and a relatively coarse nodalization of the reactor coolant and containment systems, to enable a 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. ADAM includes provisions for activation of various water injection systems, including the Engineered Safety Features and other mechanisms for assessment of accident management and recovery actions (e.g., fire water). The paper will address the ADAM features and limitations for application to on-line severe accident management and training.

1. 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 require sufficient understanding of 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

* This work is sponsored by the Swiss Federal Nuclear Safety Inspectorate (HSK)

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, for application to Leibstadt nuclear power plant by the Swiss Federal Nuclear Safety Inspectorate (HSK)[1]. Subsequently, the following versions have been developed and implemented:

- ADAM- Beznau, a Westinghouse PWR with large dry-containment (Swiss HSK)
- ADAM-Mühleberg, a General Electric BWR4 with MARK-I Containment (Swiss HSK)
- ADAM-Gösgen, a Siemens/KWU PWR with large dry-containment (Swiss HSK)
- ADAM-Bohunice, a VVER-440/213, pressure suppression containment (Slovak Nuclear Regulatory Authority)
- ADAM-Mochovce, a VVER-440/213, pressure suppression containment (Slovak Nuclear Regulatory Authority)
- ADAM-Paks, a VVER-440/213, pressure suppression containment (Hungarian Nuclear Regulatory Authority)

In general, ADAM is designed to operate in three modes:

(1) **Pikett Ingenieur (PI)** – This mode, unique to the ADAM versions implemented at HSK, is intended to provide graphical information on the condition of the plants by implementing simple diagnostics (as compared with the full diagnostics module D) criteria.
(2) **On-Line Diagnostics (D) -** In this mode, selective plant parameters (as measured by plant instrumentation sensors and stored in the plant computers), arriving into ADAM at a specified frequency (e.g., every 2 minutes for the Swiss plants), are used to assess the various safety margins (e.g., margin to core damage, margin to containment failure, margin to vent actuation, etc.) through appropriate "alarms". In addition, the state of the reactor, containment, and auxiliary building are constantly monitored to provide a symptom-based diagnostics of events (i.e., likely scenario) using a deterministic, rule-based logic structure.
(3) **Accident Management and Analysis (A) -** In this mode, the ADAM models can be used to simulate various accident scenarios, to determine the potential implications of various Severe Accident Management (SAM) actions on the evolution of the accident. ADAM provides an extremely efficient and versatile means for training, accident analysis, development of drill

[1] H. Esmaili, S. Orandi, R. Vijaykumar, M. Khatib-Rahbar, O. Zuchuat, and U. Schmocker, "ADAM: An Accident Diagnostics, Analysis and Management System," *Advances in Safety & Reliabil*ity, Volume 1, page 257, C. Guedes Soares, Editor, Pergamon, United Kingdom (1977).

scenarios, emergency planning, and other applications including source term assessment and evaluation of PSA success criteria.

The ADAM system is designed to meet the objectives of the analysts at the accident response center and/or the 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.

2. ADAM Approach

2.1 Diagnostics Module

The overall approach to development of ADAM accident diagnostics and accident management and analysis capabilities is discussed in Reference [1].

In the diagnostics mode, real time signals corresponding to a typically 20 to 30 important plant parameters are transmitted to the regulatory authority, are fed to the ADAM diagnostics system. A number of "alarms" are displayed in ADAM to monitor the state of the plant during the course of any event. Additional information is provided to monitor the state of the reactor, the reactor coolant system and the most likely symptom-oriented accident conditions. These provide a quick glance at the state of the plant without resorting to monitoring of the individual plant data.

Figure 1 shows the basic logic for the ADAM diagnostics module. It is seen that initialization and validation of the plant signals is the starting point in ADAM-D. The next step is identification of accident conditions and accident type (e.g., drywell LOCA of a given size group [BWR], steam generator tube rupture [PWR], etc.). The sensor signals used for the accident identification are the plant type dependent, and typically include the measured pressure, water level, and the radiation level inside the reactor coolant system (RCS), steam generators (PWRs), and/or the containment building.

After the accident identification step, ADAM-D calculates all the necessary thermodynamic properties in the reactor coolant system and the containment. ADAM-D then checks the reactor safety systems, the status of ECCS and possibility of feedwater injection, etc.

This is followed by calculation of various safety margins. In ADAM-D, a margin is defined as the time required until a certain pre-specified condition is satisfied. Typically "calculated margins" include:

- Core uncovery,
- Containment venting,
- Containment failure,
- Suppression pool saturation,
- Suppression pool depletion,
- Condensate storage tank water depletion
- Hydrogen combustion, Etc.

Finally, the various alarms and the states of the reactor and the containment are identified based on the analysis of the on-line data.

In addition to the parameters that are derived solely on the basis of on-line data, ADAM-D also provides supplementary information on the so-called “derived variables” that are based on performance of thermodynamic calculations using the selected “measured variables”. Examples include:

- The water injection rate required for heat removal
- Determination of potential for other failures (e.g., valves failing in “open” position, etc.)

2.2 Accident Management and Analysis Module

The accident management and analysis module includes extensive mathematical models for simulation of a complete spectrum of accidents, including severe accidents leading to reactor pressure vessel failure, core concrete interactions, and containment pressurization.

The ADAM mechanistic models include:

- Non-equilibrium, separated flow thermal-hydraulics (including critical and non-critical flows)
- Heat transfer to various steel and concrete structures
- Parametric fuel heat up, meltdown, relocation, and debris quenching
- Fission products release, transport through the RCS and containment into the environment (for both in-vessel and ex-vessel phases)
- Fission product revaporization
- Hydrogen and CO generation, transport and combustion
- Core concrete interactions
- Emergency Core Cooling System (ECCS) and decay heat removal systems
- Radionuclide decay and transmutation for 60 risk-dominant nuclides

ADAM includes provisions for operator actions in order to examine accident management strategies and their consequences. The simulation code can also be used to generate data for the diagnostic mode, and to assist in the visual display of the accident conditions. The plant initial conditions and information about the type of the accident is user-specified.

3. ADAM Applications To Training

One of the objectives of ADAM development has been application of ADAM for staff training in the areas of: (1) severe accident progression and containment challenges; (2) severe accident management and mitigation; (3) emergency planning; and (4) on-line accident diagnostics

In order to make ADAM more suitable for training applications, the ADAM display architecture, was designed to be based on a highly versatile Graphical User Interface (GUI). This versatile GUI eliminates the need for extensive formal training to enable ease of use in various applications. Examples of typical output/input screens from ADAM are provided in Figure 2.

3.1 Severe Accident Progression and Containment Challenges

ADAM can be used to train key regulatory authority or utility staff in developing an understanding of plant-specific severe accident and containment challenges, for a wide range of severe accident conditions, including LOCAs (of various sizes and locations), transients, bypass events (interfacing systems or SGTR events), with or without ECCS and other Engineered Safety Feature (ESFs). The

ADAM-calculated results can include a wide range of parametric sensitivities to help in developing an appreciation of the potential uncertainties.

Containment challenges that could be examined include various pressurization models (due to steam, non-condensable gases or combustion events), cavity erosion processes, and inadvertent actuation of ESFs potentially impacting containment loads and radiological release behavior.

3.2 Severe Accident Management and Mitigation

Typical procedural alternatives that are considered as part of SAMGs include actions such as those listed in Table 1. The "What If" type of questions and the "Impact" issues are all very important in so far as the operators and the emergency response teams are concerned. ADAM has been designed to be used for training of individuals that will be involved in the emergency and accident response organizations of either the utility or the regulatory authority.

As an example, consider the influence of recovery of offsite power during a station blackout accident with subsequent activation of the containment spray system at about 17 hours into the accident. Figure 3 shows the ADAM calculated containment pressure, where the activation of sprays is followed by rapid condensation of steam in the atmosphere, thus rendering the atmosphere deinerted, and leading to hydrogen burn in the upper compartment at a hydrogen concentration of 6%. In the absence of sprays, the containment pressurization would continue, while, hydrogen concentration within the containment would reach flammable conditions, much later than for the case in which the sprays are activated. The aerosol concentrations in the atmosphere and containment sump are shown in Figure 4 along with the activity associated with iodine and Cs radionuclides washed into the containment sump.

3.3 Emergency Planning

ADAM is being used actively at HSK in the development of emergency planning scenarios for use in various drills and training activities. Development and analysis of accident sequences which include severe accident management measures for the Nationalalarmzentrale (NAZ, National Emergency Organization). The results of ADAM predictions (i.e., timing of events such as initiation of release, duration of release, and time evolution of releases) are used in periodic exercises (approximately every 4 months). Most exercises involve only the NAZ, but one major exercise is held once per year, which involves all organizations that would be charged with emergency management.

Development of a computerized database of specific accident sequences for each Swiss plant. Approximately 60 accident sequences are analyzed for each installation, and the results can be used for fast prediction of source terms in case of an accident. The results of ADAM calculations are directly input to the code ADPIC for real time (i.e., the time when the accident physically occurs) calculation of offsite consequences. ADPIC is a detailed model for calculation of dispersal in the environment. The database will also be used for training of the HSK emergency teams.

3.4 On-Line Accident Diagnostics

One of the useful features in ADAM includes the capability to perform various accident analyses that could be saved for use in a play back mode using the ADAM diagnostics module. In this mode, the ADAM diagnostics module could be used in assisting the training of emergency personnel in identifying the potential responses to the accident based on the availability of limited signals, consistent with the actual conditions of a real accident. This requires the development of specific scenarios, including the availability of several systems/components that could be used in implemented several accident management actions.

Table 1 Typical SAMG procedural alternatives and implications for training

SAM action	Accident phase	"What if" & "impact" training issues
Addition of water to a degraded core	In-vessel	• Time of water injection was changed • Rate of water addition was changed • Impact on metal oxidation • Impact on fission product release
Manual RCS depressurization	In-vessel	• Impact on core cooling (use of low pressure systems) and damage progression • Impact on hydrogen generation • Time of depressurization was changed • Mode of depressurization was changed (Pressurizer valves versus SG relief valves)
Isolation of steam generators following SGTR	In-vessel	• Time of diagnostics and leak detection changed • Time of isolation was changed • Impact on damage progression • Impact on environmental releases
Addition of water to damaged steam generators following SGTR	In-vessel	• Impact of quantity and rate of water addition • Impact of water addition on fission product releases
Recovery of containment isolation prior to core damage	In-vessel	• Detectability/diagnostics issues • Impact on damage progression • Impact on fission product release • Impact on hydrogen combustion
Flooding of lower containment region	Ex-vessel	• Impact on core debris cooling • Impact on hydrogen generation • Impact on lower head failure • Impact on containment loading • Impact on fission product release and transport
Containment Venting	Ex-vessel	• Manual versus automatic vent actuation • Impact of time of venting on release of fission products and activity to environment • Can manual venting be used to control hydrogen combustion
Containment Heat Removal Systems	Ex-vessel	• Time of actuation/recovery and impact on containment integrity • Impact on fission product release • Impact of cooling rate

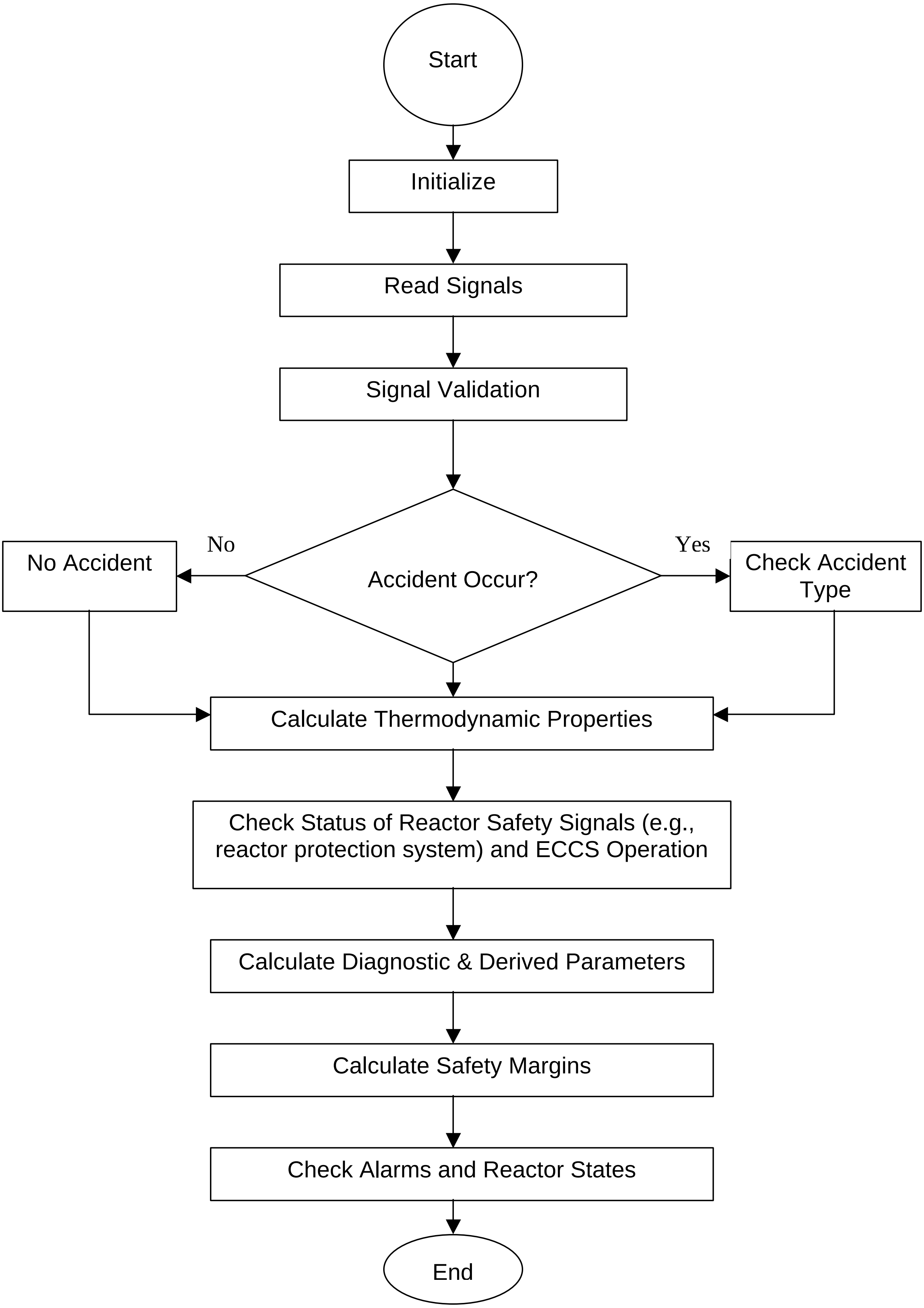


Figure 1 ADAM Diagnostics Logic

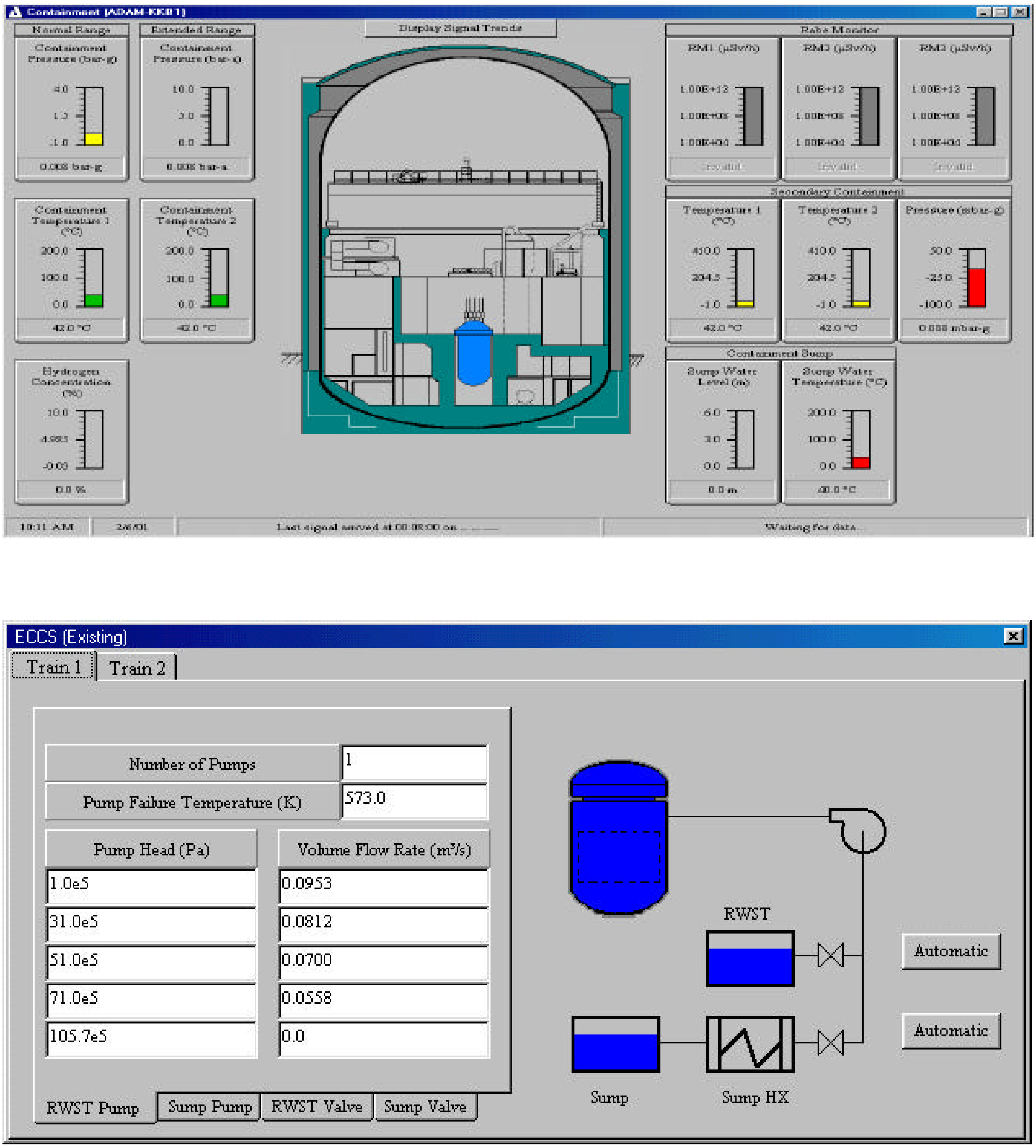
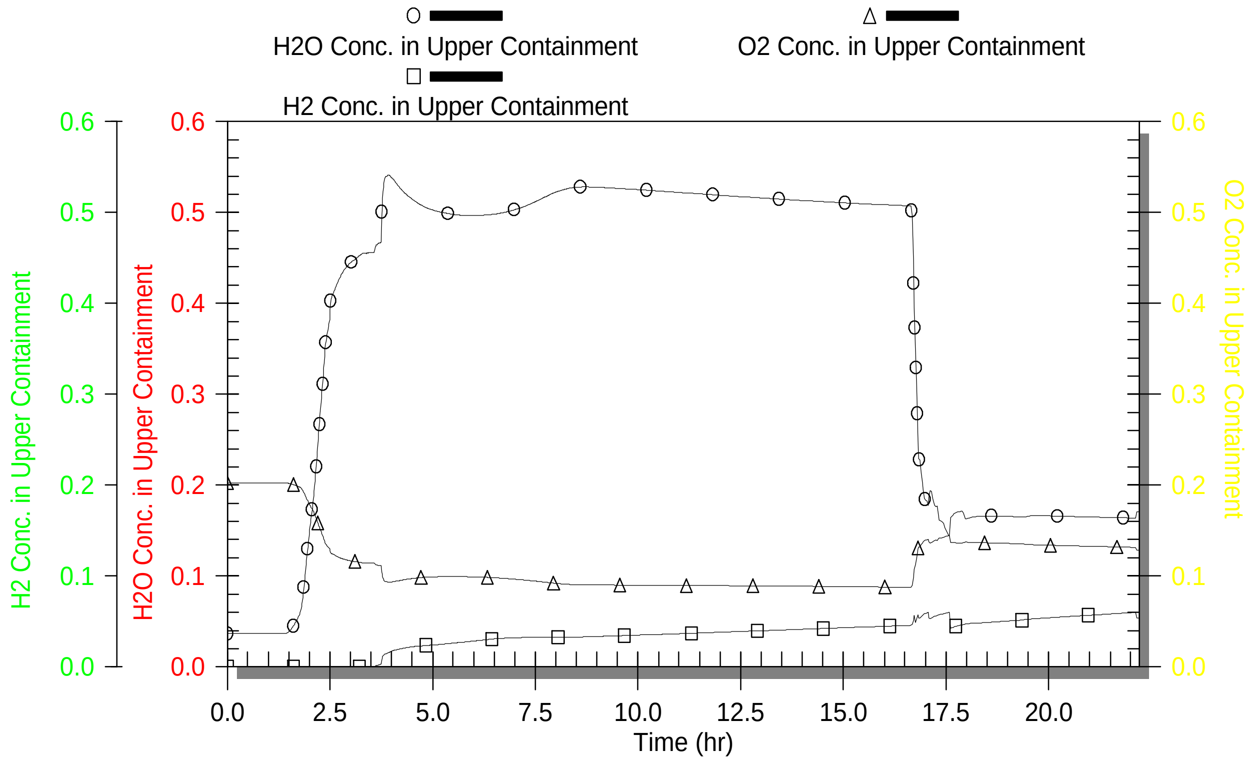


Figure 2   Examples of ADAM-D and ADAM-A Graphical User Interface Screens



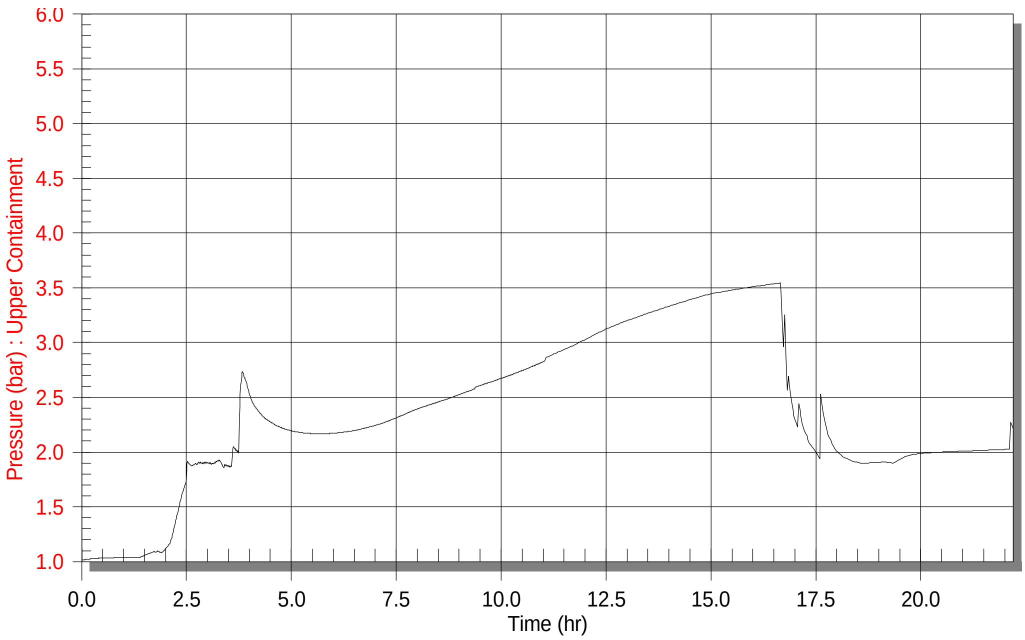


Figure 3 Concentration of various gases and the containment pressurization in the presence of sprays at 17 hours into the accident

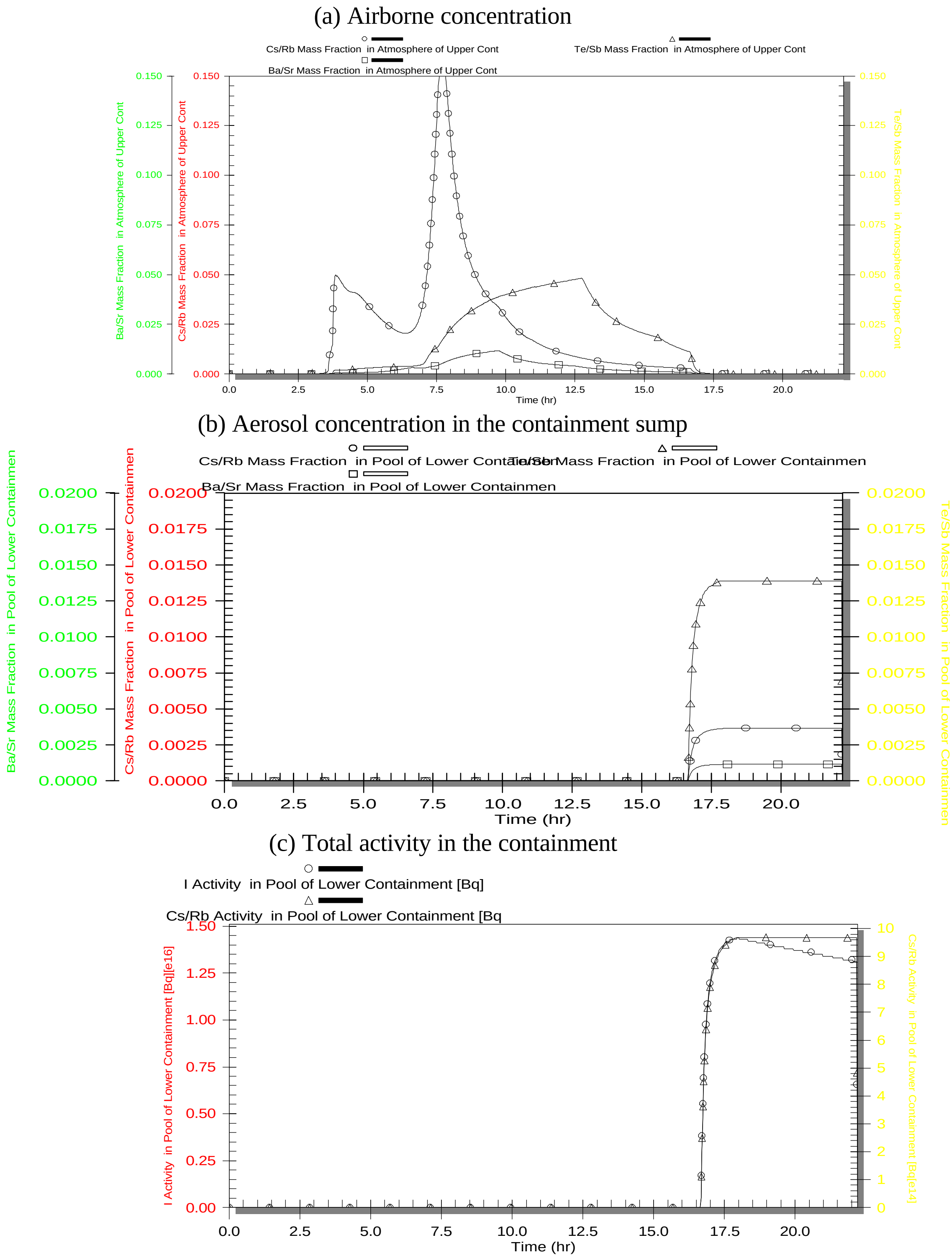


Figure 4 Impact of sprays on (a) airborne fission product concentration, (b) fission product aerosol concentration in the containment sump, and (c) the radiological activity in the containment