International Conference
Nuclear Energy for New Europe 2007
Portorož /Slovenia /September 10-13

port2007@ijs.si
www.nss.si/port2007
+386 1 588 5247, fax +386 1 588 5376
PORT2007, Nuclear Society of Slovenia, Jamova 39, SI-1000 Ljubljana, Slovenia

Simulation of Experiment on Aerosol Behaviour at Severe Accident Conditions in the LACE Experimental Facility with the ASTEC CPA Code

Ivo Kljenak, Borut Mavko
“Jožef Stefan” Institute
Jamova 39, SI-1000 Ljubljana, Slovenia
Ivo.Kljenak@ijs.si, Borut.Mavko@ijs.si

ABSTRACT

The experiment LACE LA4 on thermal-hydraulics and aerosol behavior in a nuclear power plant containment, which was performed in the LACE experimental facility, was simulated with the ASTEC CPA module of the severe accident computer code ASTEC V1.2. The specific purpose of the work was to assess the capability of the module (code) to simulate thermal-hydraulic conditions and aerosol behavior in the containment of a light-water-reactor nuclear power plant at severe accident conditions. The test was simulated with boundary conditions, described in the experiment report. Results of thermal-hydraulic conditions in the test vessel, as well as dry aerosol concentrations in the test vessel atmosphere, are compared to experimental results and analyzed.

1 INTRODUCTION

During an unmitigated severe light-water-reactor (LWR) accident with core meltdown, radioactive fission and activation products would be released into the containment as gas, vapor or, to a great extent, adsorbed on aerosols. Since the knowledge of time-dependent distributions of fission products and aerosols is very important to mitigate accidents, relevant prediction capabilities are of great importance. Experiments with aerosols are thus being used to assess the capabilities of severe accident codes to simulate aerosol behavior.

Experiments on aerosol behavior have been performed in 1986 in the LACE (LWR Aerosol Containment Experiment) experimental facility, at Westinghouse Hanford Company (USA) [1]. The objectives of the LACE program were to investigate experimentally the inherent aerosol retention behavior for postulated, high-consequence accident situations, and to provide a data base for validating containment aerosol and related thermal-hydraulic computer codes. The LACE facility is a large cylindrical vessel, in which gases and aerosols are being injected during experiments. During the experiment considered in the present work, CsOH aerosols (water soluble) were injected first. Then, a mixture of CsOH and MnO (non-soluble) aerosols was injected, followed by injection of sole MnO aerosols. Steam and nitrogen were also injected, as aerosol carrier gases as well as to pressurize the vessel.

The severe accident code ASTEC is being developed jointly by the Institut de Radioprotection et de Sureté Nucléaire – IRSN (France) and by the Gesellschaft für Anlagen und Reaktorsicherheit – GRS (Germany) [2]. The assessment of physical models, implemented in the ASTEC code, is being carried out within the Severe Accident Research Network of Excellence (SARNET), which is part of the 6th EU Framework Program. In the present work, the experiment LACE LA4 was simulated with the ASTEC CPA (Containment Part of ASTEC) lumped-parameter module of the ASTEC V1.2 code (the module is referred in the present paper as the "ASTEC CPA code") [3,4].

The first 850 min of the above-mentionned test (that is, until the vessel is finally opened to the atmosphere and left to cool down) were simulated. The calculated thermal-hydraulic conditions (pressure, atmosphere temperature, steam partial pressure and mass fraction), as well as CsOH and MnO aerosol concentrations in the vessel atmosphere are compared to experimental results.

2 EXPERIMENT

2.1 Experimental Facility

The key piece of the LACE Containment System Test Facility is the containment vessel (Figure 1). It is a vertical cylindrical steel vessel with an inner free volume of 852 m^3. The overall height of the vessel is 20.3 m, and the inner diameter of the cylindrical part is 7.62 m. The walls are not heated (their temperature is not controlled) and they are insulated on the outside with a 25-mm thick layer of insulation. The containment vessel is fabricated of carbon steel plates ranging in thickness from 16.4 mm to 19.1 mm. The total mass of the upper head, cylindrical wall and lower head is 24937 kg, whereas the total mass of the internal structures is 14020 kg. Many penetrations exist for electrical, instrumentation, water, steam, ventilation and sampling lines. The vessel can be vented through a leak path which vents to the atmosphere.

Additional details about the experimental facility are provided in the LACE LA4 final report [1].

2.2 Experimental Procedure

The test LA4 started at time -50 min with injection of gases. Aerosols were injected between times 0 min and 80.2 min. After that, the vessel was gradually vented and cooled down. The venting simulated a delayed containment failure following a severe accident and was a special feature of the test LA4.

Two aerosol materials were generated separately during different, overlapping periods. CsOH aerosol (soluble) was generated by reaction of Cs vapor with steam. Elemental Cs was heated in a pressurized supply vessel and discharged into a heated vaporizer coil. The vaporized Cs and a low flow rate of nitrogen sweep gas flowed through a heated line to a reaction chamber containing superheated steam and nitrogen. MnO aerosol (non-soluble) was generated by vaporizing Mn powder in plasma torches and discharging the Mn vapor into a reaction chamber which contained a superheated steam and nitrogen atmosphere. The species were mixed in an intermediate vessel to provide some time for coagglomeration and fallout of oversized particles to occur and then injected into the containment vessel.

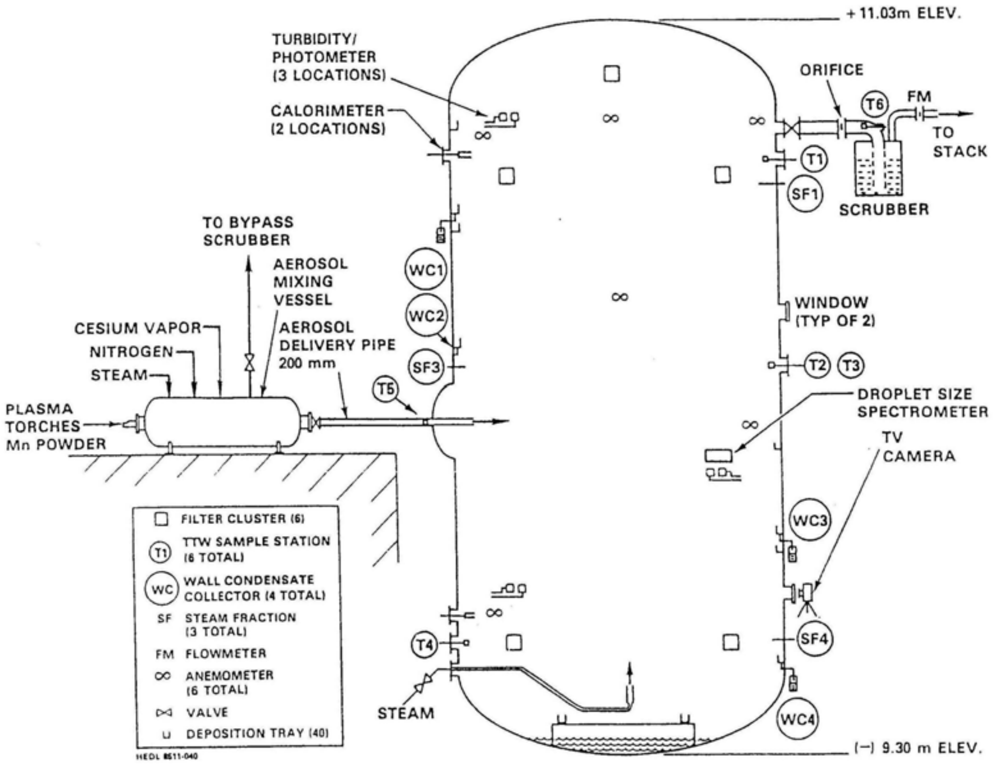

Figure 1. Schematic view of the LACE experimental facility [1].

Specifically, the test consisted of the following phases:

1. Heatup: -50 – 0 min
   - steam injection,
   - nitrogen injection through aerosol delivery line,
   - nitrogen purge to instruments.
2. Injection of CsOH aerosols: 0 – 30.5 min
   - steam injection,
   - aerosol carrier gas injection (steam, N_2, He, Ar),
   - aerosol injection,
   - nitrogen purge to instruments.
3. Injection of CsOH and MnO aerosols: 30.5 – 50.5 min
   - steam injection,
   - aerosol carrier gas injection (steam, N_2, He, Ar),
   - aerosol injection,
   - nitrogen purge to instruments.
4. Injection of MnO aerosols: 50.5 – 80.2 min
   - steam injection,
   - aerosol carrier gas injection (steam, N_2, He, Ar),
   - aerosol injection,
   - nitrogen purge to instruments.
5. Steady state: 80.2 – 280 min
   - steam injection,
   - nitrogen injection through aerosol delivery line,
   - nitrogen purge to instruments.
6. Venting: 280 – 600 min (vent flow stopped at 440 min)

- steam injection,
- nitrogen injection through aerosol delivery line,
- nitrogen purge to instruments.

7. Cooldown: 600 – 5700 min
    - nitrogen injection through aerosol delivery line,
    - nitrogen purge to instruments,
    - vent valve opened at 800 min.

3 INPUT MODEL

3.1 Test Vessel

The vessel was modeled as a single control volume (“zone”), whereas the environment was modeled as another zone. The main purpose of the development of the ASTEC code is to use it for simulations of severe accidents in actual nuclear power plants. As ASTEC CPA is a lumped-parameter code, a multi-compartment containment would in principle be modeled in such a way, that each compartment would be modeled as a single zone. As the volume of the LACE experimental vessel is of the same order of magnitude as the volume of an individual compartment in a multi-compartment containment, the modeling of the LACE vessel as a single zone is adequate to assess the code capability to model accidents in actual plants.

The vessel walls were modeled as specified in the LACE LA4 final report (see Table 1). They consisted of the top head, cylinder, and bottom head. In addition, internal steel structures were modeled as vertical and horizontal slabs. The surfaces and masses of internal structures correspond to the specifications in the LACE LA4 final report. The prescribed maximum thickness of the water film on walls and structures was 0.5 mm.

Table 1. Modeling of vessel walls

	Area	**Steel thickness**	**Insulation thickness**
	m^2	*m*	*m*
Top Head	63.0	0.0193	0.025
Cylinder	394.0	0.0169	0.025
Bottom Head	63.0	0.0193	0.025

3.2 Aerosol Modelling

Aerosol parameters were prescribed in the input model as described in the LACE LA4 final report, or by prescribing commonly used generic options. The prescribed aerosol density was 4560 kg/m^3, which is the median value of CsOH and MnO aerosol densities. Steam condensation on aerosols, deposition by diffusiophoresis and deposition by thermophoresis were prescribed.

The aerosol injection mass flow rates during the experiment were calculated in the report by combining mass balances and measurements from filter samplings. These injection rates were included in the input model. Details are provided in refs. [5] and [6].

The Kelvin effect ought to be considered for soluble CsOH aerosols and not considered for non-soluble MnO aerosols. However, the ASTEC CPA code does not allow separate modeling of the Kelvin effect for separate aerosol components. Besides, if the Kelvin effect was modeled, the simulation stopped due to numerical problems. Thus, the test was simulated without modeling the Kelvin effect.

The aerosol size range (diameters from $5 \cdot 10^{-8}$ m to $1 \cdot 10^{-4}$ m) was divided into 20 sections. Log-normal size distributions were prescribed. The mass median radii and the geometric standard deviations are shown in Table 2.

Table 2. Aerosol size distribution parameters

	CsOH		MnO	
Time interval	Mass median radius	Geom. stand. deviat.	Mass median radius	Geom. stand. deviat.
s	*μm*	—	*μm*	—
0 — 1830	0.3478	1.81	—	—
1831 — 3030	0.5746	1.80	0.5185	1.70
3031 — 4812	—	—	0.3861	2.56

3.3 Initial and Boundary Conditions

The test was simulated from time -3000 s (-50 min) to time 48000 s (800 min).

The initial conditions were prescribed as specified in the LACE LA4 final report. The pressure was 1.07 bar, the temperature of the atmosphere and of the walls was 42.5 °C, the mass of water in the sump was 950.0 kg, the temperature of the water in the sump was 41.9 °C, and the volumetric steam fraction in the vessel atmosphere was 0.0730.

The venting of the vessel during some phases of the experiment was taken into account as well. The removal of gases due to venting and sampling was prescribed according to the reported measurements in the final report. However, a correction had to be introduced. Namely, air was modeled as a mixture of oxygen and nitrogen. If the venting was modeled according to the data specified in the report, than the mass of oxygen in the vessel would drop below zero. To remedy to this situation, additional nitrogen was removed instead of oxygen from a time when the mass of oxygen attained a value close to zero.

The heating due to the internal lightning and the cooling due to the cooling water to the velocity measuring turbines were modeled as heat sources and sinks, respectively.

The experimental measurements indicate significant flow velocities in the containment atmosphere (up to 1.5 m/s). As this flow was not modeled due to a lumped-parameter description and single-zone modeling of the test vessel, this could be the cause for some discrepancies between the experimental and simulation results. Namely, the atmosphere flow in the facility probably significantly influenced atmosphere mixing, which in turn could influence steam condensation on structures as well as aerosol deposition on vessel walls, internal structures and in the sump.

According to the LACE LA4 final report, the venting accounted for a loss of about 0.2% of the injected aerosol mass into the containment vessel. The removal of aerosols by venting was not modeled.

4 RESULTS AND DISCUSSION

Experimental and simulation results are shown on Figures 2 to 8. Figure 2 shows the experimental and simulated pressure in the test vessel. The uncertainty of the experimental measurements is ± 2% [1]. The general trend was very well simulated. The calculated pressure remained somewhat too high after the stopping of the vent flow at 440 min.

Figure 3 shows the experimental and simulated atmosphere temperature in the test vessel. The uncertainty of the experimental measurements is ± 3 ºC [1]. The agreement between results is good. The calculated temperature after the stopping of the vent flow at 440 min was somewhat too high as well.

Figure 4 shows the experimental and simulated steam mass fraction in the test vessel. The uncertainty of the experimental measurements is ± 10%. The different symbols correspond to different measuring locations in the test vessel. The general agreement between results is good. The differences between experimental measurements show that, during the experiment, the atmosphere was not entirely homogeneous.

Figure 5 shows the experimental and simulated steam pressure in the test vessel. The experimental partial pressure of steam was computed by multiplying the volumetric steam fraction by the total pressure. The different symbols also correspond to different measuring locations in the test vessel. A good agreement may be observed. The calculated steam pressure remained somewhat too high after the stopping of the vent flow at 440 min. This is related to the similar overprediction of the total pressure.

Figure 6 shows the experimental and simulated mass of water in the vessel sump. The overprediction between 0 s and 20000 s seems to be an indication of the overprediction of steam condensation in this period. The discrepancy in the final phase of the simulation is probably due to the leaking from the cooling lines, reported in the LACE LA4 final report.

Figures 7 and 8 show the experimental and simulated dry aerosol mass concentration of soluble and non-soluble aerosols, respectively, in the test vessel atmosphere. The uncertainty of the experimental measurements is ± 25% [1]. The concentration of non-soluble aerosols agrees very well with the experimental results. The maximum and final value of the concentration of soluble aerosols also agree well with the experimental results. However, the simulated pattern of concentration decrease was different from the experimental one. A possible explanation for this discrepancy is the non-adequate simulation of the atmosphere saturation. Namely, according to the LACE LA4 final report, the atmosphere in the test vessel was saturated or close to saturation during the entire experiment. However, as shown on Figure 9, the simulated saturation during the first 10000 s was well below 100%, which perhaps prevented a more intense condensation of steam on soluble aerosol particles. Another possible explanation for the discrepancy is the lack of modeling of the Kelvin effect.

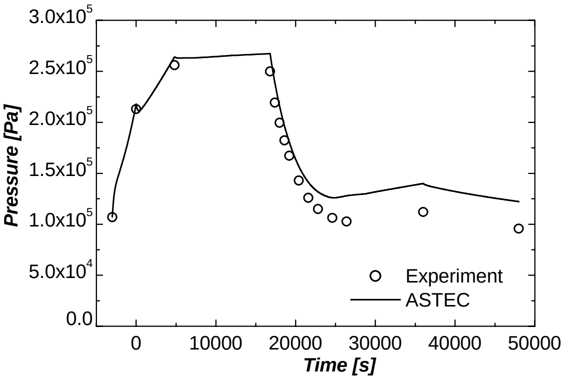

Figure 2. Experimental and simulated pressure in test vessel.

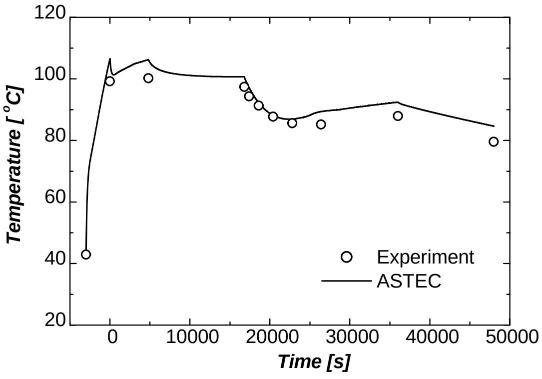

Figure 3. Experimental and simulated atmosphere temperature in test vessel.

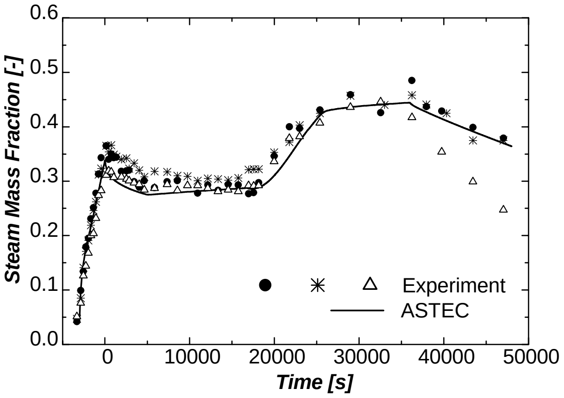

Figure 4. Experimental and simulated steam mass fraction in test vessel.

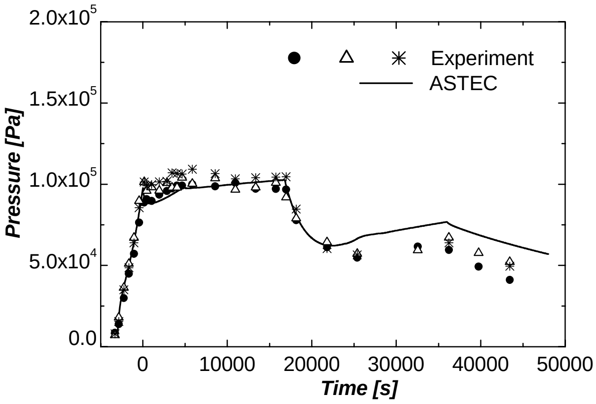

Figure 5. Experimental and simulated steam pressure in test vessel.

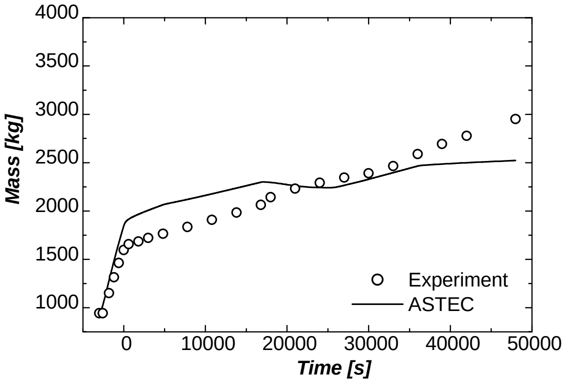

Figure 6. Experimental and simulated mass of water in vessel sump.

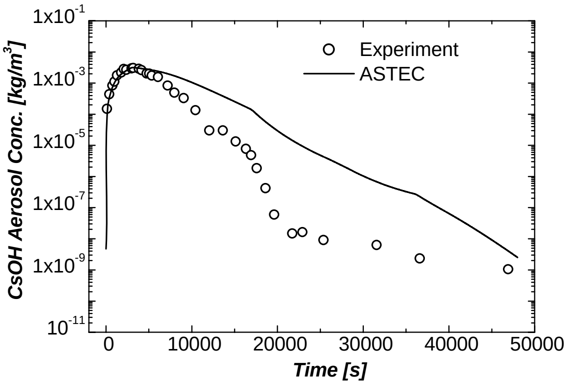

Figure 7. Experimental and simulated dry aerosol mass concentration of soluble aerosols in vessel atm.

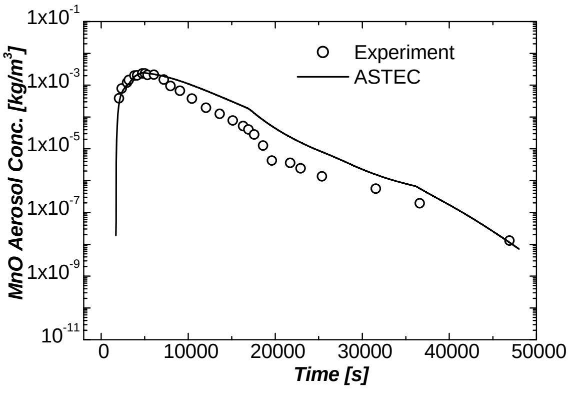

Figure 8. Experimental and simulated dry aerosol mass concent. of non-soluble aerosols in vessel atm.

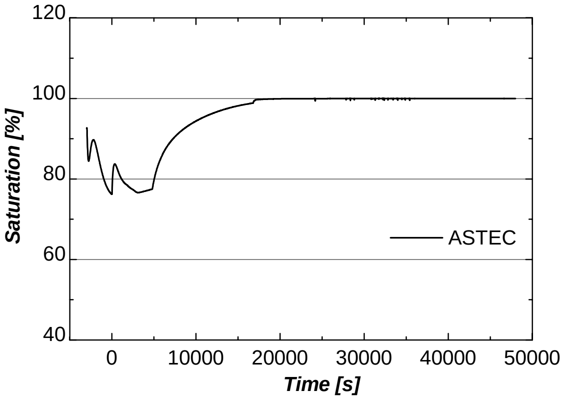

Figure 9. Simulated saturation of test vessel atmosphere.

5 CONCLUSIONS

The first 850 minutes of the experiment LACE LA4 on thermal-hydraulics and aerosol behavior in a light-water-reactor nuclear power plant containment atmosphere at accident conditions, which was performed in the LACE facility, were simulated with the ASTEC CPA V1.2 code.

The thermal-hydraulic conditions were mostly well simulated. The calculated pressure and temperature were a little too high after the stopping of the vent flow from the containment vessel. The maximum values and values at the end of the simulation of the dry aerosol concentrations in the vessel atmosphere also agreed well with the measured values. However, the simulated trend of the decrease of the soluble dry aerosol concentration was different from the trend that was observed in the experiment. This could be due to an underprediction of the atmosphere saturation during aerosol injection, or to the lack of modeling of the Kelvin effect. Nevertheless, the agreement between experimental and calculated results supports the applicability of the ASTEC CPA code to simulate thermal-hydraulic and aerosol phenomena in an LWR NPP containment at accident conditions.

ACKNOWLEDGMENTS

The research presented in the present work was performed within the research program “Reactor engineering” (contract no. 3311-04-8226614) financed by the Ministry of Higher Education, Science and Technology of the Republic of Slovenia.

The Jozef Stefan Institute is a member of the Severe Accident Research Network of Excellence (SARNET) within the 6th EU Framework Programme. The benefit from European Commission RTD Programme for research is acknowledged.

REFERENCES

[1] J.D. McCormack, R.K. Hilliard, J.M. Salgado, Final Report of Experimental Results of LACE Test LA4 – Late Containment Failure with Overlapping Aerosol Injection Periods, Westinghouse (USA), 1987.

[2] J.P. Van Dorsselaere et al., ASTEC V1.1 Overview, Rev.0, Report ASTEC-V1/DOC/04-10, IRSN (France) and GRS (Germany), 2004.

[3] W. Klein-Hessling, B. Schwinges, ASTEC V0 CPA Module, Program Reference Manual, Rev.0, Report ASTEC-V0/DOC/01-34, IRSN (France) and GRS (Germany), 1998.

[4] J. Bestele, W. Klein-Hessling, ASTEC V0 CPA Module, Containment Thermalhydraulics and Aerosol and Fission Product Behaviour, User Guidelines, Rev. 0, Report ASTEC-V0/DOC/00-14, IRSN (France) and GRS (Germany), 2000.

[5] I. Kljenak, B. Mavko, Simulation of LACE LA4 Experiment on Aerosol Behavior in a Nuclear Power Plant Containment with the ASTEC CPA V1.2 Code, Report IJS-DP-9484, Rev. 0, Jozef Stefan Institute (Slovenia), 2006.

[6] I. Kljenak, B.Mavko, “Simulation of LACE LA4 Experiment on Aerosol Behavior in a NPP Containment at Severe Accident Conditions with the ASTEC CPA Code”, Proc. 15th Int. Conf. on Nuclear Engineering, Nagoya, Japan, April 22-26, 2007.