Response of Soviet VVER-440 Accident Localization Systems to Overpressurization

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INTRODUCTION

The Soviet designed VVER-440 model V230 and VVER-440 model V213 reactors do not use a containment building to mitigate the effects of accidents. Instead, these VVER-440 units employ a sealed set of interconnected compartments, collectively called the accident localization system (ALS), to reduce the release of radionuclides to the atmosphere during accidents. The accident localization system used on these two VVER-440 models is significantly different. Descriptions of the VVER accident localization structures may be found in the report DOE NE-0084, Overall Plant Design Descriptions VVER Water-Cooled, Water-Moderated Energy Reactor. The objective of this paper is to evaluate the structural integrity of the VVER-440 ALS at the Soviet design pressure, and to determine their response to pressure loadings beyond the design value. Predictions of pressure loadings of the ALS following a loss-of-coolant accident involving the rupture of a primary coolant system pipe are presented in a companion paper (Sienicki and Horak, 1989). Complex, three-dimensional, nonlinear, finite element models were developed to represent the major structural components of the localization systems of the VVER-440 model V230 and of the VVER-440 model V213. The interior boundary of the localization system was incrementally pressurized in the calculations until the prediction of gross failure.

DESCRIPTION

Figure 1 shows the accident localization compartments of the VVER-440 model V213 which consist of the rectilinear steam generator room, the lower part of the reactor shaft, the pump room, and the upper reactor shaft. The steam generator room is a rectangular, box-like, reinforced concrete structure assumed to have the outside dimensions: 48 meters (157.5 feet) long by 39 meters (128.0 feet) wide and 16 meters (52.5 feet) high. The concrete ceiling is assumed to be 1.5 meters (4.9 feet) thick and contain two adjacent, orthogonal layers of reinforcing bars near its inside and outside faces. The floor slab of the steam generator room is assumed to be 3.0 meters (9.8 feet) thick and contains multiple layers of reinforcing steel.

The ALS exterior walls are assumed to be 1.5 meters (4.9 feet) thick and also contain orthogonal layers of rebars near their inside and outside faces. The modeling assumes that a 5.5 meters (18.0 feet) wide by 6.9 meters (22.6 feet) high opening in the wall provides a passageway to the bubbler condenser tower. Diagonal reinforced concrete walls, which are 0.75 meters (2.5 feet) thick, are

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*This work was performed by the U. S. Department of Energy's Analysis Team.

assumed located in the corners of the steam generator room. These walls reduce the ceiling span. The steam generator room wall adjacent to the turbine hall is designated as the rear wall and the wall next to the bubbler condenser tower is designated as the front wall. The ALS is elevated above grade level, supported by walls underlying the floor of the steam generator room.

Figure 2 shows the VVER-440 model V230 ALS. Since the ALS configuration is similar to that of the VVER-440 model V213, only the significant structural differences will be discussed. First, the VVER-440 model V230 is not elevated above grade; the floor slab of the steam generator room is the basemat. Second, one of the corners near the refueling pool is assumed not to have a diagonal corner wall. Third, the steam generator room is smaller; it is assumed to be 42 meters (137.5 feet) long (outside dimensions) by 39 meters (128.0 feet) wide and 11 meters (36.1 feet) high. Fourth, the walls and floor and ceiling slabs are thinner. The walls of the steam generator compartment and the ceiling slab are taken equal to 1.0 meter (3.3 feet) thick and the corner diagonal walls 0.5 meter (1.6 (feet) thick.

The steel reinforcement in the ALS is assumed to be constructed from two orthogonal layers of rebars located near each surface of the walls, pump room floor, and ceiling. The diameters of the rebars were assumed to be 20 millimeters (0.79 inches) and 32 millimeters (1.26 inches). The cover distance was assumed to be 5.0 centimeters (2.0 inches), and the pitch was taken as 20.0 centimeters (7.9 inches). The steam generator room floor and the reactor shaft were assumed to have additional reinforcement layers.

MATERIAL PROPERTIES

The concrete used to construct the localization compartment is taken to be design brand M-400 (Baikov and Sigalov, 1981) assumed to have a compressive strength of 400 kilograms of force per square centimeter (5,689 pounds per square inch). The yield strength is taken to be 200 kilograms of force per square centimeter (2,845 pounds per square inch), and the ultimate strain 0.3 percent. Young's modulus is taken equal to 302 x 10^3 kilograms of force per square centimeter (4.3 x 10^6 pounds per square inch) and Poisson's ratio 0.2.

The reinforcing steel in the localization compartment is assumed to be class A-III (Soviet designation) deformed bars (Baikov and Sigalov, 1981). The modulus of elasticity of the bars is taken to be 200 gigapascals (29 x 10^6 pounds per square inch), the yield point 400 megapascals (58 x 10^3 pounds per square inch), the ultimate strength 600 megapascals (87 x 10^3 pounds per square inch), and the ultimate strain 19 percent.

The inside surfaces of the walls of the ALS are assumed to be lined with 6 millimeter (0.24 inch) thick low carbon steel assumed to have properties similar to the Soviet carbon steel designated as 22K (Antikagn, 1986). The following material properties are assumed: Young's modulus of 207 gigapascals (30 x 10^6 pounds per square inch), Poisson's ratio of 0.3, yield stress of 265 megapascals (38 x 10^3 pounds per square inch), ultimate strength equal to 431 megapascals (62 x 10^3 pounds per square inch), and an ultimate strain of 15.5 percent.

THREE-DIMENSIONAL STRUCTURAL MODEL

A complex finite element model for the localization compartments of a VVER-440 model V213 and their underlying supporting structure has been developed. Because of the near symmetry of this structure along a vertical plane from the turbine building to the bubbler condenser tower, a model that included one-half of the localization compartments is assumed to be sufficient. The model, shown in Figure 3, includes representations for the steam generator room, the corner walls, the pump room, the cable corridor, the reactor shaft, the refueling pool, and the underlying walls.

The reinforcing steel is explicitly modeled within the concrete wall/slab model. The arrangement of the reinforcing steel assumed in the calculations is shown in Figure 4. It should be noted that the orientation of the rebars is correctly shown in the figure; however, for the sake of clarity, only one rebar per direction is shown in each element. The pitch, which is the distance between rebars, is input into the code to assure that the correct number of bars participate in the response.

To calculate the structural response of the VVER-440 model V230, the finite element model of the VVER-440 model V213 design was modified to account for the major differences between the two designs. All wall, floor, and ceiling thicknesses were changed to values appropriate for the VVER-440 model V230. However, the length, width, and height of the steam generator room were kept the same. Figure 5 is a perspective view of the complete model.

Since information was not available on localized design details, the global analysis did not take into account the fact that these details could give rise to stress or strain concentrations that could potentially lower the ultimate capacity. For example, thick anchor plates attached to the thin liner plate could cause such concentrations. The effect of the welded joints of the liner was not taken into account. The method of liner plate anchorage to the concrete is another detail that was not considered. The details of the penetrations in the ceiling through which the steam generators may be accessed and the cover with its bolting system for this penetration could affect the prediction of ultimate capacity.

The loading is a pressure applied to the interior surfaces of all the walls that belong to the interior boundary of the accident localization system.

RESULTS

The structural response of the accident localization system subjected to internal pressurization was obtained with the NEPTUNE code (Kulak and Fiala, 1988). Incremental load steps of 0.05 megapascal were applied in the calculations.

The deformed shape of the accident localization compartments and related structures predicted for the VVER-440 model V213 design are shown in Figure 6. It is seen that large displacements are calculated in the ceiling, pump room, and steam generator room rear wall. The largest calculated vertical displacement of the ceiling occurs between the pump room wall and the steam generator room side wall; note, it is closer to the rear wall than the front wall. The pump room seems to stiffen the ceiling above it. The calculated displacement history of node 51 (Figure 3), which is the point of maximum displacement in the ceiling, is shown in Figure 7. The displacement appears to be linear up to an overpressure of 0.1 megapascal (0.2 megapascal absolute, 29 pounds per square inch absolute) and has a magnitude of 0.1 centimeters (0.04 inches). Nonlinear response is evident beyond 0.1 megapascal (0.2 megapascal absolute, 29 pounds per square inch absolute) as cracking initiates and progresses over larger regions of the walls and ceiling as well as through the thickness. The displacement increases to 4.0 centimeters (1.6 inches) at 0.4 megapascal gauge (0.5 megapascal absolute, 72.5 pounds per square inch absolute). When the applied overpressure reaches 0.40 megapascal (0.50 megapascal absolute, 72.5 pounds per square inch absolute), a prediction of rebar failure at the side wall-floor junction can be assessed due to combined tensile axial stress and transverse shear stress that exceed the ultimate stress of the rebars. Once a rebar fails, the remaining rebar and liner cannot carry the load, and they also are predicted to fail. In this case, a leak path could develop through both the cracked liner and the cracked concrete. The largest displacement of the steam generator room rear wall occurs in the region of the vertical leg of the cable corridor. A comparison between the calculated horizontal movement of the ceiling and floor shows that the ceiling stretches more. Deformations of the underlying supporting structure are predicted to be relatively small.

Deformed structure plots for the VVER-440 model V230 design are shown in Figures 8 and 9. The VVER-440 model V230 ALS incorporates nine vent valves intended to prevent overpressurization by venting excess steam and air directly to the atmosphere. All of the valves are assumed to open when the pressure exceeds the 0.10 megapascal (14.5 pounds per square in gauge) design pressure. Nonetheless, the calculations were continued to higher pressure levels to obtain the calculated ultimate capacity. One of the major differences in response between the two designs is that for the VVER-440 model V230 design, the largest vertical displacement in the ceiling is calculated to take place near the corner assumed not to have a diagonal corner wall under it. The large bulge predicted for the steam generator room side wall is also shifted toward that corner. Figure 7 shows that for the same overpressure, the predicted displacements for the VVER-440 model V230 are significantly higher than those for the VVER-440 model V213. The ALS is predicted to respond nonlinearly, as cracking initiates and propagates, at an overpressure of 0.05 megapascal (7.3 pounds per square inch gauge). At an overpressure of 0.3 megapascal (43.5 pounds per square inch gauge) a through-crack is predicted in the concrete wall at the junction of the side wall and floor slab of the steam generator room.

CONCLUSIONS

The accident localization system of the VVER-440 model V213 was predicted to respond in the linear elastic range for overpressures up to the Soviet design overpressure of 0.15 megapascal (21.8 pounds per square inch) gauge. The ultimate capacity was predicted to be an overpressure of 0.40 megapascal (58.0 pounds per square inch) gauge following the rupture of a rebar at an existing through-crack in the side wall of the steam generator room.

For the earlier designed VVER-440 model V230, concrete cracking was predicted to occur in the ALS at overpressures below the Soviet design overpressure of 0.10 megapascal (14.5 pounds per square inch) gauge. The ultimate capacity was calculated to be an overpressure of 0.30 megapascal (43.5 pounds per square inch) gauge. The failure mode was similar to that of the VVER-440 model V213 described above.

ACKNOWLEDGMENT

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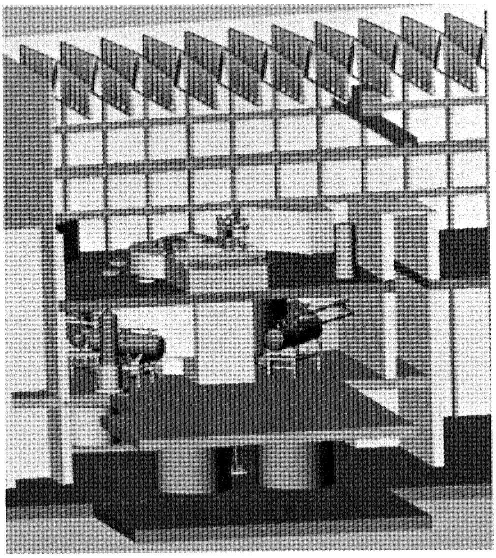

Fig. 1. VVER-440 Model V213 Accident Localization System

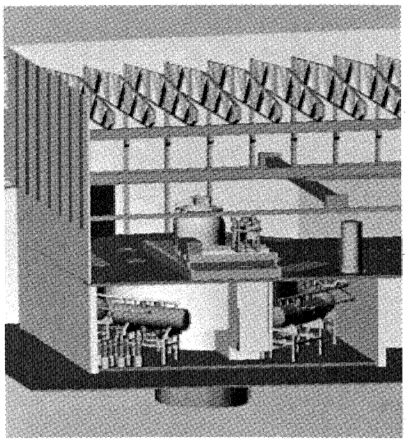

Fig. 2. VVER-440 Model V230 Accident Localization System

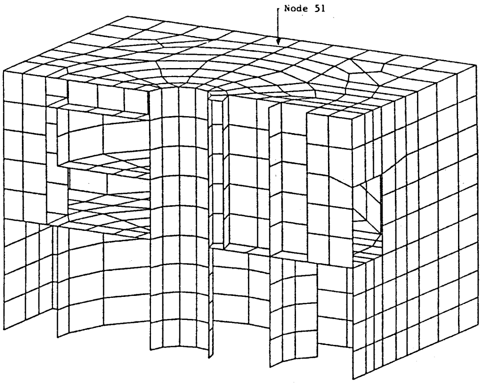

Fig. 3. Finite Element Model of the VVER-440 Model V213 ALS and Underlying Supporting Structure

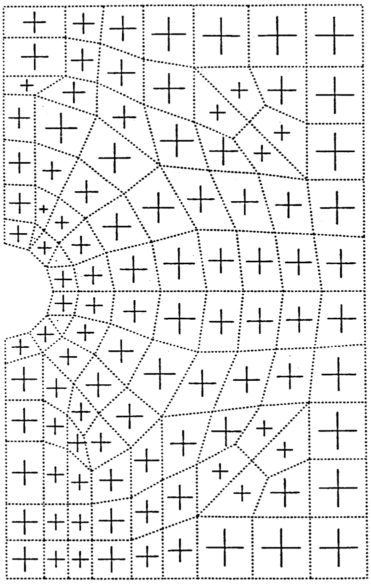

Fig. 4. Assumed Layout of Reinforcing Steel in the Steam Generator Compartment Floor of a VVER-440 Model V213

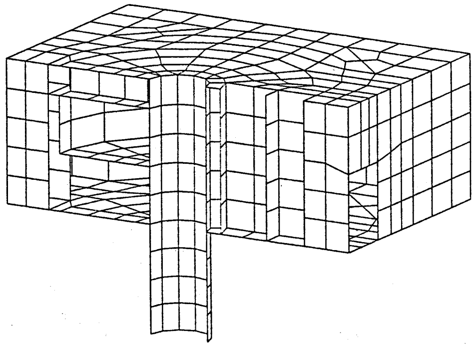

Fig. 5. Finite Element Model of the VVER-440 Model V230 ALS

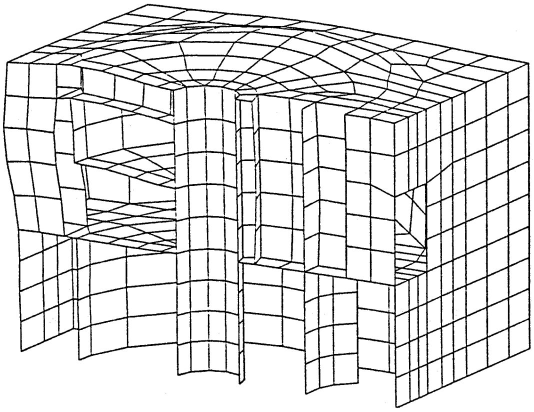

Fig. 6. Deformed Shape of the VVER-440 Model V213 ALS Calculated at an Overpressure of 0.40 Megapascal (58 pounds per square inch; mag. 10x)

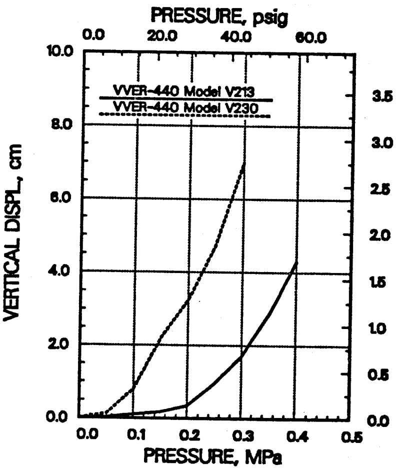

Fig. 7. Calculated VVER-440 Model V213 and VVER-440 Model V230 ALS Ceiling Displacement Histories During Overpressurization

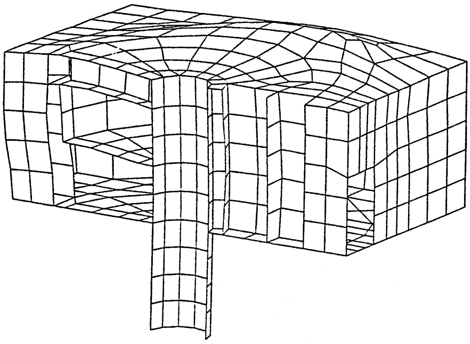

Fig. 8. Deformed Shape of the VVER-440 Model V230 ALS Calculated at an Overpressure of 0.30 Megapascal (43.5 pounds per square inch; mag. 10x)

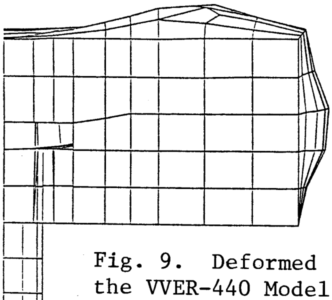

Fig. 9. Deformed Shape of the VVER-440 Model 230 ALS Calculated at an Overpressure of 0.30 Megapascal (43.5 pounds per square inch; mag. 10x)

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