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Development of vital area identification procedure against vehicle attack

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1. Introduction

Physical protection design should be implemented to identify structures and elements that require physical protection for essential facilities from the potential of High Radiological Consequences (HRC) or Unacceptable Radiological Consequences (URC). However, the practical implementation of the physical protection design becomes difficult if the identified vital areas exist independently of the yard.

The Condensate Storage Tank (CST) is a typical example of equipment that cannot be identified as a vital area but is located independently in the yard outside of the major buildings in a nuclear power plant. It is true that CST is the most efficient prevention set.

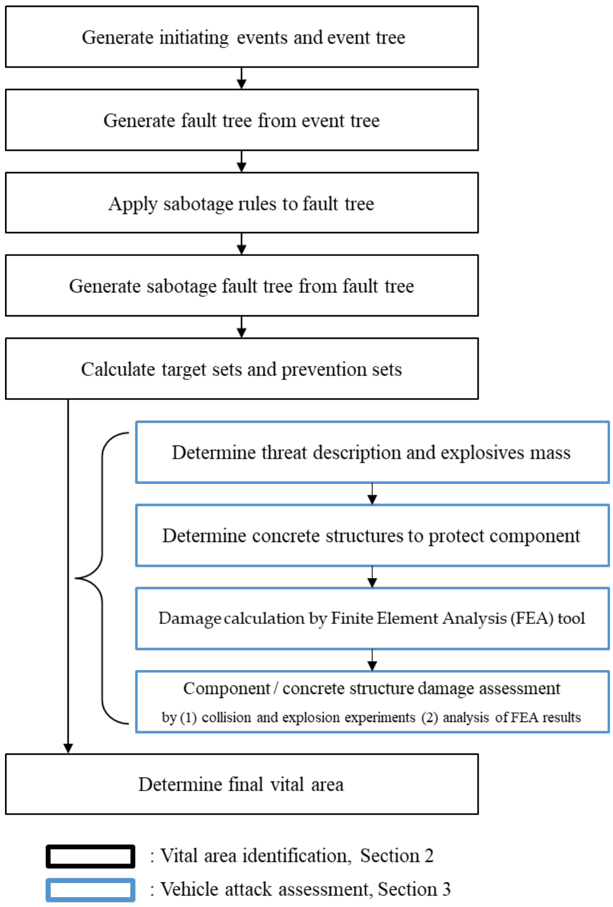


Fig. 1. VAI procedure against vehicle attack

This paper presents a method for efficiently selecting vital areas reflecting the physical protection design of vehicle attacks and CST, using a threat evaluation procedure. In Section 2, vital areas were selected through the Vital Area Identification (VAI) method, and changes in vital area selection were presented by comparing existing cases and the case of reinforcing concrete facilities in the CST.

Section 3 conducted an analysis to reinforce the concrete structure in the CST, which was identified as a weak vital area. This included (1) establishing specifications for structures and reinforcement structures, and (2) conducting damage calculation based on the maximum weight of explosives that could reasonably enter the vehicle.

Finally, Section 4 presents the conclusions of the study. Figure 1 shows the overall procedure, which involves changing drone threats to vehicle threats and incorporating procedures for selecting vital areas by referring to drone threat assessment procedures from the development of procedures for drone risk assessment (NSTAR-21PS32-86) [1].

2. Vital Area Identification (VAI)

This section presents the procedures for selecting vital areas [1] and how they change when reinforcing concrete facilities in the CST. The procedure for selecting vital areas is as follows:

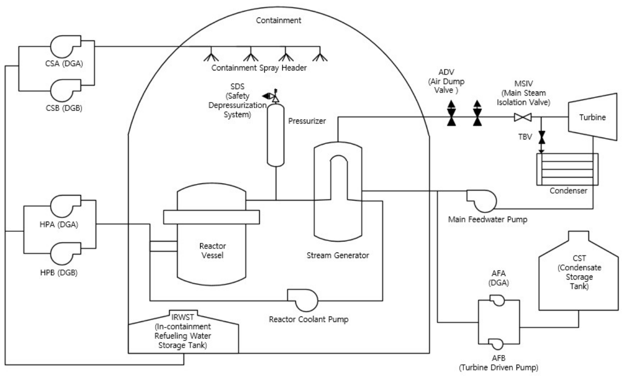


Fig. 2. Virtual nuclear power plant for VAI

To create sabotage fault trees, virtual nuclear power plants were established as depicted in Fig. 2, and the detailed device configuration of each system is presented in Table 1.

Table I. Device compositions for each system trains by virtual nuclear power plant system

System trains	Device compositions
CSA	CSA-HW+DGA
CSB	CSB-HW+DGB
HPA	HPA-HW+DGA
HPB	HPB-HW+DGB
AFA	AFA-HW+DGA
AFB	AFB-HW
CSA-HW	CSA-MOV1+CSA-CV1+CSA-PUMP+CSA-CV2+CSA-MOV2
CSB-HW	CSB-MOV1+CSB-CV1+CSB-PUMP+CSB-CV2+CSB-MOV2
HPA-HW	HPA-MOV1+HPA-CV1+HPA-PUMP+HPA-CV2+HPA-MOV2
HPB-HW	HPB-MOV1+HPB-CV1+HPB-PUMP+HPB-CV2+HPB-MOV2
AFA-HW	AFA-MOV1+AFA-CV1+AFA-PUMP+AFA-CV2+AFA-MOV2
AFB-HW	AFB-MOV1+AFB-CV1+AFB-PUMP+AFB-CV2
Etc.	RWST, CST

Secondly, a Loss of Off-site Power (LOOP) was selected from the initial events that could occur during the operation of a nuclear power plant. Thirdly, basic rules and assumptions were applied to preserve the nature of identifying vital areas. Fourthly, the sabotage rules were applied. Fifthly, a sabotage fault tree was created by mapping the compartment and the basic event. The generated sabotage fault trees are illustrated in Figure 3.

Sixthly, the Fault Tree Reliability Expert (FTREX) was used to calculate the target set and prevention set for the sabotage fault tree in Figure 3. As a result of the calculation, 17 target sets and 6 prevention sets were identified (see Table II and III).

Table II. A list of the prevention sets for sabotage fault tree

No.	Room 1	Room 2	Room 3	Room 4	Room 5
1	R-CST	R-AFB-HW			
2	R-CST	R-DGA	R-AFA-HW		
3	R-CONT	R-DGA	R-HPA-HW	R-CSA-HW	
4	R-CONT	R-DGB	R-HPB-HW	R-CSB-HW	
5	R-CONT	R-DGA	R-DGB	R-HPA-HW	R-CSB-HW
6	R-CONT	R-DGA	R-DGB	R-HPB-HW	R-CSA-HW

Table III. A list of the target sets for the sabotage fault tree

No.	Room 1	Room 2	Room 3	Room 4
1	R-CST	R-CONT		
2	R-CST	R-DGB	R-HPA-HW	
3	R-CST	R-DGA	R-DGB	
4	R-CST	R-DGB	R-CSA-HW	
5	R-CST	R-HPA-HW	R-HPB-HW	
6	R-CST	R-DGA	R-HPB-HW	
7	R-AFB-HW	R-DGA	R-HPB-HW	
8	R-AFB-HW	R-DGA	R-DGB	
9	R-AFB-HW	R-CSB-HW	R-DGA	
10	R-CSB-HW	R-CST	R-DGA	
11	R-AFA-HW	R-AFB-HW	R-CONT	
12	R-AFB-HW	R-CONT	R-DGA	
13	R-CSA-HW	R-CSB-HW	R-CST	
14	R-AFA-HW	R-AFB-HW	R-HPA-HW	R-HPB-HW
15	R-AFA-HW	R-AFB-HW	R-CSA-HW	R-DGB
16	R-AFA-HW	R-AFB-HW	R-DGB	R-HPA-HW
17	R-AFA-HW	R-AFB-HW	R-CSA-HW	R-CSB-HW

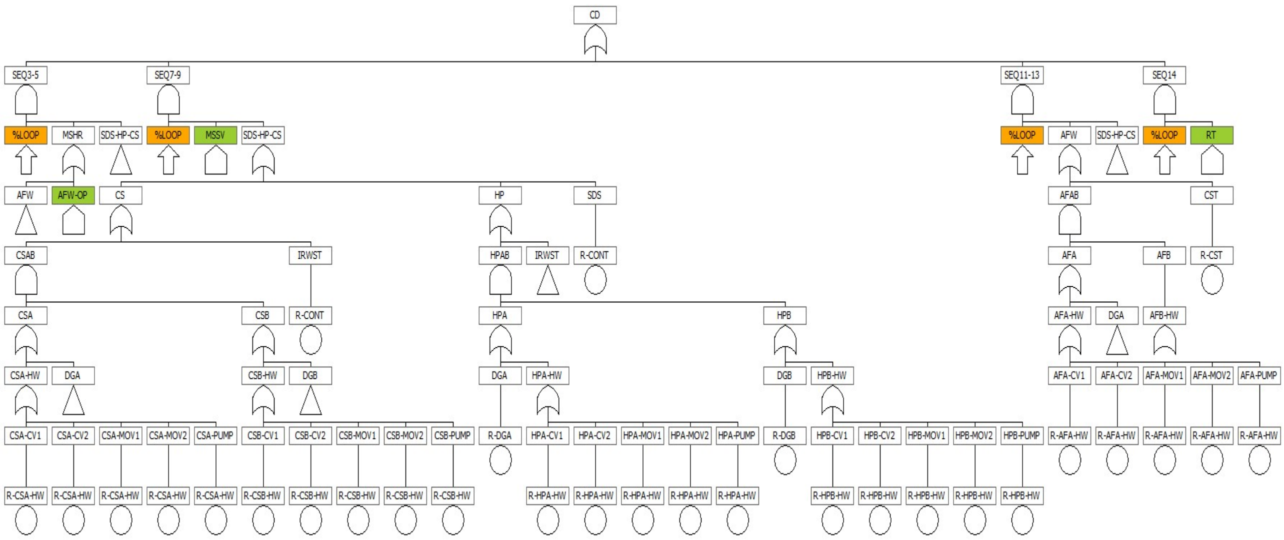


Fig. 3. Sabotage fault tree for LOOP

Seventhly, one of the seven prevention sets is chosen as the final vital area. In Table II, set 1 and set 2 have the shortest length and include the R-CST, which is entirely exposed to the outside. Facilities that are exposed to the outside are highly susceptible to attacks and cannot be chosen as vital areas. Therefore, set 3 is selected as the vital area, as depicted in Figure 4.

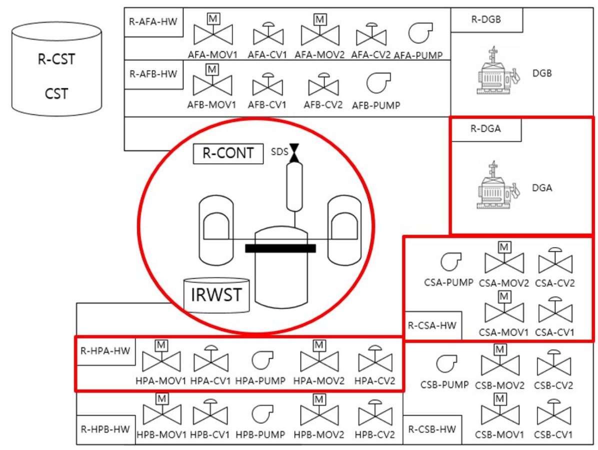


Fig. 4. Final vital area before reinforcement

If the CST, which is exposed to the outside, is reinforced with concrete structures, the vital area may change to set 1, as depicted in Figure 5. Examples of physical protection designs that reinforce the CST with concrete structures are discussed in Section 3.

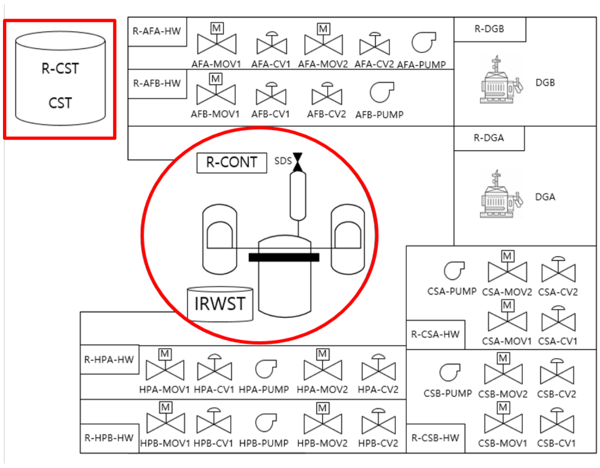


Fig. 5. Final vital area after reinforcement

Table IV presents the maximum weight of explosives that can reasonably enter a container or vehicle [2]. The explosive weight was set at 227kg and 454kg, equivalent to compact sedans and sedans, respectively, as sufficient sedan-type vehicles were permitted to enter the nuclear power plant.

Table IV. The maximum amount of explosives mass

High Explosives (TNT Equivalent)	Threat Description	Explosives Mass
	Pipe Bomb	2.3 kg
	Suicide Belt	4.5 kg
	Suicide Vest	9 kg
	Briefcase/Suitcase Bomb	23 kg
	Compact Sedan	227 kg
	Sedan	454 kg
	Passenger/Cargo van	1,814 kg
	Small Moving Van/Delivery Truck	4,536 kg
	Moving Van/Water Truck	13,608 kg
	Semi-trailer	27,216 kg

Table 5 displays the specifications of the concrete structures. The thickness was set at 18 inches (about 450 mm), which is sufficient to withstand missile collisions and tornadoes [3, 4, 5]. The height and thickness were determined based on the size of the CST, as depicted in Figure 6. The concrete damage plasticity model properties specified in the ABAQUS manual were used for the concrete facility [7].

Table V. Concrete structure dimensions and properties

Variable	Value
Height	11950 mm
Diameter	15500 mm
Thickness	600 mm, 450 mm, 300 mm
Density	2400 kg/m^3
Young's modulus	26.79 GPa
Poisson's ratio	0.167

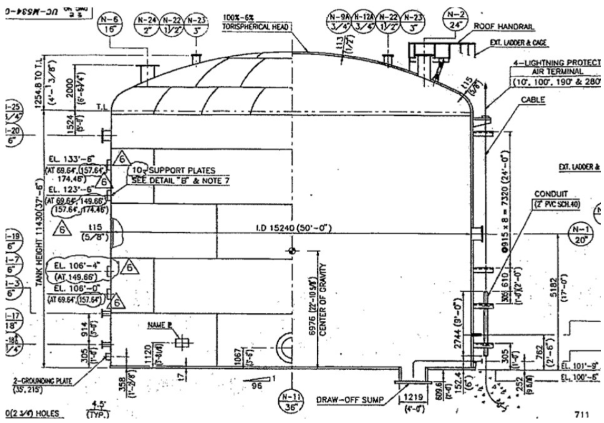
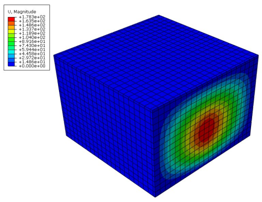
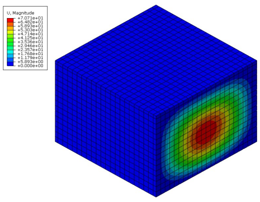
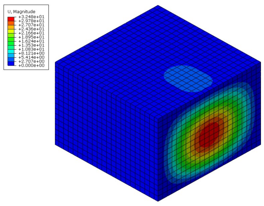
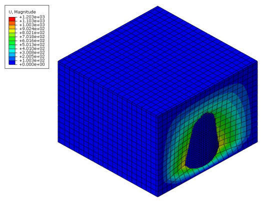
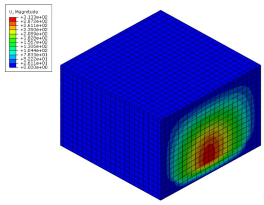
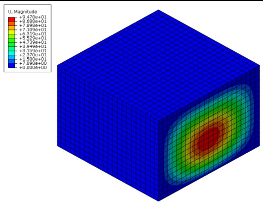


Fig. 6. Elevation view of the CST (KEPCO) [6]

The ABAQUS program was employed to perform explosion analysis with the floor surface of the concrete structure fixed. The explosive was set to detonate at a point 5 m away from the wall of the concrete structure. The simulation results are presented in Table VI.

Table VI. Simulation results

TNT Weight	Maximum center displacement	Thickness
227 kg	177.98 mm	 300 mm
227 kg	70.65 mm	 450 mm
227 kg	31.67 mm	 600mm
454 kg	1134.8 mm(+α)	 300 mm
454 kg	306.30 mm	 450 mm
454 kg	93.9 mm	 600 mm

The maximum displacement increases with the TNT weight, and thicker wall thickness leads to greater maximum displacement. Therefore, designing the concrete structure with the thickest possible wall thickness can help reduce the impact of the explosion.

As shown in Table 7, CST is placed in yards for most types of nuclear power plants. Reinforcing CST through concrete facilities can reduce the impact of explosions as much as possible and efficiently select vital areas.

Table VII. Auxiliary feedwater system and installation location by plant type [8]

No	Plant type	Units	Auxiliary feedwater system	Installation location
1	APR1400	SKN34	AFWST	In Aux. Building
2	APR1400	SHU12	AFWST	In Aux. Building
3	OPR+	SKN12	AFWST	In Aux. Building
4	OPR+	SWN12	AFWST	In Aux. Building
5	OPR	HBN34	CST	On Yard
6	OPR	HUN34	CST	On Yard
7	OPR	HBN56	CST	On Yard
8	OPR	HUN56	CST	On Yard
9	FR	HUN12	AFWST	On Yard
10	W900	KRN34	CST	On Yard
11	W900	HBN12	CST	On Yard
12	W600	KRN2	CST	On Yard

In general, a method of protecting a building from explosion is to limit the deflection or deformation of a member. The deformation limit is defined in various ways. In this paper, we introduce two methods of assessment of component damage.

The first is to determine the approximate damage level through the explosion pressure and impulse charts. The PDC-TR 06-08 Technical Report [9], prepared by U.S. Army Corps of Engineers, provides a diagram that shows the approximate extent of damage by pressure and impulse. The diagram is shown in Figure 7.

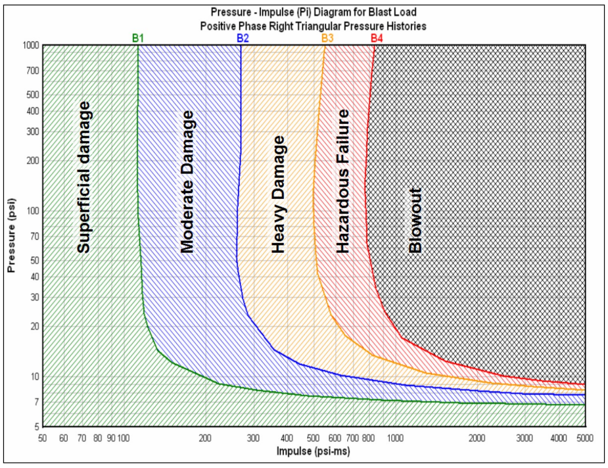


Fig. 7. Pressure – Impulse (P-I) diagram showing component damage levels [9]

The second is a method of determining the level of damage using the values of the ductility ratio and the rotation angle. In PDC-TR 06-08, the maximum displacement range corresponding to each section corresponding to the damage level is presented with the values of μ (ductility ratio) and θ (rotation angle) based on the response limit of the component. For example, the response limits for the boundaries of component damage levels for reinforced concrete members are shown in Figure 8.

Member		B1		B2		B3		B4	
		μ	θ	μ	θ	μ	θ	μ	θ
Flexure	No shear reinforcing/ without tension membrane	1	-	-	2°	-	5°	-	10°
	With compression face steel reinforcement and shear reinforcing/without tension membrane [2]	1	-	-	4°	-	6°	-	10°
	With tension membrane (L/h>=5) [3, 4]	1	-	-	6°	-	12°	-	20°
Combined Flexure & Compression [5]	No shear reinforcing/ without tension membrane	1	-	-	2°	-	2°	-	2°
	With compression face steel reinforcement and shear reinforcing/without tension membrane [2]	1	-	-	4°	-	4°	-	4°
Compression [5, 6]	Walls & Seismic Columns	0.9	-	1	-	2	-	3	-
	Non-Seismic Columns	0.7	-	0.8	-	0.9	-	1	-
Tension or Combined Flexure & Tension		No response limits in this report, see SBEDS Methodology Manual							

Fig. 8. Response limits for reinforced concrete

4. Conclusions

Through the selection of existing vital areas reflecting basic threats and safety and the design of physical protection, the differences between the previously selected vital areas were compared and changes in the selection of vital areas were presented.

Explosion analysis was conducted to reflect vehicle threats and physical protection was designed. The exact physical properties of concrete were not known, and the experiment was difficult to proceed, so the evaluation was conducted roughly using the basic physical properties. As a result of the evaluation, reinforcing CST with thick concrete structures can be less affected by explosion, resulting in less damage, and reducing damage to the structure to explosion pressure.

The purpose of this paper is to develop a procedure for selecting vital areas more efficiently by integrating all vital area procedures, reinforcement procedures, and simulation procedures rather than numerical accuracy of explosive data.

Acknowledgments

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