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Determination of Design Extension Conditions List and Design Optimization of Safety Systems for ADS by Lines of Defenses Method

ZHAO XU[1,2], LIZHI WANG[1,2], AND MING JIN[1]
[1]Key Laboratory of Neutronics and Radiation Safety, Institute of Nuclear Energy Safety Technology, Chinese Academy of Sciences, Hefei 230031, China
[2]University of Science and Technology of China, Hefei 230027, China

Corresponding author: Ming Jin (ming.jin@fds.org.cn)

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ABSTRACT During the conceptual design phase of an accelerator-driven sub-critical system (ADS), the reliability requirements of safety systems need to be determined for future practical construction to balance the economy performance with the safety performance. In this paper, the design optimization of the safety-related systems reliability for the ADS based on China LEAd-based Research Reactor was performed by applying the lines of defense (LODs) method to this ADS. First, a tentative LOD type, such as a strong line (a LOD) or a medium line (b LOD), was assigned to the main safety related systems. These systems include the accelerator trip system, decay heat removal system, reactor vessel, secondary cooling system isolation, decompression system, emergency diesel engine, and containment systems. Second, the failure of the LODs were combined with initiating events that were identified early, and a preliminary list of design extension conditions (DECs) was obtained. Third, the suitability of the conditions for classification into the design basic condition (DBC) or the DEC and their unacceptable consequences for the DBC or criteria limitation were discussed. Last, the LOD types of safety systems were re-assigned considering the results to optimize the design. The complementary events in the list of DECs are obtained. This paper can provide important references for the construction and operation of future ADSs.

INDEX TERMS Accelerator-driven sub-critical system (ADS), lines of defense (LOD), design extension condition (DEC).

I. INTRODUCTION

An Accelerator-Driven Sub-critical System (ADS) is widely considered as a promising device for the transmutation of nuclear waste [1].

An ADS has the following advantages: an ADS can be utilized for generating power from thorium-based fuels due to its powerful transmutation capability. ADSs are operated in sub-critical mode, which enhances their inherent safety; therefore, a super-critical accident will not occur within adequate margins. The safety of ADSs is significant because an entire ADS is shut down once the accelerator system is turned off [2]–[4].

An accelerator-driven system consists of a high-power proton accelerator, a heavy-metal spallation target and a sub-critical core [2].

A lead-based reactor has favorable neutronics, thermal hydraulic properties, and safety features. Lead-based materials are extremely suitable for spallation target material due to their excellent thermo-physical properties. Thus, a lead-based reactor is considered to be the most promising reactor option for the ADS [5]–[7].

In the design stage of an ADS, the definition and classification of situations is an essential part of the safety analysis and license application.

For traditional categorization of plant states, normal operation (NO), anticipated operational occurrences (AOOs), design basis accidents (DBAs) and beyond design basis accidents (BDBAs) are classified according to the frequency of occurrence and the severity of events. Only the events of NO, AOO and DBA, which are related to the safety requirements and safety objectives, are considered in the plant design [8].

However, some limitations exist for making a systematic list that is better for the traditional categorization of plant states, which considers events that would probably induce core melting.

After the Fukushima Dai-ichi nuclear accident, design extension conditions (DECs) have been introduced in the requirements for the safe design of nuclear power plants. Some events in a BDBA are considered in a DEC; thus, a plant's capability of withstanding accidents that are more severe than design basis accidents is improved [8].

To define some selected sequences due to multiple failures, the term "DEC" was officially introduced in the European Utility Requirements (EUR) [9].

The DECs are defined by the EUR as follows [8], [9]:

A specific set of accident sequences that surpass the Design Basis Conditions (DBC) are selected on a deterministic and probabilistic basis, including complex sequences and severe accidents. Both complex sequences and severe accidents are attributed to multiple failures of safety systems. Complex sequences can cause some core damage without core melt. Severe accidents refer to sequences that cause core melt.

The initiating faults that are considered in the design of the Lead/Lead bismuth eutectic-cooled Fast Reactor (LFR) are split into the Design Basis Conditions (DBC) DEC according to the EUR and the LFR safety approach [10], [11]. The DBCs are similar to events in NO, AOO and DBA for the IAEA approach. The postulated initiating events frequency and categorization for the DBCs of the EUR, are listed in Table 1.

TABLE 1. Categorization of the DBCs of EUR.

Category	Definition	Frequency of initiating event(per year)
I	Normal operation (DBC1)	
II	Incidents (DBC2)	$f>10^{-2}$
III	Accidents (low frequency) (DBC3)	$10^{-2}>f>10^{-4}$
IV	Accidents (very low frequency) (DBC4)	$10^{-4}>f>10^{-6}$

The International Atomic Energy Agency (IAEA) defined DECs as follows [12]:

Accident conditions that are not considered for design basis accidents but that are considered in the design process of the facility in accordance with a best estimate methodology, for which releases of radioactive material are kept within acceptable limits. In addition, DECs include DECs without core damage and severe accidents in the current IAEA approach.

For IAEA safety requirements, a set of DECs should be derived on the basis of engineering judgment, deterministic assessments and probabilistic assessments to improve the safety of a nuclear power plant [8], [12].

At the beginning, the Western European Nuclear Regulation (WENRA) [13] adopted a concept similar to the DEC from the EUR, although the terminology of the DEC is not explicitly employed. The WENRA proposes to distinguish between the sequences with core melt from sequences without core melt when considering multiple failures sequences selected in the design [8].

However, the definition of DECs in a latter WENRA guidance file is the same as the definition of DECs by the IAEA [14].

Currently, the term DEC is extensively employed after the publication of SSR-2/1, and even the Member States that do not explicitly use this term in their regulations frequently refer to it. The DEC is becoming a new controversial topic for nuclear safety requirements.

A systematic or certain method for making a list of DECs, even some reference lists of DECs without core melt were given by the IAEA, EUR and WENRA.

In this paper, a preliminary list of DECs for an ADS based on the China LEAd-based Research Reactor (CLEAR-I) was obtained using the lines of defense (LOD) method. First, main safety-related systems, such as the accelerator trip system, decay heat removal system, decompression system, safety vessel, secondary cooling system isolation, emergency diesel engine and containment system, were selected as research objects. A tentative LOD type, strong line (a) or medium line (b), were assigned to these systems. Second, the initial list of DECs for an ADS was given by combining with the failure of LOD and initiating events that were identified early. Last, the LOD types were discussed by evaluating whether the conditions were suitable for classification into DECs and considering the importance of the selected systems. The LOD type was re-assigned considering the discussed results to further optimize the safety-related systems design. This study can provide important references for safety features requirements and guidance for condition classification and system design of future ADSs.

II. CONDITION CATEGORIZATION OF ADS BASED ON CLEAR-I

To develop an ADS for nuclear waste transmutation, the Chinese Academy of Sciences launched an engineering project in 2011. CLEAR, which was designed by the Institute of Nuclear Energy Safety Technology, was chosen as the reference reactor for ADS development [6]. During the first stage, a 10-MW lead–bismuth cooled research reactor named CLEAR-I coupled with a proton linac and heavy metal spallation target will be designed and constructed [7], [15].

The condition classification and initiating events of ADS based on CLEAR-I are presented in Table 2 [16].

III. LOD METHOD

To appraise the severe accidents of the fast breeder reactors, the LODs method was introduced based on the approach of the LOD [17]. Costa *et al.* [18] performed a safety evaluation by the application of the lines of defense (LODs) method for a diverter LOFA and LOCA accident of the International Thermonuclear Experimental Reactor (ITER). The results demonstrated the applicability of the LODs method for fusion

TABLE 2. Initiating events list.

Number	Initiating events	Categorization
1	Primary pump failure	II
2	Loss of normal feed of primary heat exchanger	II
3	Loss of AC power	II
4	Inadvertent opening of a second side pressurizer safety value	II
5	Target unit vacuum support system malfunction	II
6	Target coolant pump failure	II
7	Main vessel leak	III
8	Loss of power to 2 primary pumps	III
9	Second side pipe leak	III
10	Proton beam tube leak	III
11	Fuel assembly partial blockage	III
12	Primary pump shaft break	IV
13	Primary pump shaft seizure	IV
14	Second side main pipe break	IV
15	Uncontrolled increase of beam current	IV
16	Incorrect beam direction	IV
17	Beam current focus failure	IV
18	Primary loop main pipe break	IV
19	Steam generator tube rupture (SGTR)	IV
20	Target cooling loop break (inside of reactor)	IV
21	Target cooling loop break (outside of reactor)	IV
22	Main vessel pipe break of target unit	IV

TABLE 3. LOD types.

LOD type	Expected failure rate		Features
strong LOD (a)	10^{-3} to 10^{-4} per demand	✓	High-quality active systems with internal redundancy.
		✓	High-quality passive component.
		✓	Inherent behavior that allows long delays for fault rectification
medium LOD (b)	10^{-1} to 10^{-2} per demand	✓	Classical active systems without internal redundancy.
		✓	Operator actions (accident management measures)

TABLE 4. General requirements for LOD.

Category of resulting event or sequence	Category of starting event or sequence			
	II	III	IV	DEC
III	b			
IV	a	b		
DEC	2a	a+b	a	
Residual risk (RR)	2a+b	2a	a+b	b

TABLE 5. LOD method for classifying sequences.

Initiating event	Failure of LOD	Limits to be respected
II	2a	DEC
III	a+b	DEC
IV	a	DEC

plants. Costa [19] applied the LODs method to the safety classification of the ITER Reactor-Fusion Power Shutdown System (FPSS). The FPSS was classified as safety class 3, and the available ITER requirements for the FPSS has been verified. This finding revealed excellent capability of the LODs method in ITER systems.

The concept has been synthesized and unceasingly improved in the frame of the classical logical scheme of risk analysis. The latest definition of LOD is presented as follows:

Line of defense (LOD) is an effective defense. This term is used for (1) any inherent characteristic, equipment, and system that is implemented in the safety-related plant architecture, (2) any procedure that is coherently foreseen with the General Rules for Plant Operation (e.g., human actions: preventive and protective) [19].

The lines of defense are classified into two types considering their expected reliability as shown in the table 3 [20]:

Two independent medium lines are equivalent to one strong line: b + b = a.

To define certain plant conditions and confirm that they will not produce unacceptable consequences, the operating conditions are protected by a combination of LOD.

The general requirements of LOD are listed in the table 4:

For example, any condition initiated by a Category II initiating event should be protected by a strong LOD to categorize the possibility of unacceptable consequences as Category IV.

To categorize the possibility of unacceptable consequences as RR, any condition initiated by a Category III initiating event should be protected by two strong LOD [20].

Using the previously presented rules and definitions, the LOD method can be employed to provide general requirements for use of the LOD for classifying sequences, as listed in the table 5:

For example, a sequence starting from a Category II initiating event combined with the failure of two strong LOD may be assimilated to a DEC condition [20].

Therefore, the DEC list can be obtained by the method of combination with initiating events and LOD failure.

IV. PRELIMINARY LIST OF DECS FOR ADS

A. SAFETY SYSTEMS AND LOD TYPE ASSIGNMENT OF ADS

LOD can comprise a system, architecture, equipment or procedure. However, some architecture and systems failure have been considered when initiating events for DBC were defined. In this study, only some safety systems and equipment that need to be operational after failure were selected for LOD assignment as shown in the table 6 [21].

B. COMBINATION WITH INITIATING EVETS AND LOD FAILURE

In the process of defining the list of DECs for an ADS by combining with initiating events and LOD failure, a tentative LOD defense line type was assigned to the main safety-related systems at the beginning, as shown in the Table 7.

Accelerator shutdown should be maintained in accident conditions, and therefore, the ATS was assigned to a strong LOD.

Two independent DHR exist. DHR1 was assigned to a strong LOD, and the DHR2 was assigned to a medium LOD.

The ATIS can maintain the radiological materials in the confinement during the event of proton tube break and prevent the proton current from flowing into the reactor in the case of accelerator trip failure. Thus, the ATIS was assigned to a strong LOD. Two starting modes were set for the ATIS—manual mode and electric mode.

From the point of view of the reactor core pressure, the steam pressure may uninterruptedly increase due to the SGTR, and the DS helps to release the steam pressure to prevent the steam pressure from continuing to the core and avoid core pressures that exceed the design limitation. It can, therefore, be considered as a strong LOD for the DS.

The SV is very important for protecting the main vessel but is also protected by CS. Thus, the SV was assigned to a medium LOD first.

The release after the breakage of SG tubes was directed toward the oil system, which is a closed system and constitutes an additional barrier [20]. Therefore, the SCSI was considered to be a medium LOD.

The emergency power was very important for cooling the reactor core when AC power was lost after the Fukushima Dai-ichi nuclear accident. Thus, the EDES was assigned to a strong LOD.

The CS was assigned to a strong LOD considering that it is the last barrel for the confinement of radioactive products.

Thus, a preliminary list of DECs for an ADS based on CLEAR-I was obtained using the LOD method as follows:

- ✓ Primary pump failure + ATS failure + DHR1failure
- ✓ Loss of normal feed of primary heat exchanger + ATS failure + DHR1failure
- ✓ Loss of AC power + DHR1 failure + EDES failure
- ✓ Inadvertent opening of a second side pressurizer safety value + ATS failure + DHR1 failure
- ✓ Target unit vacuum support system malfunction + ATS failure + ATIS failure
- ✓ Target coolant pump failure + ATS failure + ATIS failure
- ✓ Main vessel leak + CV leak + CS failure
- ✓ Loss of power to 2 primary pumps + DHR1 failure + DHR2 failure
- ✓ Second side pipe leak + ATS failure + SCSI failure
- ✓ Proton beam tube leak + ATS failure + ATIS failure
- ✓ Fuel assembly partial blockage + ATS failure + DHR2 failure

TABLE 6. Safety related systems and functions.

Safety related system	Function
Accelerator Trip System (ATS)	This system is designed to turn off the proton beam, and any actions that shut down the proton beam will be considered effective to fulfill this function.
Decay Heat Removal System (DHRS)	This system is designed to remove the residual heat at accident conditions, including decay heat in the reactor core and sensible heat in the primary coolant system. Two independent DHRSs exist—DHR1 and DHR2—considering the redundancy and single failure criteria of a safety system.
Decompression System (DS)	The steam pressure will increase in the steam generator due to the reaction of lead/LBE and water when the steam generator tubes rupture. The DS can unload the steam pressure.
Safety Vessel (SV)	The SV can protect the main vessel from impacting in normal operations and ensure the containment of the primary coolant in case of main vessel leakage.
Accelerator Tube Isolation System (ATIS)	In the event of a break in the target window or accelerator tube, which is close to the target, the ATIS must isolate the target from the remainder of the accelerator to prevent the release of secondary radioactive spallation products from the target that enters the accelerator tube.
Secondary Cooling System Isolation (SCSI)	Four cooling loops exist on the secondary side of the ADS. When SGTR occurs in the tubes of any of the SGs, this system will isolate the corresponding loop.
Emergency Diesel Engine System (EDES)	The emergency diesel engine will be activated to supply electrical power for primary pumps, second pumps and DHRS during AC power loss.
Containment System (CS)	Containment can protect safety vessels from impacting in normal operations; it is the last barrel for the confinement of radioactive products.

TABLE 7. Combination Of LOD failures.

No.	Category	Safety systems and LOD type								
		ATS (a)	DHR1 (a)	DHR2 (b)	ATIS (a)	DS (a)	SV (b)	SCSI (b)	EDES (a)	CS (a)
1	II	×	×							
2	II	×	×							
3	II		×						×	
4	II	×	×							
5	II	×			×					
6	II	×			×					
7	III						×			×
8	III		×	×						
9	III	×						×		
10	III	×			×					
11	III	×		×						
	III		×	×						
12	IV	×								
	IV		×							
13	IV	×								
	IV		×							
14	IV	×								
	IV		×							
	IV							×		
15	IV	×								
16	IV	×								
	IV				×					
17	IV	×								
	IV				×					
18	IV	×								
	IV		×							
19	IV	×								
	IV		×							
	IV					×				
20	IV	×								
	IV				×					
21	IV	×								
	IV				×					
	IV									×
22	IV	×								
	IV				×					

- ✓ Fuel assembly partial blockage + DHR1 failure + DHR2 failure
- ✓ Primary pump shaft break + ATS failure
- ✓ Primary pump shaft break + DHR1 failure
- ✓ Primary pump shaft seizure + ATS failure
- ✓ Primary pump shaft seizure + DHR1 failure
- ✓ Second side main pipe break + ATS failure
- ✓ Second side main pipe break + DHR1 failure
- ✓ Second side main pipe break + SCSI failure
- ✓ Uncontrolled increase of beam current + ATS failure
- ✓ Incorrect beam direction + ATS failure
- ✓ Incorrect beam direction + ATS failure
- ✓ Beam current focus failure + ATS failure
- ✓ Beam current focus failure+ ATS failure
- ✓ Primary loop main pipe break + ATS failure
- ✓ Primary loop main pipe break + DHR1 failure
- ✓ Main heat exchanger tube rupture + ATS failure
- ✓ Main heat exchanger tube rupture + DHR1 failure
- ✓ Main heat exchanger tube rupture + DS failure
- ✓ Target cooling loop break(inside of reactor) + ATS failure
- ✓ Target cooling loop break(inside of reactor) + ATIS failure
- ✓ Target cooling loop break(outside of reactor) + ATS failure
- ✓ Target cooling loop break(outside of reactor) + ATIS failure
- ✓ Target cooling loop break(outside of reactor) + CS failure
- ✓ Main vessel pipe break of target unit+ ATS failure
- ✓ Main vessel pipe break of target unit+ ATIS failure

The preliminary list of DECs contained 36 initiating events. The following events may cause a large radiological release:

- ✓ Main vessel leak + SV leak + CS failure
- ✓ Target cooling loop break(outside of reactor) + CS failure

In addition, the following events had the potential of causing core melt:

- ✓ Loss of power to 2 primary pumps + DHR1 failure + DHR2 failure
- ✓ Fuel assembly partial blockage + ATS failure + DHR2 failure
- ✓ Fuel assembly partial blockage + DHR1 failure + DHR2 failure
- ✓ Uncontrolled increase of beam current + ATS failure

V. DESIGN OPTIMIZATION FOR RELIABILITY OF SAFETY RELATED SYSTEMS OF ADS

In this section, the LOD types of DHR, the SV and the CS were analyzed and re-assigned to optimize the design.

The DHRS is a crucial system for core cooling; thus, DHR2 was also assigned to a strong LOD. If DHR1 and DHR2 were assigned to a strong LOD, the following events would be complementary in the list of DECs. The occurrence probability of the following events would be reduced which is better for safety acceptance because these events were divided between category IV and DEC.

- ✓ Primary pump failure+ ATS failure + DHR2 failure
- ✓ Loss of normal feed of primary heat exchanger + ATS failure + DHR2 failure
- ✓ Inadvertent opening of a second side pressurizer safety value + ATS failure + DHR2 failure

- ✓ Primary pump shaft break + DHR2 failure
- ✓ Primary pump shaft seizure + DHR2 failure
- ✓ Second side main pipe break + DHR2 failure
- ✓ Primary loop main pipe break + DHR2 failure
- ✓ Main heat exchanger tube rupture + DHR2 failure

The following events would be removed from the preliminary list of DECs and would be divided into RR or divided between DEC and RR:

- ✓ Loss of power to 2 primary pumps + DHR1 failure + DHR2 failure
- ✓ Fuel assembly partial blockage + ATS failure + DHR2 failure
- ✓ Fuel assembly partial blockage + DHR1 failure + DHR2 failure

The occurrence probability of these events would be reduced. The occurrence probability of core melt would be reduced.

The sequences of these 3 situations were simulated, and the dose value after 24 hours of the accident was compared with the dose limitation of DEC and RR. DHR1 would be assigned to a strong LOD, and DHR2 would be assigned to a medium LOD if all simulation dose values of these 3 situations did not exceed the dose limitation of DEC. If the simulation dose values of one of these 3 situations exceeded the dose limitation of DEC, DHR1 would be assigned to a strong LOD, and DHR2 would be assigned to a strong or a medium LOD. However, DHR2 was assigned to a medium LOD considering the aspect of cost. Both DHR1 and DHR2 would be assigned to a strong LOD if the simulation dose values of 2 of these 3 situations exceeded the dose limitation of the DEC.

The SV can maintain the primary coolant inventory in the event of a main vessel leak; thus, the LOD type of the SV could be optimized to a strong line. If both of the SV and the CS were assigned to a strong line, the occurrence probability of a main vessel leak + SV leak + containment leak would be very low. The probability of radiological release would be very low, and the corresponding conditions would be divided into RR. However, the cost was also very high. The isolation function may depend on the operator action although the SC was the last barrel for the confinement of radioactive products by referring to the eXperimental Accelerator Driven System (XADS) design [20]. Therefore, the CS is assigned to a medium LOD. In this case, the main vessel leak + SV leak + containment leak is also assimilated to the DEC. The reliability of the SV was enhanced and the possibility for radiological release was prevented from the part closer to the accident sequence source. Thus, the SV was assigned to a strong LOD, and the CS was assigned to a medium LOD.

VI. CONCLUSION

A list of DECs for an ADS was compiled based on CLEAR-I by combining initiating events with LOD failure. A preliminary list of DECs for an ADS was obtained by assigning a tentative LOD type to selected safety-related systems. After analyzing the importance and function of the selected safety systems, the LOD type was re-assigned to optimize the safety-related systems design of ADS, and the preliminary list of DECs was revised. The following conclusions were obtained from the results:

(1) For DHRS, DHR1 is assigned to a strong LOD and DHR2 is assigned to a strong or medium LOD depending on the comparison results between the sequences calculation dose value and the dose limitation of the DEC.
(2) The ATS was assigned to a strong LOD, which should ensure the independence and diversity of the ATS.
(3) The ATIS was assigned to a strong LOD, and both manual mode and electric mode were set for the start of operation.
(4) The DS was assigned to a medium LOD.
(5) The SV was assigned to a strong LOD, and the CS was assigned to a medium LOD.
(6) The SCSI was considered to be a medium LOD.
(7) The EDES was assigned to a strong LOD.

The list of DECs should be defined based on a combination of engineering judgments, deterministic assessments, probabilistic assessments and reactor properties. Thus, the filter and complement of the preliminary DECs of the ADS obtained in this paper would be performed in the future.

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ZHAO XU was born in Hefei, China, in 1989. She received the B.S. degree in biology technology from Anhui Normal University, Wuhu, China, in 2011. She is currently pursuing the Ph.D. degree in nuclear science and engineering with the University of Science and Technology of China, Hefei, China.

Her research interests include biological effects of radiation, nuclear power plant state categorization, nuclear reactor safety, and accelerator driven sub-critical system safety analysis.

LIZHI WANG is currently pursuing the Ph.D. degree with the Science Island Branch of Graduate School, University of Science and Technology of China, and also with the Institute of Nuclear Energy Safety Technology, Chinese Academy of Sciences, Hefei, China. His research interests include nuclear power plant safety analysis and nuclear reactor thermal hydraulic analysis.

MING JIN is currently an Associate Researcher with the Institute of Nuclear Energy Safety Technology, Chinese Academy of Sciences, Hefei, China. His research interests include accelerator driven sub-critical system accident analysis, nuclear power plant safety analysis, numerical simulation, nuclear reactor thermal hydraulic analysis, and nuclear power plant design.

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