An Accident-tolerant Control Drum System for a Small Space Reactor

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1. Introduction

A power supply system of a spacecraft plays a key role in deep space exploration and the only practically applicable option for the power supply of a spacecraft exploring beyond Jupiter or out of the solar system is nuclear energy [1]. Since SNAP-10A launched in 1965, many small fission reactors for power supply of a spacecraft have been developed. Recently, a small fission reactor with a fast spectrum, KRUSTY, has been developed by the United States (US) National Aeronautics and Space Administration (NASA) and Los Alamos National Laboratory (LANL) for deep space mission, where highly enriched uranium (HEU) is used as fuel [2]. A small thermal reactor with low enriched uranium (LEU) fuel is being studied at Korea Atomic Energy Research Institute (KAERI) as a possible electric power supplier for deep space probe [1]. A control rod (CR) system was adopted as the reactivity control system of the reactors in the study and the reactors in the study were designed so that they remain subcritical when they were immersed in water, wet sand or dry sand regardless of whether they had no or minor damage (as launched or coolant pipes broken) or they had major damage (reflector and some of control rods are missing). However, it is inevitable for the reactors with a control rod system to become supercritical in the worst-case accident scenarios in which the control rods are missing without any damage in the reflector [1].

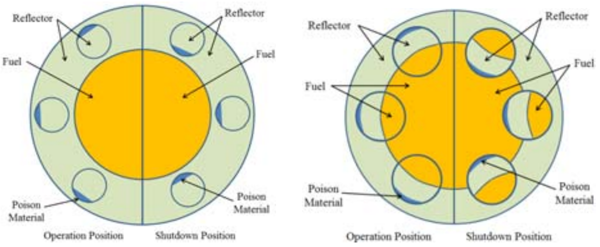
Besides the control rod system which has been widely used for nuclear reactors since Chicago Pile-1, many concepts of reactivity control system for space reactor such as the control drum (CD) system [3], the sliding reflector or the control shutter concept [4], and the hinged reflector or the petals reflector concept adopted in SP-100 space reactor [5] have been proposed and studied widely [6,7,8,9,10]. As mentioned above, the loss of control rods during launch accidents inevitably results in an increase of core reactivity and so does the loss of control drums. In case of a reactor with a sliding reflector or hinged reflector system, on the contrary, the loss of the reactivity control system (the reflector itself) results in a decrease of core reactivity. However, the reflector can accidently move to its operation position when there is an external impact on the reactor. For example, a crash on the ground can move the sliding or hinged reflector to its operation position due to the inertia of the reflector or the core. With any of the reactivity control system mentioned above, the event in which the reactor becomes supercritical is still likely to happen though the absolute value of the probability is quite small.

In this paper, an accident-tolerant control drum (ATCD) system is proposed as the reactivity control system of a space reactor to resolve the criticality problems during the launch accidents. The neutronic performance of the accident-tolerant control drum system was investigated when it was adopted in a LEU-fueled and a HEU-fueled small space reactor. All calculations were performed using a Monte-Carlo code, McCARD [11] with continuous energy ENDF/B-VII.0 cross-section libraries.

2. The Accident-tolerant Control Drum System

2.1 Concept of the Accident-tolerant Control Drum System

Figure 1 compares the concept of conventional control drum system and the accident-tolerant control drum system proposed in this study. In the conventional control drum system, the control drums each of which is consist of poison or absorber part and reflector part are placed in the reflector region. The poison part of the control drums is faced to the core when the reactor is shutdown while the reflector part of the drums is faced to the core when the reactor is in operation. In the accident-tolerant control drum system, on the other hand, the control drums contain not only the poison and reflector parts but also fuel part which comprises the reactor core when the drums are in operation position. The poison part is inserted deep into the core and the fuel part is moved to a position far from the core when the drums are in shutdown position, which results in a large drum worth.



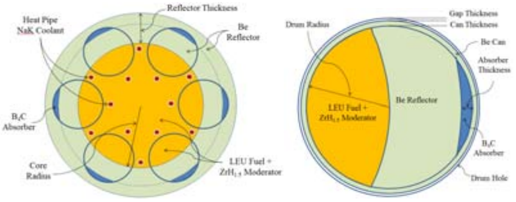
(a) Conventional Control Drum (b) Accident-tolerant Control Drum

Figure 1. Comparison of a Conventional and an Accident-tolerant Control Drum System

In case of a reactor with the conventional control drum system, the reactivity will increase when the reactor is immersed in water or wet sand with the control drums missing and the reflector attached as it was in case of a reactor with a control rod system [1]. In case of a reactor with the accident-tolerant control drum system described above, on the contrary, a small reactivity increase or even a reactivity decrease can be achieved in the same situation because the loss of control drum results in a loss of fuel as well as the absorber.

2.2 Performance of the Accident-tolerant Control Drum System in a LEU-fueled Space Reactor

Figure 2 illustrates the geometry of a small LEU-fueled space reactor with an accident-tolerant control drum system and Table I lists the design parameters for two cases. The first case, case A, has a homogeneous core configuration while the second case, case B, has a heterogeneous core configuration in which 20 fuel plates and 21 moderator plates are stacked one after the other as in the LEU-fueled space reactors with a control rod system presented in our previous work [1]. The same value of the moderator to fuel volume ratio (f_m=15.45) was used for both cases. The reactors with an accident-tolerant control drum system have smaller total reactor mass (168.5 kg and 159.3 kg, respectively) than that of the reactors with a control rod system in our previous work (240.8 kg, and 187.1 kg, respectively) [1]. The mass reduction is attributed to the fact that there is no control rod hole in the core which increases critical core radius and in turn increases the reactor mass.



(a) Reactor Top View (b) Control Drum Top View

Figure 2. Geometry of a LEU-fueled Small Space Reactor with an Accident-tolerant Control Drum System

Table II shows the neutronic performance of the reactors during their life time. The standard deviation of the effective multiplication factors are about 10pcm. We can find that the reactors have similar neutronic performance to that of the reactors with a control rod system in our previous work except for the cold zero power (CZP) shutdown state [1]. The control drum worth is about 33000 pcm and 44000 pcm for the homogeneous core case, case A, and heterogeneous core case, case B, respectively, while control rod worth was about 16000 pcm for both cases with a control rod system in our previous work [1]. The relatively large total drum worth was achieved not only because a large amount of absorber was inserted deep into the core but also because some fuel was moved to a position far from the core.

Table III lists the criticality of the reactors with an accident-tolerant control drum system for various accident scenarios. The standard deviations of the effective multiplication factors were around 10 pcm but they were omitted from Table III. The reactors with an accident-tolerant control drum system remain subcritical not only when there is no or a minor damage to the reactor but also when some or all the control drums are missing while the reactors with a control rod system became supercritical when some control rods are mission without any damage in the reflector as shown in our previous work. Figure 3 shows the missing control drum positions for the scenarios listed in Table III. It was assumed that all the control drums are missing when the reflector is missing. It is clear, from table III, that the reliability of the accident-tolerant control drum system proposed in this study is much higher than that of the control rod system or conventional control drum system during the launch accidents.

Table I. Design Parameters of the LEU-fueled Space Reactor with an ATCD System

Parameters	Case A	Case B
Thermal Power (kW)	5.0	5.0
Life Time (year)	15.0	15.0
Operation Temperature (K)	1100	1100
Fuel Material	LEU	LEU
Moderator Material	$ZrH_{1.5}$	$ZrH_{1.5}$
Moderator to Fuel Ratio, f_m	15.45	15.45
Reflector Material	Be	Be
Active Height/Diameter Ratio	1.00	1.00
Number of Control Drums	6	6
Control Drum Gap Thickness (cm)	0.05	0.05
Control Drum Can thickness (cm)	0.10	0.10
Control Drum Radius (cm)	6.00	6.00
Control Drum Absorber Thick. (cm)	0.55	0.55
Control Drum Absorber Material	B_4C	B_4C
^{10}B Enrichment in B_4C (wt% $^{10}B/B$)	18.43	18.43
Control Drum Can Material	Be	Be
Number of Heat Pipes	12	12
Heat Pipe Inner Radius (cm)	0.4	0.4
Heat Pipe Thickness (cm)	0.1	0.1
Heat Pipe Material	Zr	Zr
Coolant Material	NaK	NaK
Inner Heat Pipe Position (cm)	5.73	5.75
Outer Heat Pipe Position (cm)	10.38	8.90
Reflector Thickness (cm)	7.30	7.00
Core Radius (cm)	13.38	12.9
Core Heterogeneity	Homo.	Hetero.
Number of Fuel Plates	-	20
Fuel Mass (kg)	16.73	14.94
Moderator Mass (kg)	75.77	67.68
Reflector Mass (kg)	73.07	64.82
Reactor Total Mass (kg)	168.5	150.3

Table II. Neutronic Performance of the LEU-fueled Space Reactor with an ATCD System

Reactor State	Drum Position	k_{eff}	
		Case A	Case B
BOL, CZP	Shutdown	0.80130	0.72896
BOL, CZP	Operation	1.08529	1.06868
BOL, HFP a)	Operation	1.03154	1.03435
BOL, HFP b)	Operation	1.01685	1.01843
EOL, HFP b)	Operation	1.00827	1.00876

a) No thermal expansion was considered.

b) A thermal expansion of 1% was considered.

Table III. Accident Scenario Analysis of the LEU-fueled Space Reactor with an ATCD System

Accident Scenario		k_{eff}	
		Case A	Case B
In Water	As Launched	0.92451	0.85869
	Coolant Pipe Broken	0.93552	0.86844
	One Control Drum Missing	0.93001	0.86002
	Two Control Drums Missing (1)	0.92679	0.85606
	Two Control Drums Missing (2)	0.92470	0.85169
	Two Control Drums Missing (3)	0.92412	0.85079
	Three Control Drums Missing (1)	0.92347	0.85188
	Three Control Drums Missing (2)	0.92116	0.84706
	Three Control Drums Missing (3)	0.91954	0.84331
	Four Control Drums Missing (1)	0.92017	0.84730
	Four Control Drums Missing (2)	0.91822	0.84337
	Four Control Drums Missing (3)	0.91799	0.84311
	Five Control Drums Missing	0.91753	0.84371
	All Control Drums Missing	0.91685	0.84471
	Reflector Missing	0.88630	0.82014
In Wet Sand	As Launched	0.93244	0.86621
	Coolant Pipe Broken	0.93788	0.87126
	One Control Drum Missing	0.93449	0.86533
	Two Control Drums Missing (1)	0.93149	0.86091
	Two Control Drums Missing (2)	0.93117	0.85895
	Two Control Drums Missing (3)	0.93085	0.85826
	Three Control Drums Missing (1)	0.92835	0.85626
	Three Control Drums Missing (2)	0.92797	0.85409
	Three Control Drums Missing (3)	0.92814	0.85224
	Four Control Drums Missing (1)	0.92521	0.85144
	Four Control Drums Missing (2)	0.92515	0.84938
	Four Control Drums Missing (3)	0.92480	0.84897
	Five Control Drums Missing	0.92221	0.84635
	All Control Drums Missing	0.91965	0.84385
	Reflector Missing	0.87187	0.80291
In Dry Sand	As Launched	0.90667	0.83725
	Coolant Pipe Broken	0.90847	0.83938
	One Control Drum Missing	0.89381	0.82390
	Two Control Drums Missing (1)	0.87978	0.80925
	Two Control Drums Missing (2)	0.87675	0.80570
	Two Control Drums Missing (3)	0.87631	0.80483
	Three Control Drums Missing (1)	0.86396	0.79259
	Three Control Drums Missing (2)	0.85991	0.78746
	Three Control Drums Missing (3)	0.85692	0.78395
	Four Control Drums Missing (1)	0.84457	0.77195
	Four Control Drums Missing (2)	0.84071	0.76694
	Four Control Drums Missing (3)	0.83967	0.76597
	Five Control Drums Missing	0.82208	0.74752
	All Control Drums Missing	0.80076	0.72527
	Reflector Missing	0.72647	0.66123

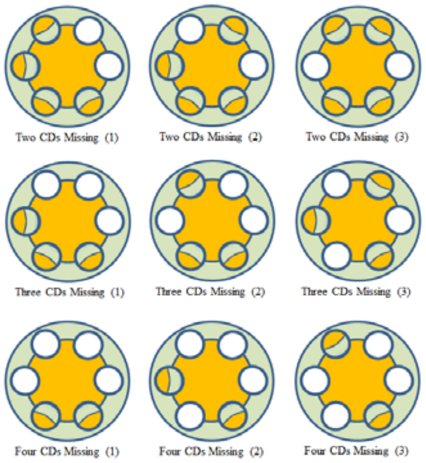


Figure 3. The Positions of the Missing Control Drums

Nevertheless, the reactor can be supercritical when the control drums are accidently rotated to the operation position even though the probability of the drum rotation is much smaller than that of losing drum during launch accidents such as rocket explosion of crash on the ground or the ocean. Table IV shows the criticality of the reactors with one or two adjacent control drums rotated to the operation position. The effective multiplication factors of the reactor in the homogeneous core case, case A, are less than 0.98 even when one control drum is accidently rotated to the operation position regardless of whether the other drums are present or missing. The reactor in the heterogeneous core case, case B, has much higher reliability than the reactor in case A. It remains subcritical (k_{eff}<0.98) even when two adjacent control drums are rotated to the operation position.

Table IV. Criticality Analysis with Some Drums Rotated to Operation Position

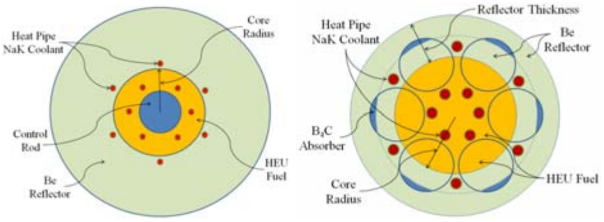
Accident Scenarios			k_{eff}	
			Case A	Case B
In Water	One CD Rotated	No CD Missing	0.97729	0.91899
		The Other CDs Missing	0.96550	0.90710
	Two Adjacent CDs Rotated	No CD Missing	1.02272	0.97716
		The Other CDs Missing	1.01664	0.97185
In Wet Sand	One CD Rotated	No CD Missing	0.97821	0.92059
		The Other CDs Missing	0.97272	0.91261
	Two Adjacent CDs Rotated	No CD Missing	1.02213	0.97677
		The Other CDs Missing	1.02314	0.97727
In Dry Sand	One CD Rotated	No CD Missing	0.95673	0.89814
		The Other CDs Missing	0.88429	0.82274
	Two Adjacent CDs Rotated	No CD Missing	1.00636	0.96115
		The Other CDs Missing	0.96632	0.92192

2.3 Performance of the Accident-tolerant Control Drum System in a HEU-fueled Space Reactor

The performance of the accident-tolerant control drum system was also investigated when it was adopted as the reactivity control system of a HEU-fueled space reactor. Figure 4 illustrates the geometry of the HEU-fueled space reactors with a control rod system and an accident-tolerant control drum system, respectively and Table V lists the design parameters of three HEU-fueled space reactors. No moderator was used in these designs to minimize the total reactor mass [1]. The second column lists the design parameters of a HEU-fueled space reactor with a control rod system while the third and the fourth columns list those of HEU-fueled space reactors with an accident-tolerant control drum system. In the control rod case, a very thick reflector was required to meet some safety criteria described below. The first design (case A) with an accident-tolerant control drum system has a relatively thin reflector while the second one (case B) has a relatively thick reflector. The reactors with an accident-tolerant control drum system have smaller total reactor mass. Especially, the total reactor mass in case A is less than a half of the reactor mass in the control rod case.

Table V. Design Parameters of the HEU-fueled Space Reactors

Parameters	Control Rod	Accident-tolerant Control Drum	
		Case A	Case B
Thermal Power (kW)	5.0	5.0	5.0
Life Time (year)	15.0	15.0	15.0
Operation Temperature (K)	1100	1100	1100
Fuel Material	HEU	HEU	HEU
Reflector Material	Be	Be	Be
Active Height/Diameter Ratio	1.00	1.00	1.00
Number of Heat Pipes	12	12	12
Heat Pipe Inner Radius (cm)	0.4	0.4	0.4
Heat Pipe Thickness (cm)	0.1	0.1	0.1
Heat Pipe Material	Zr	Zr	Zr
Coolant Material	NaK	NaK	NaK
Inner Heat Pipe Position (cm)	4.45	2.80	2.52
Outer Heat Pipe Position(cm)	7.14	7.65	7.27
Number of Control Elements	1 Rod	6 Drs	6 Drs
Rod/Drum Absorber Mat.	B_4C	B_4C	B_4C
^{10}B Enrichment in B_4C (w/o)	89.11	89.11	89.11
Rod/Drum Can Thick. (cm)	0.10	0.10	0.10
Rod/Drum Gap Thick. (cm)	0.05	0.05	0.05
Rod/Drum Can Material	Be	Be	Be
Rod Absorber Radius (cm)	3.00	-	-
Drum Radius (cm)	-	2.80	2.80
Drum Absorber Thick. (cm)	-	1.40	1.50
Reflector Thickness (cm)	13.98	5.55	11.50
Core Radius (cm)	6.24	6.55	6.17
Fuel Mass (kg)	20.60	30.75	25.45
Reflector Mass (kg)	91.73	15.96	59.84
Reactor Total Mass (kg)	114.9	48.47	87.34



(a)HEU-fueled Reactor with CR (b)HEU-fueled Reactor with ATCD

Figure 4. HEU-fueled Space Reactors with a Control Rod system and an Accident-tolerant Control Drum system

Table VI compares the neutronic performance of the three reactors during their life time from the beginning of life (BOL) cold zero power state to the end of life (EOL) hot full power (HFP) state. The three reactors show very similar neutronic performance during their life time except for the beginning of life cold zero power shutdown state. The total drum worth in case A and B is much larger than the total rod worth in the control rod case as it was in the LEU-fueled reactors.

Table VI. Neutronic Performance of the HEU-fueled Space Reactors during Their Life Time

Reactor State	Rod/Drum Position	k_{eff}		
		Control Rod	ATCD	
			Case A	Case B
BOL, CZP	Shutdown	0.92713	0.81994	0.87228
BOL, CZP	Operation	1.02601	1.02507	1.02374
BOL, HFP $^{a)}$	Operation	1.02601	1.02499	1.02353
BOL, HFP $^{b)}$	Operation	1.00707	1.00732	1.00699
EOL, HFP $^{b)}$	Operation	1.00609	1.00672	1.00629

a) No thermal expansion was considered.
b) A thermal expansion of 1% was considered.

Table VII shows the criticality of the HEU-fueled reactor with a control rod system during various launch accidents. The effective multiplication factors are less than 0.98 except for the scenarios in which the control rod is missing without any damage in the reflector. In such a scenario, the reactor became supercritical regardless of the surrounding materials. Table VIII shows the criticality of the HEU-fueled reactors with an accident-tolerant control drum system for various accident scenarios. The maximum value of the effective multiplication factors is around 0.95 for both cases. Table IX compares the criticality of the reactors with one or two control drums rotated to the operation position. The effective multiplication factors of the reactor with a thin reflector, case A, are less than 0.98 even when it is immersed in dry sand, wet sand, or water with one control drum is rotated to the operation position regardless of whether the other drums are present or missing. The reactor with a thick reflector, case B, remains subcritical (k_{eff}<0.98) even when two adjacent control drums are rotated to the operation position regardless of the surrounding materials. The major difference between the two reactors is the reflector thickness as pointed above.

Table VII. Accident Scenario Analysis of the HEU-fueled Space Reactor with a CR System

Accident Scenario			k_{eff}
In Water	No Damage in Reflector	As Launched	0.96782
		Coolant Pipe Broken	0.97881
		CR Missing	1.17519
	Reflector Missing	CR Inserted	0.83333
		CR Missing	0.96932
In Wet Sand	No Damage in Reflector	As Launched	0.96749
		Coolant Pipe Broken	0.97360
		CR Missing	1.13355
	Reflector Missing	CR Inserted	0.82892
		CR Missing	0.93608
In Dry Sand	No Damage in Reflector	As Launched	0.95841
		Coolant Pipe Broken	0.96091
		CR Missing	1.08719
	Reflector Missing	CR Inserted	0.72932
		CR Missing	0.78913

3. Conclusions

In this paper, an accident-tolerant control drum system was proposed to enhance the safety of space reactors in various launch accidents such as rocket explosion and crash on the ground or the ocean and the safety enhancement was demonstrated for a LEU-fueled and a HEU-fueled space reactor. The space reactors with an accident-tolerant control drum system remains subcritical even when all the control drums are missing while the reactor with a control rod system becomes supercritical when a control rod is missing without any damage in reflector.

The homogeneous LEU-fueled space reactor with an accident-tolerant control drum system remains subcritical even when it is immersed in dry sand, wet sand, or water with one control drum rotated to the operation position. The safety of a space reactor can be further enhanced by adopting a heterogeneous core configuration. The heterogeneous LEU-fueled space reactor with an accident-tolerant control drum system remains subcritical even when two adjacent control drums are rotated to the operation position regardless of the surrounding materials. Besides the safety enhancement, a reduction of the total reactor mass, more than 30kg for LEU-fueled reactor in this study, was achieved by adopting an accident-tolerant control drum system instead of a control rod system.

The accident-tolerant control drum system proposed in this work showed a good performance when it was adopted in a HEU-fueled space reactor. The HEU-fueled space reactor with an accident-tolerant control drum system remains subcritical even when it is immersed in various surrounding materials with one or two control drums rotated to the operation position depending on the thickness of the reflector. When a thin reflector was used, the total mass of the HEU-fueled reactor with an accident tolerant control drum system was less than half of that of the HEU-fueled reactor with a control rod system.

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Table VIII. Accident Scenario Analysis of the HEU-fueled Space Reactor with an ATCD System

Accident Scenario		k_{eff}	
		Case A	Case B
In Water	As Launched	0.93903	0.93736
	Coolant Pipe Broken	0.94848	0.94708
	One Control Drum Missing	0.94901	0.94489
	Two Control Drums Missing (1)	0.94953	0.94208
	Two Control Drums Missing (2)	0.94950	0.94232
	Two Control Drums Missing (3)	0.94956	0.94257
	Three Control Drums Missing (1)	0.94980	0.93925
	Three Control Drums Missing (2)	0.94982	0.93954
	Three Control Drums Missing (3)	0.94960	0.93949
	Four Control Drums Missing (1)	0.94984	0.93623
	Four Control Drums Missing (2)	0.94981	0.93633
	Four Control Drums Missing (3)	0.94994	0.93623
	Five Control Drums Missing	0.95003	0.93277
	All Control Drums Missing	0.95006	0.92946
	Reflector Missing	0.88731	0.83040
In Wet Sand	As Launched	0.94176	0.93780
	Coolant Pipe Broken	0.94829	0.94389
	One Control Drum Missing	0.94187	0.93620
	Two Control Drums Missing (1)	0.93727	0.93140
	Two Control Drums Missing (2)	0.93477	0.92791
	Two Control Drums Missing (3)	0.93471	0.92769
	Three Control Drums Missing (1)	0.93218	0.92572
	Three Control Drums Missing (2)	0.92966	0.92207
	Three Control Drums Missing (3)	0.92708	0.91814
	Four Control Drums Missing (1)	0.92646	0.91914
	Four Control Drums Missing (2)	0.92396	0.91530
	Four Control Drums Missing (3)	0.92386	0.91549
	Five Control Drums Missing	0.92031	0.91154
	All Control Drums Missing	0.91606	0.90739
	Reflector Missing	0.85727	0.79078
In Dry Sand	As Launched	0.90735	0.92328
	Coolant Pipe Broken	0.91079	0.92613
	One Control Drum Missing	0.89367	0.90854
	Two Control Drums Missing (1)	0.87737	0.89194
	Two Control Drums Missing (2)	0.87490	0.88840
	Two Control Drums Missing (3)	0.87411	0.88744
	Three Control Drums Missing (1)	0.85953	0.87321
	Three Control Drums Missing (2)	0.85580	0.86805
	Three Control Drums Missing (3)	0.85309	0.86431
	Four Control Drums Missing (1)	0.83849	0.85051
	Four Control Drums Missing (2)	0.83477	0.84530
	Four Control Drums Missing (3)	0.83423	0.84432
	Five Control Drums Missing	0.81451	0.82323
	All Control Drums Missing	0.79170	0.79706
	Reflector Missing	0.72611	0.65596

Table IX. Criticality Analysis of HEU-fueled Space Reactors with Some Drums Rotated to Operation Position

Accident Scenario			k_{eff}	
			Case A	Case B
In Water	One CD Rotated	No CD Missing	0.96835	0.95909
		The Other CDs Missing	0.97618	0.95441
	Two Adjacent CDs Rotated	No CD Missing	0.99336	0.97804
		The Other CDs Missing	1.00152	0.97835
In Wet Sand	One CD Rotated	No CD Missing	0.96878	0.95546
		The Other CDs Missing	0.95059	0.93568
	Two Adjacent CDs Rotated	No CD Missing	0.99419	0.97414
		The Other CDs Missing	0.98490	0.96496
In Dry Sand	One CD Rotated	No CD Missing	0.93907	0.94015
		The Other CDs Missing	0.85402	0.85041
	Two Adjacent CDs Rotated	No CD Missing	0.97102	0.96049
		The Other CDs Missing	0.91646	0.90303