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Developing Installed DC Power Backup System for the APR1400 for Station Black-Out (SBO) Coping.

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Abstract*:- On March 11, 2011 the Fukushima Daichi and Daini nuclear plants were severely impacted by the Great East Japan earthquake. Seismic damage to the transmission system led to the loss of nearly all offsite power. Internal flooding damage from the concomitant tsunami resulted in loss of all medium voltage emergency AC power buses at the four (4) original units at the Daichi site. These units were then subjected to Station Blackout (SBO) conditions for an extended period. Several units at the Fukushima Daini site were similarly subjected to SBO conditions. Following the events described above, the nuclear industry and regulators have issued many analyses and reports which focus on Fukushima specific design margins, safety features, and operator actions. However, little attention is paid to the near complete loss of instrumentation and control power which made operator monitoring and response to the accident significantly more difficult. Despite heroic efforts to restore power to the DC instrument buses (e.g., using car batteries connected in series) operators were 'left in the dark'. This paper examines proposed designs for direct onsite charging of DC instrumentation bus batteries (independent of the AC medium voltage buses) which utilize decay heat as a source of energy.

Keywords:- APR1400, Fukushima Daichi, Micro Steam Turbine-Generator Station Black-Out, Systems Engineering,

INTRODUCTION

Following the tragic events at the Fukushima Daichi nuclear plant following the Great East Japan earthquake, the nuclear industry, its critics, and nuclear regulators have engaged in a re-examination of nuclear safety in particular and of the use of nuclear power in general. The Fukushima disaster has shaken public confidence in nuclear safety and led to a re-examination of the way in which many of the core principles which underlie the safety of commercial nuclear power plants have been implemented. These include 'defense-in-depth', 'nuclear safety culture', 'design basis', 'beyond design basis', and nuclear safety regulation. Many safety improvements in the areas of design, regulation, and culture have been proposed including 'post-Fukushima action items' in the U.S. In Korea, the nuclear operator, KHNP has committed to a long list of safety post-Fukushima improvements in many areas including: (i) design enhancements, (ii) flooding vulnerability reviews, (iii) mobile emergency diesel generator units, (iv) upgrades to emergency procedures, and (v) post-accident containment vent systems.

However, in reviewing various responses to the Fukushima experience, it appears that one area which has not received sufficient attention is robust power supply for DC instrumentation. Most proposals assume that power for providing power supply to DC buses and for charging of DC batteries can be provided by medium voltage AC power buses once such power is restored. In the event these buses become damaged or are inoperable, power will likely be subsequently lost to the DC buses. An increase in battery capacity for supplying the DC buses can address this concern to some extent but capacity alone does not result in a robust capability. To help operators cope with SBO conditions until recovery of AC bus power can be achieved (either from onsite or offsite sources) the ability to provide direct and sustained charging of emergency DC batteries will greatly improve the ability to cope with prolonged SBO conditions.

From a human factors standpoint, it is critical that operators have the ability to monitor and respond to the SBO event sequence while other groups are working to restore emergency shutdown capability. Proposed here are relatively simple design concepts which can maintain the charge in the DC batteries and hence power to the DC instrument and control buses. This will permit the operators to monitor conditions and execute responses for an indefinite period while others work to restore AC power.

An energy source for charging DC batteries is available in the form of decay heat as released to the atmosphere via steam relief from the secondary side to the atmosphere. Two options to harness this steam are examined here, one using the steam discharged from the atmospheric dump valve and the other using steam supplied to the steam turbine driven auxiliary feed water pump.

This paper presents the physical arrangements for these proposed designs. Next analysis which demonstrates that required battery charging for an extended period can be maintained. Option 1 has a greater capability but requires direct interface with the safety related piping which supplies the turbine driven auxiliary feed water pump.

BACKGROUND

After the Fukushima Daiichi accident, Design Extension Conditions (DECs) such as total loss of feed water (TLOFW), and prolonged Station Black-Out

(SBO) attracted the attention of nuclear experts. The focus was on the defense in depth concept, redundancy and sustainability of the systems, and development of the passive safety systems which rely on natural physics laws.

Likewise, the SBO event is the largest contributor to Core Damage Frequency (CDF) for many operating plants. Figure 1 shows the CDF contribution for the APR1400 by internal initiating events.

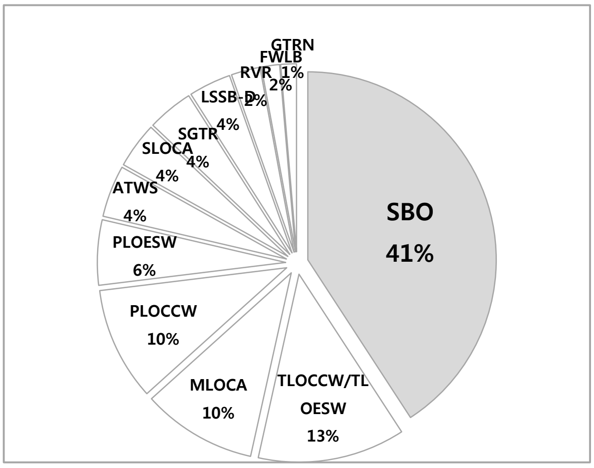

Fig. 1. CDF Contribution by Internal Initiating Events

Maanshan - Ten years before Fukushima Daiichi nuclear disaster, Maanshan NPP Unit 1 in Taiwan experienced an SBO event. On March 18, 2001 a seasonal sea smog resulted in containing salt deposits which caused a malfunction of all four 345KV power transmission lines. The 4.16 kV essential bus A breaker No. 17 opened and the No. 15 closed, transferring supply from the 161 kV offsite power. A few minutes later, power to the 345 kV was restored, but during transfer a ground fault at essential bus A occurred. The unit then lost power from all offsite sources. Furthermore, both the emergency diesel generators failed to operate, resulting in an SBO accident.

There was also report from onsite staff that heavy smoke was coming out from the control building at floor location 46-ft below the control room, where the essential buses were located. Examination subsequent to the event indicated a severely damaged essential bus (medium voltage bus 1A).

During that night, as the DC batteries drained, operators lost plant control and monitoring instrumentation. Plant workers were focused on restoring the EDGs and connecting them manually to bus A. The work was conducted in darkness, under very challenging conditions. Firemen helped by providing lighting. Despite this, operators could not estimate plant conditions and parameters. After several attempts, workers successfully returned one EDG to operation. Following that, plant staff separated the Unit 1 Bus B from the damaged Bus A. Bus B was powered via 161KV from Unit 2 transformer.

The Fukushima Daichi, Fukushima Daini, and Maanshan events all illustrate that the ability to restore a source of power to the medium voltage essential AC buses does not provide robust assurance that power can be restored to the essential DC buses. This paper examines an alternative approach to restoring power to the DC buses with available power sources under SBO scenarios.

METHODOLOGY

Systems Engineering – A Systems Engineering (SE) approach has been used for this study, by which an interdisciplinary approach is employed to assure the realization of successful Micro Steam Turbine-Generator System (MSTGS). The SE approach for developing the MSTGS involves inputs, process activities, enablers, controls, and outputs. The processes of SE approach for developing the MSTGS are shown in Fig. 2.

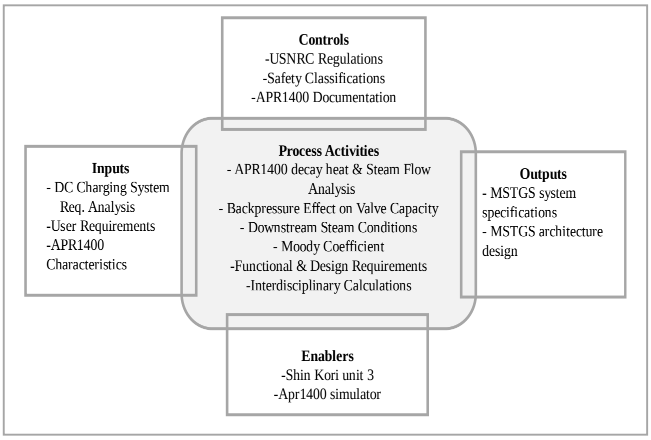

Fig. 2. Systems Engineering Processes

For input to the SE, the requirements analysis consists of determining the APR1400 DC power system loads under SBO conditions. Table 1 summarizes the power demand. The required power to supply all essential and non-essential DC buses is 200 kW (i.e., 192 kW with applied margin). The MSTGS will operate intermittently (e.g., based on ADV operating cycle) and therefore the design must then provide an average of this power for battery charging while accommodating the existing battery capacity (e.g., 8-hrs).

DC power system continuous loads					
Class 1E 125 VDC Power System				**Non-Class 1E 125 VDC Power System**	
Train A		**Train B**		**Division I**	
441.4 A	55175 W	384.1 A	48012.5 W	72.4 A	9050 W
Train C		**Train D**		**Division II**	
291.9 A	36487.5 W	289 A	36125 W	59.4 A	7425 W
Train A+C		**Train B+D**			
733.3 A	91662.5 W	673.1 A	84137.5 W		
Total Class 1E load is		**175.80 kW**		**Total Non-Class 1E load is**	**16.48 kW**
Total continuous loads is 192.28 kW					

Table [1] APR1400 On-site DC Power System Loads.

The onsite DC power system is divided into independent Class 1E and non-Class 1E DC power systems. Table 2 shows the functionality of the existing APR1400 DC power system.

Furthermore, a set of user requirements were defined based on APR1400 characterizations and systems design. The user requirements are:

i. The MSTGS shall be able to generate an average of 200 kW power under SBO conditions
ii. The MSTGS shall be able to work even under discontinuous and varying steam flow rate.
iii. The MSTGS shall not affect the function or performance of other safety systems and must meet the classification requirements.
iv. The MSTGS have to be connected to the existing DC system converters.

Under the process activities section of the SE process (Fig. 1.) the available APR1400 decay heat was analyzed and the amount of the steam generated by the decay heat was calculated versus time. Two system configurations are considered in this study. Case 1 assumes that all steam which is discharged from the ADV's is directed to the MSTGS. Case 1 assumes the microturbine skid is located in the turbine drive auxiliary feedpump room and steam is supplied by the steam supply line to the pump turbine. For Case 2 the microturbine is located in or adjacent to the Main Steam Isolation Valve room. Steam is taken from the non-safety related discharge line serving the MS ADV

Table [2] The Functionality of Existing APR1400 DC Power System

DC power system					
Class 1E DC power systems			**Non-Class 1E DC power system**		
System	**Functionality**	**Comment**	**System**	**Functionality**	**Comment**
Class 1E 125 VDC Power System	supplies reliable power to the plant safety system dc loads and essential I&C system loads	Included in this study	**Non-Class 1E 125 VDC Power System**	The system is designed to supply The emergency lighting and emergency lighting panel	Included in this study
Class 1E 120 VAC Instrumentation and Control Power System	Is required for all plant operating conditions. The Class 1E 120 Vac I&C power system supplies a continuous, reliable, and regulated ac power to the safety-related plant instruments, control equipment, and engineered safety feature – component control system (ESF-CCS), which are required to be operational during the momentary or complete loss of onsite ac power.	Excluded from this study since its AC load	**Non-Class 1E 250 VDC Power System**	Supplies power to high-inrush dc loads that generally serve as backups to turbine generator ac loads.	Excluded from this study since the turbine has been tripped off

Case 1 - For this case, steam is supplied to the MSTGS from the steam supply line to the turbine driven pump. The parameters for available steam (i.e., to drive the MSGTS) are calculated as a function of time following the initiation of the SBO accident in three time intervals as shown in Table 3. Note that only a small fraction of available steam is required to drive the AF pump turbine to provide sufficient makeup for heat removal (i.e., the pump add less than 8 BTU/lbm while each pound of water supplied to the S/G absorbs ~1000 BTU/lbm). Thus steam delivered to the MSGTS will not impact the ability of the AF system to deliver water to the S/G.

Table [3] Steam Parameters for Case 1

	Steam Flow Rate	**S/G T**	**S/G P**	**Hin**	**Sin**	**Hisen**	**Energy Available**
	lbm/hr	(Deg F)	(psia)	(BTU/lbm)	(BTU/lbm-deg F)	(BTU/lbm)	(BTU/lbm)
3 hours							
	142,000	482	579.1	1203.94	1.450	962.14	242
27 hours (1 Day)							
	107,000	290	57.6	1176.81	1.647	1098.08	79
55 hours (2 days)							
	78,000	290	57.6	1176.81	1.647	1098.08	79

Case 2 - For this case, steam is supplied to the MSTGS from the non-safety related ADV discharge line. However, for the existing design, the available steam pressure from this line is too low. Thus the APR1400 configuration is modified by placing an orifice in the ADV discharge line. This will increase pressure in the discharge line while the ADV is releasing steam which in turn will increase available energy to the MSTGS.

As a result of this configuration change, the inlet steam pressure to the MSTGS then equals the back-pressure which is produced from the orifice. However, the orifice will also increase backpressure on the ADV potentially impacting ADV flow capacity. To address this issue, analysis of required ADV capacity was performed.

Fig. 3 illustrates the required ADV steam flow coefficient as a function of back-pressure ratio (downstream pressure ‘P2’ divided by upstream pressure ‘P1’). There are three design basis conditions placed on the ADV flow capacity, (i) maximum flow, (ii) minimum guaranteed flow, and (iii) controlling flow, from top curve to bottom curve, respectively. For all three conditions, the increase in steam flow coefficient from the current fully choked flow condition to the predicted backpressure for Case 2 is ~20%, within the capacity for the existing valve body.

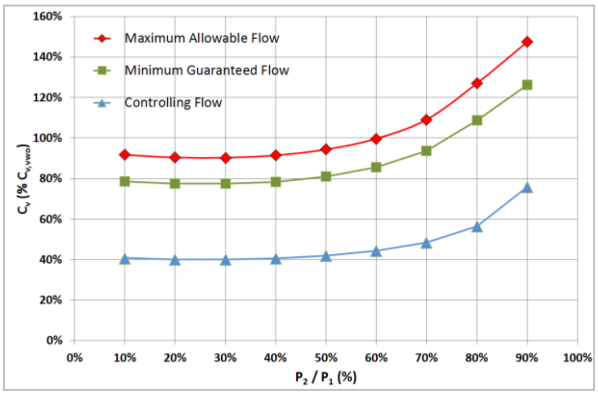

Fig. 3 ADV Required Cv vs. Back-Pressure.

The parameters for available steam to power the microturbine for Case 2 are calculated after the initiation of the SBO accident in three time intervals shown in Table 4.

Table [4] Steam Parameters for Case 2

Microturbine Steam Flow	**Inlet Pressure**	**Inlet Enthalpy**	**Inlet Entropy**	**Outlet Enthalpy Isentropic**	**Isentropic Power**
(lbm/hr)		(BTU/lbm)	(BTU/lbm-oF)	(BTU/lbm)	(10^3 BTU/hr)
3 hours (10,000 sec)	142,000				
	91.65		254.47		
10,000	85.20	1184	1.6157	1069.2	1,150
20,000	78.75	1183	1.6221	1073.6	2,184
30,000	72.29	1181	1.6290	1078.3	3,087
40,000	65.84	1179	1.6365	1083.4	3,839
50,000	59.38	1177	1.6448	1089.1	4,418
60,000	52.93	1175	1.6540	1095.4	4,790
70,000	46.47	1173	1.6645	1102.5	4,914
80,000	40.02	1170	1.6764	1110.6	4,730
27 hours (1 Day)					
	107,000				
	69.06	60	254.47		
10,000	62.61	1178	1.6406	1086.2	922,
17,000	58.09	1177	1.6466	1090.3	1,474
24,000	53.57	1175	1.6531	1094.7	1,937
31,000	49.05	1174	1.6601	1099.5	2,300
38,000	44.54	1172	1.6679	1104.8	2,548
45,000	40.02	1170	1.6764	1110.6	2,660
52,000	35.50	1167	1.6860	1117.2	2,613
55 hours (2 days)	78,000				
	50.35	60	254.47		
8,000	45.18	1172	1.6667	1104.0	544
12,000	42.60	1171	1.6714	1107.2	765
16,000	40.02	1170	1.6764	1110.6	946
20,000	37.44	1168	1.6818	1114.3	1,083
24,000	34.85	1167	1.6875	1118.2	1,173
28,000	32.27	1166	1.6937	1122.4	1,209
32,000	29.69	1164	1.7003	1126.9	1,184

In the output process using SE, the estimated power from the available steam for powering the microturbine for Cases 1 and 2 is presented in Tables 5 and 6, respectively.

Table [5] The DC Power Generated in Case 1

Time Interval	**Req'd Power**	**Req' Steam for 200 kWe**	**% Available Steam**
	(BTU/hr = 200 kWe)	(lbm/hr)	(%)
3 hours (10,000 sec)	682,428	4,704	3%
27 hours1 (Day)	682,428	14,447	14%
55 hours (2 days)	682,428	14,447	19%

Table [6] The DC Power Generated in Case 2

Microturbine Steam Flow	**Inlet Pressure >2 bar**	**Isentropic Power**		**Isentropic Power**	**Generator Output**
(lbm/hr)	(1 = TRUE)	(10^3 BTU/hr)		(kWe)	(kWe)
3 hours (10,000 sec)					
10,000	1	1,150		337.1	202
20,000	1	2,184		640.2	384
30,000	1	3,087		904.8	543
40,000	1	3,839		1125.3	675
50,000	1	4,418		1294.8	777
60,000	1	4,790		1404.0	842
70,000	1	4,9141		1440.3	**864**
80,000	1	4,730		1386.3	832
27 hours (1 Day)					
10,000	1	922,		270.4	162
17,000	1	1,474		432.1	259
24,000	1	1,937		567.9	341
31,000	1	2,300		674.2	405
38,000	1	2,548		746.8	448
45,000	1	2,660		779.8	**468**
52,000	1	2,613		765.8	459
55 hours (2 days)					
8,000	1	544		159.7	96
12,000	1	765		224.2	135
16,000	1	946		277.3	166
20,000	1	1,083		317.6	191
24,000	1	1,173		343.9	206
28,000	1	1,209		354.4	**213**
32,000	1	1,184		347.1	208

Furthermore, MSTGS system specifications based on the requirements which had been developed early in this study and component specifications which are available in the commercial market are generated in Table 7. Fig. 4 and 5 illustrate the MSTGS conceptual design configurations for Cases 1 and 2, respectively

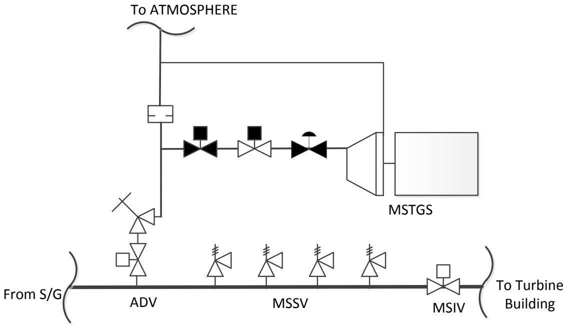

Fig. 4. Case 1 MSTGS Design Configuration.

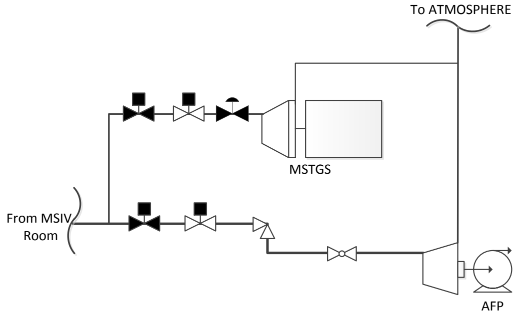

Fig. 5. Case 2 MSTGS Design Configuration

Table [7] MSTGS System Specifications.

	System Specification	**Comments**
Full Load Power Output	550 kWe @ 480 V, 60 Hz, 3 Phase	- 275 kWe/ micro turbine-generator unit - For micro turbine-generator exciting in the market
Standard Maximum Inlet Pressure	200 psig	- A reduction steam valve is placed at the steam inlet pipe. - For micro turbine-generator exciting in the market
Standard Minimum Discharge Pressure	2 psig	For micro turbine-generator exciting in the market
Steam Flow Rate	54,355 lb/h,	13,589 lb/h from each ADV
Dimension	34" x 42" x 78"	- For each micro turbine-generator - Vertical Shaft - Similar specifications for micro turbine-generator exciting in the market
Life time	60 years	The turbine generator units will be changed Every 15 years

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CONCLUSION

The ability to maintain monitoring and control a nuclear unit under the challenging conditions associated with loss of all AC power is critical to successfully bringing the unit to a cold shutdown condition. As shown by recent events at Maanshan, Fukushima Daichi, and Fukushima Daini, unit status and shutdown actions cannot be adequately monitored without proper instrumentation. A key to maintaining proper instrumentation is a supply of reliable, continuous power to the buses which power the instruments.

Proposed here are two options which using available decay heat can provide an installed capability to maintain DC bus power for an extended period. The results of steam and decay heat calculations in this study have demonstrated that decay heat from the APR1400 can provide a sufficient amount of dumped steam for at least 55 hours from initiating the extended SBO accident. Two cases were developed. In Case 1, the MSTGS requires only 3-19% of the steam generated by decay heat to provide 200 kW of DC power. Case 2 results proved that generating the targeted DC power is also possible but for a somewhat shorted period. The MSTGS is the product of systems engineering approach in this research which is qualified to produce power enough to maintain charging the existing batteries for an extended period (more than 24 hours and as much as 60 hrs). This will provide sufficient power for instrumentation and control system loads, plant safety system DC loads, and emergency lighting under SBO of similar accident conditions.

REFERENCES

[1] Fukushima Nuclear Accident Analysis Report, *Tokyo Electric Power Company, Inc.* (2012)

[2] APR1400 Design Control Document, Tier 2, Chapter 6, Engineered Safety Features, *Korea Electric Power Corporation (KEPCO) and Korea Hydro & Nuclear Power Co., Ltd. (KHNP)*

[3] APR1400 Design Control Document, Tier 2, Chapter 19, Probabilistic Risk Assessment and Severe Accident Evaluation, *Korea Electric Power Corporation (KEPCO) and Korea Hydro & Nuclear Power Co., Ltd. (KHNP)*

[4] APR1400 Design Control Document, Tier 2, Chapter 6, Electric Power, *Korea Electric Power Corporation (KEPCO) and Korea Hydro & Nuclear Power Co., Ltd. (KHNP)*

[5] D.D. WALDEN, G.J. ROEDLER, K.J FARSBERG, R.D. HAMELIN, T.M. SHORTELL, INTERNATIONAL COUNCIL ON SYSTEMS ENGINEERING, *"Systems Engineering Handbook A Guide: A Guide for System Life Cycle Process and Activities" 4th Edition,*. Chapter 5, John Wiley &, Hoboken, New Jersey, (2015)

[6] Loss of All Alternating Current Power, U.S.NRC Regulation, Title 10 Code of Federal Regulations Part 50, Section 63

[7] *JONGROK HWANG, "Developing Optimal Procedure of Emergency Outside Cooling Water Injection for APR1400 Extended SBO Scenario Using MARS Code", Gyeongju, Korea, Transactions of the Korean Nuclear Society Autumn Meeting October 24-25, (2013)*

[8] The Station Blackout Incident of the Maanshan NPP Unit 1, *Atomic Energy Council Taiwan, R.O.C.* (2001)

[9] DENNIS M. BUEDE, WILLIAM D. MILLER, "*The Engineering Design of Systems: Models and Methods" 2nd Edition*, Chapter 1, John Wiley &, Hoboken, New Jersey, (2009).