

HFE Study About Environment Design Indexes for Main Control Room of Nuclear Power Plant

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Abstract Main control room (MCR) is an important site of the nuclear power plant (NPP), and the environmental condition in MCR shall be benefit to operators performing their task effectively and comfortably. With the development of HFE (human factor engineering), there is more attention to environment design of MCR. the MCR environment design mainly include noise reduction, illumination, air condition, interior and colour design, earthquake protection, fire protection, radiation protection, missile protection, and so on. At present, the indexes for environment design of domestic and international regulations and standards are inconsistent. None of regulations and standards is comprehensive, detailed and fully adapting to the MCR environment design of NPP, and some indexes are difficult to achieve. This paper compares the indexes of MCR environment of regulations and standards, performs HFE study about the indexes of MCR environment design combining with engineering experience in different NPPs. Finally, this paper proposes a set of environment design indexes applied to MCR of NPP, which will guide the MCR environment design of third generation NPPs.

Keywords NPP · MCR · HFE · Environment design indexes

1 General

The MCR environment of NPP affects the health, performance and human factors effect of operators, even the safety of NPPs. For the MCR design, firstly to complete the basic structure and equipment arrangement of the control room according to HFE theory, then the MCR environment design consider the following indexes: noise reduction, illumination, air conditions, interior and colour design, earthquake protection, fire protection, radiation protection, missile protection, and so on. But now, the indexes of MCR environment design in different regulations and standards

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are inconsistent. None of regulations and standards is comprehensive, detailed and fully adapting to the MCR environment design of NPPs, and some indexes are difficult to achieve. So it's necessary to establish a set of comprehensive, consistent and suitable indexes for MCR environment design of NPPs.

2 MCR Environment Design Indexes in Regulations and Standards

This chapter compare and analyse the indexes for MCR environment in regulations and standards to expound the present situation of the environment design requirements of the MCR.

2.1 Noise Level

Noise is an important index that affects the environment of MCR in NPP and a major contributor to operator fatigue and effectiveness. Noise reduction is the emphasis and difficulty of MCR environment design. The indexes of MCR noise level in regulations and standards are shown in Table 1.

Table 1 The noise level indexes in the regulations and standards

Regulations and standards	Indexes
IEC 60964-1989 [1]	Maximum ambient noise: 45 dB Background noise should not exceed 45 dB
IEC 60964-2009 [2]	Guidance for environmental specifications under normal conditions is provided in ISO 11064
ISO 11064-6:2005(E) [3]	The ambient noise should not exceed 45 dB $L_{Aeq,T}$ The background level should be in the range 30–35 dB $L_{Aeq,T}$
EUR [4]	MCR shall have an ambient noise level no greater than 50 dB
URD [5]	MCR shall have an ambient noise level no greater than 60 dB (A) Mid-frequency reverberation times should not exceed 0.75 s and should preferably be closer to 0.4 s—dependent on room
Nureg0700 [6]	Background noise levels should not exceed 65 dB (A) The acoustical treatment of the control room should limit reverberation time to 1 s or less
HAF J0055-1995 [7]	Ambient noise should not exceed 45 dB Reverberation (Chinese word is “huisheng” in this standard) time should be limited to below 1 s
GB/T 13630-1992 [8]	Equivalent to the requirements in IEC 60964-1989
EJT 638-1992 [9]	Background noise in the control room should not exceed 45 dB (A) Reverberation (Chinese word is “huixiang” in this standard) time should not exceed 1 s
NB/T 20190-2012 [10]	Noise limitation of MCR is 55 dB (A)

According to Table 1, the noise indexes mainly include ambient noise, background noise level and reverberation time, but the indexes in different regulations and standards are inconsistent. The suggesting indexes will be provided in Sect. 4.

2.2 Illumination

In normal condition, normal lighting works in MCR, but the possibility of losing normal lighting should be considered, so emergency lighting is as a backup. The indexes of MCR illumination in regulations and standards is shown in Table 2.

Table 2 The illumination indexes in the regulations and standards

Regulations and standards	Indexes
IEC 60964-1989 [1]	Level of illumination: minimum: 200 lx, maximum: 750 lx Uniformity of illumination (ratio): not less than 0.5 Incident illumination to VDU screen: minimum: 50 lx, maximum: 100 lx Minimum emergency illumination: 200 lx
IEC 60964-2009 [2]	Guidance for environmental specifications under normal conditions is provided in ISO 11064
ISO 11064-6:2005(E) [3]	Illuminance levels on work surfaces where paperwork is undertaken should be “maintained” at a level of 200–750 lx with an upper limit of 500 lx where VDUs are used Dimming should be provided with a lower limit of “maintained” 200 lx on the work surface at all times For working areas where mainly paperwork is undertaken, an illumination level of 500 lx should be maintained Electric lighting should achieve a glare index (UGR) of 19 or less for all work positions
EUR [4]	Illumination for the lighting areas (e.g. Operator workstations, auxiliary and supervisor areas) may be in the range of 50–250 lx More detailed guidance is given in IEC 60964: Design for control rooms of nuclear power plants
URD [5]	Control stations shall be provided with lighting which can be adjusted by the operators to provide uniform illumination in the range of 10–50 foot-candles The emergency lighting system shall provide a minimum illumination level of 10 foot candles Note: 1 footcandle = 10.761 lx
Nureg0700 [6]	Nominal illumination levels for various tasks and work areas indicate in Table 1 of Chapter “A Study about Software Development QC and QA of the Digital RPS in Nuclear Power Plant” are 50 or 100 foot-candles, reading on VDU: 10 footcandles Emergency operating lighting: 10 footcandles

(continued)

Table 2 (continued)

Regulations and standards	Indexes
HAF J0055-1995 [7]	Average illumination is 100–500 lx, adjustable Uniformity of illumination is not less than 0.7 Incident illumination (Chinese word is “shigu zhaodu” in this standard) to VDU screen is 50–100 lx Emergency illumination is not less than 200 lx
GB/T 13630-1992 [8]	Equivalent to the requirements in IEC 60964-1989
EJ/T 638-1992 [9]	The illumination requirements are from 200 to 1000 lx distinguishing between different areas, and please see the original text for details Emergency illumination is not less than 200 lx and can work 8 h at least

According to Table 2, the illumination indexes mainly include nominal illumination level, emergency illumination level, uniformity of illumination and UGR, but the indexes in different regulations and standards are inconsistent. The suggesting indexes will be provided in Sect. 4.

2.3 Air Conditions

The MCR of NPP should have appropriate temperature, humidity and air flow organization. The indexes of MCR air condition in regulations and standards are shown in Table 3.

Table 3 The air condition indexes in the regulations and standards

Regulations and standards	Indexes
IEC 60964-1989 [1]	No requirements
IEC 60964-2009 [2]	Guidance for environmental specifications under normal conditions is provided in ISO 11064
ISO 11064-6:2005(E) [3]	For sedentary activity during winter conditions: the operative temperature should be between 20 and 24 °C (i.e. 22 ± 2 °C) The mean air velocity should be less than 0.15 m/s The relative humidity should be between 30 and 70% For sedentary activity during summer conditions: the operative temperature should be between 23 and 26 °C (i.e. 24.5 ± 1.5 °C) The mean air velocity should be less than 0.15 m/s The relative humidity should be between 30 and 70%
EUR [4]	Applicable values for the temperature of the HMI rooms are in the range of 18–25 °C with a humidity rate of 40–60%
URD [5]	73–78 °F; 35–50% relative humidity

(continued)

Table 3 (continued)

Regulations and standards	Indexes															
	Within a temperature range of 73–78 °F with a 1 h maximum of 85 °F and a relative humidity range of 25–60% maximum For a loss of all ac power event, provisions shall be made to limit the average temperature rise to 15 °F maximum at 72 h into the event Note: conversion formula of temperature: $F = 9C/5 + 32$															
Nureg0700 [6]	The climate control system should maintain temperatures of 68–75 °F in winter and 73–79 °F in summer and relative humidity levels between 30 and 60% The ventilation system should be capable of introducing fresh air into the control room at a rate of at least 20 cubic feet per minute per occupant															
HAF J0055-1995 [7]	Temperature: 18–25 °C; Relative humidity: 20–60% The mean air velocity through the body of main area should be less than 15 m/min. Introducing fresh air into the control room is at a rate of at least 0.43 m ³ per minute per occupant															
GB/T 13630-1992 [8]	No requirements															
EJ/T 638-1992 [9]	Temperature: 20–25 °C Relative humidity: 30–60% The mean air velocity through the body of main area should be less than 0.23 m/s In normal situation, introducing fresh air into the control room is at a rate of at least 0.43 m ³ per minute per occupant Temperature requirements in extreme environment <table><tr><td>Duration time of work: h</td><td>1</td><td>2</td><td>4</td><td>12</td></tr><tr><td>Extreme maximum temperature: °C</td><td>38</td><td>35</td><td>32</td><td>29</td></tr><tr><td>Extreme minimum temperature: °C</td><td>0.1</td><td>13</td><td>15</td><td>17</td></tr></table>	Duration time of work: h	1	2	4	12	Extreme maximum temperature: °C	38	35	32	29	Extreme minimum temperature: °C	0.1	13	15	17
Duration time of work: h	1	2	4	12												
Extreme maximum temperature: °C	38	35	32	29												
Extreme minimum temperature: °C	0.1	13	15	17												

According to Table 3, the air condition indexes mainly include temperature, humidity, the mean air velocity and introducing fresh air requirements, even the temperature requirements in extreme environment. But the indexes in different regulations and standards are inconsistent. The suggesting indexes will be provided in Sect. 4.

2.4 The Interior and Color Design

The technical indexes of MCR decoration material of NPPs are an important index in the interior design. In addition to considering the basic requirements of human health, fire, etc., but also need to be combined with the principles of human engineering and effectiveness.

The reflection coefficient of a variety of colours should be considered in colour design, and the choice of main tone is also consider the user's needs to provide a pleasant working environment and a calming backdrop. The requirements of interior and colour design in regulations and standards is not too much and shown in Table 4.

Table 4 The interior and color design indexes in regulations and standards

Regulations and standards	Indexes																								
IEC 60964-1989 [1]	No requirements																								
IEC 60964-2009 [2]	No requirements																								
ISO 11064-6:2005(E) [3]	In selecting materials and finishes for the control areas the following should be considered (a) The reflectance value of the floor finishes should be between 0.2 and 0.3 (b) Wall finishes should have a surface reflectance of between 0.50 and 0.60. The surface reflectance value should not fall below 0.50, as values below this can increase the contrast between the ceiling and walls, contribute to a gloomy environment, and increase electric light power consumption (c) The glazing bars and solid areas of the partitions should have a similar reflectance value (0.5–0.6) to the periphery walls (d) Where indirect lighting systems are used, ceilings should be white, should be of matt finish and should have a minimum surface reflectance of 0.8																								
EUR [4]	Typically the floor covering material and the flooring system provide resistance values from 50 to 100 MΩ measured between two points on the floor spaced by 1 m																								
URD [5]	General requirements of material storage and surface finishes but no indexes																								
Nureg0700 [6]	Reflectances <table><tr><td>Surface</td><td>Preferred (%)</td><td>Permissible (%)</td></tr><tr><td>Ceiling</td><td>80</td><td>60–95</td></tr><tr><td>Upper wall</td><td>50</td><td>40–60</td></tr><tr><td>Lower wall</td><td>15–20</td><td></td></tr><tr><td>Instruments/displays</td><td>80–100</td><td></td></tr><tr><td>Cabinets/consoles</td><td>20–40</td><td></td></tr><tr><td>Floor</td><td>30</td><td>15–30</td></tr><tr><td>Furniture</td><td>35</td><td>25–45</td></tr></table>	Surface	Preferred (%)	Permissible (%)	Ceiling	80	60–95	Upper wall	50	40–60	Lower wall	15–20		Instruments/displays	80–100		Cabinets/consoles	20–40		Floor	30	15–30	Furniture	35	25–45
Surface	Preferred (%)	Permissible (%)																							
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Cabinets/consoles	20–40																								
Floor	30	15–30																							
Furniture	35	25–45																							
HAF J0055-1995 [7]	No requirements																								
GB/T 13630-1992 [8]	No requirements																								
EJ/T 638-1992 [9]	Equivalent to the requirements in Nureg0700																								

According to Table 4, the interior and colour design indexes mainly include reflectance which can't satisfy the design requirements fully. The detailed suggestions will be provided in Sect. 4.

2.5 Other Requirements

In addition, there are some other requirements for MCR environment design in IEC 60964-1989, IEC 60964-2009, ISO 11064-6:2005(E), EUR, URD, Nureg0700, GB/T 13630-1992, EJ/T 638-1992, e.g. fire protection, radiation protection, missile protection, earthquake protection, prevention of hostile acts, and so on. These requirements are the general or basic requirements for the MCR environment design, and no indexes requirements generally (except the indexes requirements of radiation protection in EJ/T 638-1992). But such general or basic requirements should be complied with. For example, the requirements in EJ/T 638-1992 is following: For discontinuous running equipment in control room, such as cable tray and catheter, ceiling, lamps and lanterns, their fault should not injure operators and damage the safety system function during or after S2 earthquake [9]. So these requirements will not be analysed in this paper.

3 Environment Design Indexes in Different NPPs

This chapter analyse the actual or design indexes of noise, illumination, air conditions, interior and colour design of MCR environment design of Ling Ao phase II (LA II), CPR1000 new project, EPR, AP1000 projects. The general or basic requirements without detailed indexes are not analysed here.

3.1 Noise Level

The actual value or design target value of MCR noise of different NPPs is shown in Table 5.

According to the above situation, the 45 dB index requirement of noise level is difficult to achieve.

During the MCR environment design, a questionnaire investigation was performed with six crews to estimate the noise level of MCR [11].

The estimation criteria are:

- Perfect satisfied design (10)
- Good satisfied design (8–10)
- Satisfied design (6–8)
- Bad design (0–6) (Table 6).

Table 5 The actual value or design target value of MCR noise of NPPs

No.	Project	Indexes
1	Actual value of LA II	Less than 52 dB, reverberation time in some frequency is less than 1 s
2	Actual value of CPR1000 new project	Hong Yanhe: less than 51 dB Fang Chenggang: less than 50 dB; reverberation time is less than 1 s
3	Actual value of Tian Wan NPP	55–60 dB; before improvement, the smooth surround wall and ground, and simple perforated plate with big hole on ceiling have low frequency noise absorption function and perform a large reverberation sound field
4	Design target value of EPR basing on EUR	50 dB
5	Design target value of AP1000 basing on Nureg0700	55 dB (A), peak value is not exceeding 65 dB (A). Reverberation time is not exceeding 1 s
6	Actual value of Ling Ao phase I	55 dB, some measuring points exceed 60 dB
7	Actual value of N4	65 dB

Table 6 The estimation for the noise in MCR

Project	Estimation item	Score
LAI	How about the noise in MCR?	7.4
Hong Yanhe	How about the noise in MCR?	7.8

So the background noise level with about 50 dB is reasonable.

For the LAI, the shift team put forward the requirement to reduce the noise level of MCR, c about 60 dB is not ideal.

3.2 Illumination

- Actual value of LA II basing on IEC 60964-1989: normal illumination is from 200 to 750 lx distinguishing between different areas and can be adjusted continually; the emergency illumination in main operation area is about 200 lx.
- Actual value of Fang Chenggang basing on IEC 60964-1989: normal illumination is from 200 to 750 lx distinguishing between different areas and can be adjusted continually; optimal illumination in main digitized operation area is 500 lx, the uniformity of illumination is not less than 0.5; Emergency illumination is not less than 200 lx and can work 8 h at least.
- Design target value of EPR mainly basing on IEC 60964-1989: The illumination level shall be 500 lx in the area of the workplaces and in the other areas.

- Design target value of AP1000 basing on Nureg0700: overall illumination can be adjusted from 250 to 500 lx; illumination of reading zone is from 800 to 1000 lx. Emergency illumination is not less than 100 lx in all areas.

The optimal illumination in main digitized operation area is 350 lx of Hong Yanhe MCR. After commercial operation, a questionnaire investigation was performed that 41.7% operators think that such illumination is a little dark. Optimal illumination in main digitized operation area is improved to 500 lx of Fang Chenggang, a questionnaire investigation was also performed that 26.4% operators are no comments because the MCR is not running, but 73.6% operators think that such illumination is ideal according to simulator.

3.3 *Air Condition*

- Actual value of LAII: satisfy the indexes of HAF J0055 in Table 3. But a questionnaire investigation shows that 18 °C is a little cold.
- Actual value of CPR1000: satisfy the indexes of HAF J0055 in Table 3.
- Design target value of EPR mainly basing on EUR: The temperature is between 18 and 22 ± 2 °C max. 24 °C and the relative humidity between 40 and 60% and in accidental conditions between 10 and 30 °C for 24 h.
- Design target value of AP1000: design basing on the indexes of Nureg0700 in Table 3.

3.4 *Interior and Colour Design*

At the beginning of design of LAII, a questionnaire investigation was performed and shown that the interior and colour design of MCR environment is important. Please see Figs. 1 and 2 and Tables 7, 8 and 9.

The choice of main tone of color is considering the user's opinion. A survey result shows that the blue color image perceived by the operators was classified into fresh, cheerful, and comfortable. So the blue is chosen as the main color of LAII.

For the interior design, it's important to improve working efficiency and make operators feel more comfortable. For the technical indexes of the decoration materials, besides the requirement in Table 4, the functionality should be considered, e.g. the sound absorption index. In Fang Chenggang project, the technical indexes of the decoration materials are optimized entirely. The technical factors of MCR floor is as following table that solves the wear, reflection, antiskid and other issues of ground effectively.

The indexes of above factors are provided according to the standards and engineering experience in NPPs.

AP1000: design basing on the requirements of Nureg0700 in Table 4.

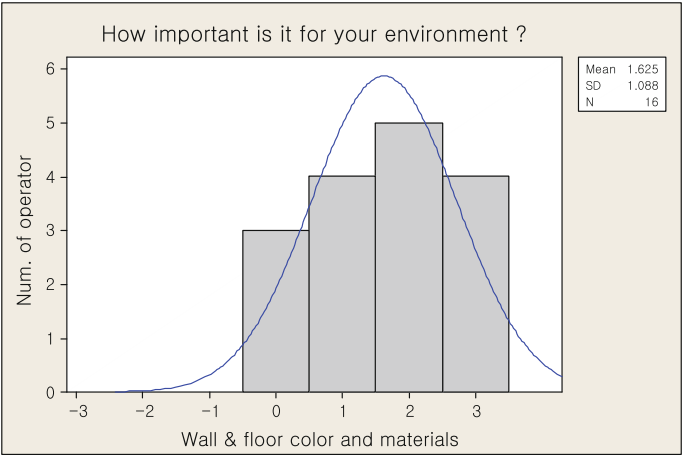


Fig. 1 Questionnaire investigations on wall and floor color and materials

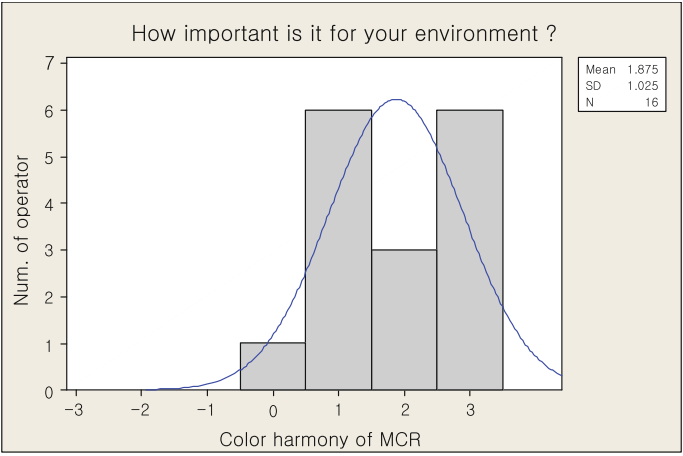


Fig. 2 Questionnaire investigations on color harmony

Table 7 Statistical result of Fig. 1

No.	Number of operator	Mean	<i>P</i> -value (0.05)	Result
1	16	1.63	0.00	Important

Table 8 Statistical result of Fig. 2

No.	Number of operator	Mean	<i>P</i> -value (0.05)	Result
2	16	1.88	0.00	Important

Table 9 Technical factors of floor material of Fang Chenggang project

No.	Technical factor
1	Specification
2	Color
3	Impact strength
4	Density
5	Water absorption rate
6	Combustion performance
7	Wearing strength
8	Moh’s hardness
9	Compressive strength
10	Reflectance value
11	Glossiness
12	Meet the requirements of class A decoration materials standards in GB6566-2010 (limits of radionuclides in building materials)
13	Friction index (wet)

4 Analysis and Project Experience of Environment Design Indexes

Basing on the analysis in Sects. 2 and 3 and the research achievement of NPPs, this chapter put forward that the suggested indexes of noise level, illumination, air condition, interior and colour design of MCR environment.

4.1 Noise Level

Background noise level and reverberation time are suggested to consider for MCR noise level of NPPs. The detailed indexes are as following:

- Background noise in MCR should not exceed 50 dB (A) according to the project experience.
- Mid-frequency reverberation times should not exceed 1 s according to the project experience.

In Table 1, the description of “huisheng” in HAF J0055 and “huixiang” in EJ/T 638-92 is not accurate; the correct interpretation is “hunxiang” originating from word “reverberation”. This should be corrected when the regulations and standards are updated.

4.2 *Illumination*

The MCR should be provided with several lighting areas, which can be manually adjusted to provide illumination suitable for the Operators to perform their tasks.

Suggesting indexes:

- Level and uniformity of illumination are suggested subjecting to IEC 60964-1989 and optimal illumination in main digitized operation area is 500 lx.
- Level and working time of emergency illumination is suggested subjecting to EJ/T 638-1992.
- Uniformity of illumination (ratio) is not less than 0.5 subjecting to IEC 60964-1989.
- For direct light, electric lighting should achieve a glare index (UGR) of 19 or less for all work positions subjecting to ISO 11064-6:2005(E) and project experience.

In Table 2, the description of “shigu zhaodu” in GB13630 and HAF J0055 is not accurate; the correct interpretation is “rushe zhaodu” originating from word “incident illumination”. This should be corrected when the regulations and standards are updated.

4.3 *Air Condition*

The different index of temperature for winter and summer is more reasonable. Suggesting indexes are as following:

- The temperature, humidity and mean air velocity of normal air condition is suggested subjecting to ISO 11064-6:2005(E).
- The rate of introducing fresh air is suggested subjecting to HAF J0055-1995.
- Temperature requirements in extreme environment subjects to EJ/T 638-1992.

4.4 *The Interior and Color Design*

For the interior design, suggest considering the surface reflectance basing on Table 4 and actual requirements, and specify detailed technical indexes of the decoration materials according to the functionality. The author suggests determining the main tone of colour with the users together to provide a pleasant working environment and a calming backdrop.

4.5 Others

The requirements in Sect. 2.5 are general or basic requirements for MCR environment design and should be complied with.

5 Conclusion

The MCR of NPP is an important work place for the operation staff. A good environment of MCR can improve the work efficiency of MCR staff and the safety of NPP. This paper put forward a set of entire, specific and strongly adaptive indexes for MCR environment design. This research achievement lays a solid foundation for the MCR environment design of the third generation NPPs.

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