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γ射线照相在大亚湾核电站无损检验中的应用

APPLICATION OF γ-RAY RADIOGRAPHY IN NON-DESTRUCTIVE EXAMINATION AT DAYA BAY NUCLEAR POWER PLANT

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摘　要

介绍了在核电站核岛安装中焊缝无损检验时应用 γ 射线探伤的方法。内容包括 γ 射线探伤设备、γ 射线放射源的选择；不同部件上焊缝无损检验 γ 射线探伤的方法；X，γ 射线照相的灵敏度及其比较；γ 射线照相的优点及其应用。

APPLICATION OF γ-RAY RADIOGRAPHY IN NON-DESTRUCTIVE EXAMINATION AT DAYA BAY NUCLEAR POWER PLANT

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ABSTRACT

The method of γ-ray radiographic examination for NDE of welds in Nuclear Island erection works is presented. The content includes selection of γ-ray examination equipment, γ-ray source, different methods of γ-ray examination on different parts, comparison of sensitivity of X-ray examination with that of γ-ray examination, advantages and application of γ-ray radiographic examination.

Normally, the two commonly used methods of radiographic examination are X-ray and γ-ray radiograph. There are not any essential difference between these two methods. But since γ-ray radiograph is less sensitive than X-ray radiograph, it is generally used when X-ray radiograph can not be performed due to thicknrss, special shape of the weld and inaccessibility of the weld by X-ray detector. Its application is also limited due to the existing problems in operational safety of γ-ray examination devices. Recently because of the improvement made in γ-ray equipment, fabrication technique of sources and radiographic technique, etc., the application of γ-ray radiography has become gradually extensive. According to certain information, the application of γ-ray and X-ray radiography in some countries is fifty-fifty.

In recent years, some manufacturers in our country began to produce γ-ray examination devices and sources, such as ^{60}Co, ^{192}Ir, etc. But γ-ray radiography is not yet widely used.

γ-ray radiography with ^{192}Ir was applied for radiographic examination of all welds during prefabrication and installation of piping and tank in Nuclear Island (NI) auxiliary systems at Daya Bay NPP. Exposure thickness is 8~80 mm. It is the first time in our country that X-ray radiography is completely substituted by γ-ray during the whole project.

1 GAMMA RAY SOURCES

Commonly used sources in NDE are ^{60}Co, ^{192}Ir, ^{137}Cs and ^{170}Tm sources. Some of their properties are listed in Table 1.

Table 1 Properties of common sources

radioactive isotope	^{60}Co	^{192}Ir	^{137}Cs	^{170}Tm
energy, MeV	1.77~1.33	0.355	0.66	0.072
half-life	5.3 years	75 days	30 years	130 days
equivalent to X-ray, kV	2000~3000	300~800	600~1500	100~300
specific activity, Bq/g	1.85E12	1.30E13	9.25E11	highest
price	low	relatively low	medium	high

^{60}Co and ^{192}Ir are most commonly used in radographic examination, ^{60}Co is generally used on large and thick pieces while ^{192}Ir is the most widely used source. It can be obviously seen from Table 1 that iradium can be used on thin or thick pieces with a middle level of energy. Since it has high specific activity, the size of sources can be rather small, and thus the films have high definition.

It is also cheaper. Its drawback is the short half-life. One source can only be used for more than half a year.

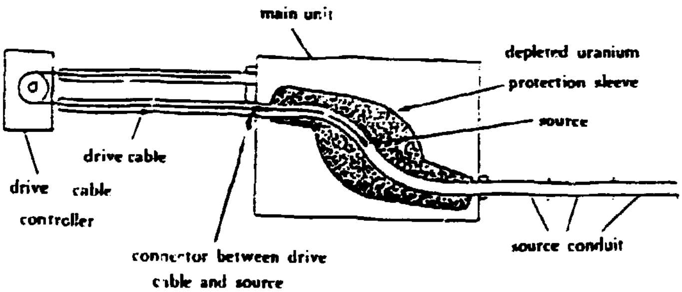
Iradium sources were used in the construction of Daya Bay NPP. The shape of sources is cylinder with sizes of ϕ 3×2 mm, ϕ 3×1 mm and specific activity higther than 3.33×10^{12} Bq (90 Ci) at the time of delivery.

2 GAMMA RAY EXAMINATION EQUIPMENT

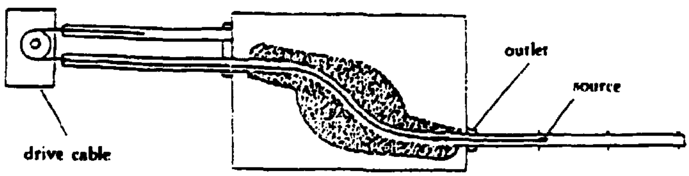
Iradium source radiographic examination equipment can be seperated into 3 main parts.

Main unit—also called as container, with iron casing, internal protection sleeve made of depleted uranium and S-shaped storage channel. (Fig. 1)

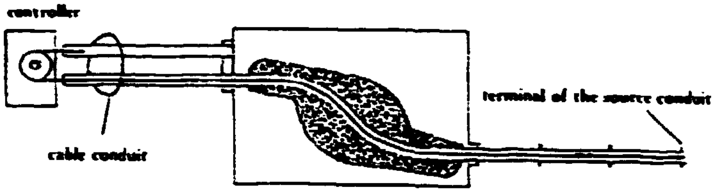
Source conduit—flexible metallic conduit with plastic coat seperated into 3 ×2.1 mm long sections, which may be used seperately or as a whole, but the section with terminal must be used every time. The terminal is as Fig. 2, the source is placed in it for exposure at time of radiography.



A. Source at storage position



B. During process of taking back the source



C. Source at operation position (shooting)

Fig. 1 Operation process of γ-ray detection device

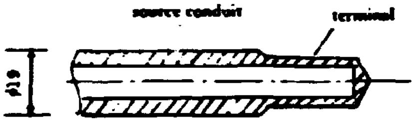


Fig. 2 Terminal of source conduit

Drive cable and controller—flexible steel drive cable whose end can be connected with source connector. By using the handle of the controller, the gear inside the controller moves the drive cable back and forth.

The operation sequence of the equipment is as follows:

(1) The source is placed inside the shield which is at the middle of the S-channel. The radioactivity leaked out of the container is lowest at this time. It shall comply with relevant regulations. In Fig. 1 A, the drive cable is already connected with the source.

(2) Use the handle to move the source forward from the outlet into the source conduit. Fig. 1 B.

(3) The source moves forward along the conduit until the end of the conduit, which is the location of source for exposure. Fig. 1 C.

(4) After exposure, use the handle to move the source backward along the conduit to the same state as in Fig. 1 B.

(5) Keep moving the source to the shield, the same state as in Fig. 1 A.

3 RADIOGRAPHIC EXAMINATION METHODS

(1) For $\phi \geqslant 89$ mm pipes, double wall radiographic examination procedure

is adopted. ϕ3×2 mm or ϕ3×1 mm sources are used according to geometrical unsharpness requirements. Sources are located on the surface of the weld opposite the films.

For each weld, 4~5 films are exposed in accordance with the pipe diameter and its wall thickness.

(2) For ϕ<89 mm pipes, double wall superimposed image procedure is adopted. The source-to-film distance is no less than 8 times of the weld diameter. The size of the source is no less than ϕ3×2 mm to ensure the required geometrical unsharpness. GB 5618-85 linear penetrameter is used and is placed on source side. For each weld, 3 exposures are required at 120° (or 60°).

(3) Socket joints

Fig. 3 shows this kind of joint. Double wall superimposed image exposure is adopted (Fig. 3). The distance between the source and the film is no less than 10 times of the diameter of the socket pipe. 2 exposures are required at 90° apart for each weld.

(4) Set-in branch pipes

Radiographic examination with internal source is adopted. The distance between the source and the film is calcutlated according to geometrical unsharpness requirements. The required geometrical unsharpness is no greater than 0.6 mm (for ϕ<250 mm) or 0.9 mm (for ϕ≥250 mm).

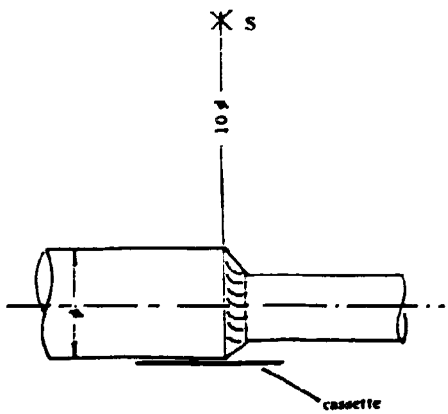


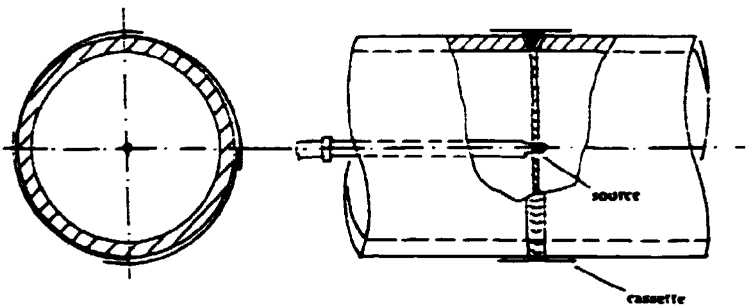
Fig. 3 Shooting of socket joint

(5) Set-on branch pipes

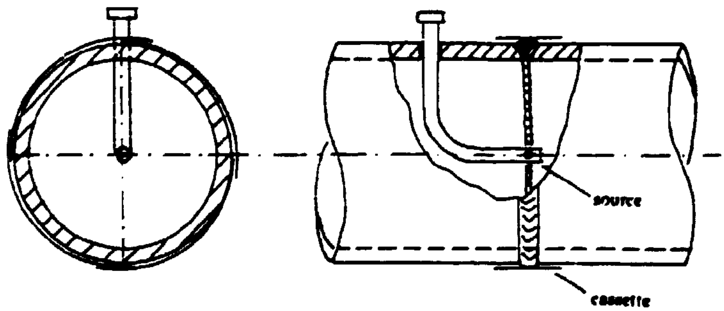
Radiographic examination with external source is adopted. The distance betweer ..e source and the film is calculated on basis of 0.3 mm geometrical unsharpness.

(6) For butt welds on pipes, if it is possible to place the source inside, single wall panoramic exposure with film outside and source inside is adopted. There are three methods to place the source inside:

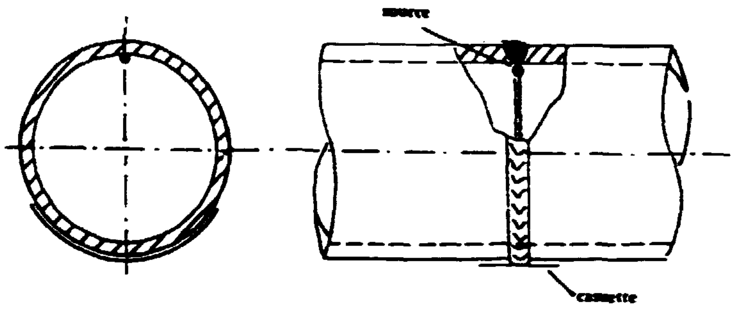
It is placed inside through the pipe, as in Fig. 4 A. If this is not possible, holes for radiographic examination may be drilled on the wall of the pipe, the source is then put at the center of the pipe through it, as in Fig. 4 B. The source might also be eccentric instead of being centered in the pipe, as in Fig. 4 C.



A. Placing source through pipe wall



B. Placing source through pipe wall



C. Offset source

Fig. 4 Eccentric source exposure

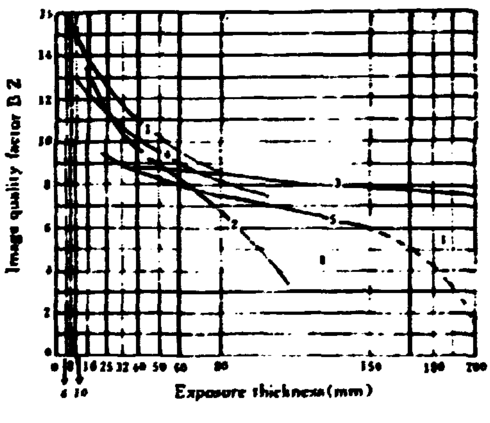


Fig. 5 Image quality factor obtained through various shooting methods & minimum requirements on image quality (Class I and II image quality)

1. X-ray <300 kV, lead intensifying screen, fine particle film
2. X-ray <300 kV, high ampplifying halogen intensifying screen
3. microtron lead intensifying screen, fine particle film
4. ^{192}Ir, lead intensifying screen, fine particle film
5. ^{60}Co, lead intensifying screen, fine particle film

I. minimum requirement of Class I BZ

II. minimum requirement of Glass II BZ

4 SENSITIVITY OF RADIOGRAPHIC EXAMINATION

The most essential criteria for assessment of the radiograph quality is the sensitivity of radiographic examination. Sensitivity is an indicator of radiograph quality (including quality of darkroom processing), and has no direct link with the dimension of the slightest defect possibly detected.

Generally speaking, the sensitivity of γ-ray radiographic examination is less than that of X-ray examination, especially when shooting workpieces with light thickness (Fig. 5). The lower limit of γ-ray exposure thickness is defined in standards of many countries in order to avoid the decrease of sensitivity caused by γ-ray exposure on workpieces of light thickness. Table 2 is the minimum exposure thickness of ^{192}Ir. However, if the applied radiography justifies the radiographic sensitivity, the thickness limit can still be lowered. In standards of some countries, there is not any clear provisions on it at all as long as the requirements of film quality is met.

Table 2 Minimum exposure thickness with ^{192}Ir source

standards		minimum exposure thickness, mm
IS/R 1106		10
BS 2600 Part 1, 2		10
ASME Sec. V		19
DIN 54111-1	class A	20
	class B	40
GB 3323-87	class A	20
	class AB	30
	class B	40

The requirements at Daya Bay Power Plant for sensitivity of γ-ray radiography as per RCCM are as follows (Table 3).

Table 3 Sensitivity of γ-ray radiography at Daya Bay Power Plant

thickness T mm	AFNOR penetrameter			GB 5618-85 penetrameter		
	source side	film side	I. Q. I.	source side	film side	I. Q. I.
$T \leq 3$	0.25		H3	0.20	0.20	10/16
$3 < T \leq 6$	0.32		H3	0.20	0.20	10/16
$6 < T \leq 10$	0.40	0.40	HA	0.20	0.20	10/16
$10 < T \leq 16$	0.50	0.50	HA	0.25	0.25	10/16
$16 < T \leq 25$	0.63	0.63	HA	0.32	0.32	10/16
$25 < T \leq 32$	0.8	0.63	HA	0.40	0.32	10/16
$32 < T \leq 40$	1.00	0.80	HA	0.50	0.40	6/12
$40 < T \leq 80$	1.25	1.00	HB	0.63	0.50	6/12

There is no restriction of minimum exposure thickness for γ-ray examination in RCC-M, but we can see from Table 3 that in RCC-M the requirement of exposure sensitivity on thin welds is lower than that in other standards of the same kind. In the case of exposure thickness$>$10 mm, the sensitivity is about 2% or $<$2%. This is the same as some other standards such as JISZ 3140-1968, but is higher than ISO 2504-1963 (Table 4).

The requirements in Table 3 can always be met in actual practice, and the sensitivity of most films are higher than that in Table 3. For instance, a line of 0.125 mm of I.Q.I on the film of circular butt weld on ϕ88.9×3.05 mm pipe can be seen through double wall radiographic examination procedure. The exposure thickness (including weld reinforcement) of most pipe welds is no less than 10 mm, and its sensitivity is no less than 2%, this is also the same as in other similar standards.

Table 4 Requirements of Sensitivity in ISO 2504-1963

radiation penetration thickness of ^{192}Ir, mm	hole ϕ mm	wire ϕ mm
$10<T\leqslant16$	0.8	0.32
$16<T\leqslant25$	0.8	0.4
$25<T\leqslant32$	1.0	0.5
$32<T\leqslant40$	1.0	0.5
$40<T\leqslant60$	1.25	0.63
$60<T\leqslant80$	1.25	0.8

5 CONCLUSION

The main reason of low sensitivity of γ-ray radiography is that γ-rays have higher energy than X-rays. For example, ^{192}Ir is equivalent to the X-rays of 300~800 kV (see Table 1), therefore, the contrast on film is smaller. In addition, for certain films the intrinsic unsharpness of γ-rays is greater than that of X-rays.

The above condition can be improved if certain measures are taken at the time of exposure. The proper application of measures, such as application of fine or super fine particle higher contrast films, small-sized sources, adequate filter, intensifying screen and exposure arrangement, can improve the contrast and definition of the films, and thus may improve its sensitivity.

When sensitivity meets the requirements in regulations, γ-ray radiography has many advantages. It is worthwile to extend its application.

——γ-ray radiographic devices are light in weight and small in size (see

Table 5). It is easy to handle at construction site. Normally a group with two workers can perform the job while the X-ray machine needs 3~4 people to operate. And welds of special location on site can not be examined due to inaccessiblility of X-ray machine. However, γ-ray detector can be easily put into working position because of its small dimension, particularly, the diameter of the terminal of the source conduit is no greater than 20 mm. It can also be easily moved away after each shooting, there is hardly any inaccessible position.

X-ray machine needs to be cooled by circulation water. There must be water on site. Sometimes water pipes have to be laid specially for this purpose. Radiographic examination spots are spread all over the site, it is very complicate to lay pipes for this purpose. When there is no water on site, the radiographic examination group has to bring with pumps, water tubes and buckets with them to realise cooling of the X-ray machine with water. Furthermore, there must be an interval between two shootings to avoid overheating of the machine. Continuous shooting is not allowed. Duration of preheating before shooting is also rather long. All these affect the efficiency. But they do not exist in γ-ray radiographic examination device.

Table 5 Comparison between several types of X-ray machines and γ-ray machine

equipment		weight, kg	size, mm	insulation medium
γ-ray detector Amersham	main unit	24	330×133×248	
	controller	11	533×305×168	
X-ray detector xxQ-2505	head	36	ϕ315×744	gas (SF6)
	controller	15	330×380×150	
X-ray detector xx-3005	head	95	865×480×310	oil
	controller	22	385×305×179	
X-ray detector Ereso 300/5L	head	58	ϕ280×1000	oil
X-ray detector Ereso 200/5L	head	36	555×215×320	oil

——X-ray machine requires adequate power supply. Work can not be proceeded once power is cut due to certain reason. Therefore, an electrician is required to be on duty to solve any power supply problem.

——Because of the small size of γ-ray detection devices, panoramic exposure with centered source can be easily realized not only to obtain good quality radiograph but also to raise efficiency. For thick pipes with inaccessible internal wall, examination hole can be drilled beside the weld to place the source at the center of the pipe for single wall panoramic exposure (Fig. 4 B). For example, a ϕ355.6×31 mm pipe, if it is shooted by double wall radiographic examination procedure with a source of 1.85×10^{12} Bq and AGFA negatives, 46 minutes are needed for shooting one film, and one weld needs five shootings, altogether it takes 3 hours and 50 minutes. But if panoramic exposure with centered source is applied, it takes only 1.5 minutes to shoot the whole weld with one exposure. The difference of exposure time for one weld is more than 150 times.

——X-ray detector is a precision electronic instrument with complex electrical structure, failure can easily occur during site works so that frequent maintenance on the equipment is necessary. Maintenance period is sometimes long and maintenance cost is high. γ-ray detection devices are fully mechanically connected, and simply structured. Failure seldom occurs; common failure can be easily eliminated.

——It is considered that the application of γ-ray radiographic examination is indeed necessary to be extended in our future nuclear power plant projects according to the actual application of γ-ray radiographic examination at Daya Bay and the above analysis.

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