

COMPUTED RADIOGRAPHY PLUS RHYTHM SOFTWARE PLATFORM FOR FAC INSPECTION IN NUCLEAR SECONDARY CIRCUIT

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This paper will cover determining and ensuring proper follow up of Flow Accelerated Corrosion (FAC) in secondary circuit of Nuclear Power Plant using Computed Radiography. What are the influent parameters on the pipes and weld wall thickness reading. How precise and reliable are the data and how best to record and archive. One challenge always faced with inspections is how to share the data and gain expert opinion when the expert is on-site; with digital inspection data and the use of software tools this challenge can be overcome. As you begin to collect all the inspection data the true "power of the data" can be unfolded. Archiving of digital inspection data provides the foundation of asset management, allowing you to look at trends over time throughout inspection results done in one plant or multiple locations around the world.

Introduction

This document describes the process and results of tests performed through Computed Radiography technic (CR) for the detection and sizing of thickness losses in weld roots areas. The tests were performed according to a pre-established programme including a phase of testing on standard blocks and tubes and a phase of testing on components with real defects.

Description of Problem.

On pipes in the machine rooms of our power stations, the particular sensitivity of welds to corrosion-erosion was brought up during the Technical Review on "corrosion/erosion" at the end of 2004, following up the MIHAMA accident in Japan. A report on the cases of weld degradation occurring in the EDF facilities and a major programme of expertise on removed parts containing affected welds has been performed by the EDF laboratory (CEIDRE) in 2005 and 2006.

This expertise work reveals cases of degradation at the root of the weld and/or near the roots. The form of such degradation is closely linked to the chrome content of the deposited weld metal and also to the chrome content of the base metal in the adjacent components.

Research into this degradation can be carried out using several non-destructive examination methods including Computed Radiography.

Examination using Computed Radiography.

Computed Radiography (CR) is a non-destructive examination technic based on same radiation principles as conventional radiography but using a phosphor screen also called phosphor plate instead of a silver film as used in conventional radiography.

Screen principles are based on the properties of phosphor molecules to capture energy (latent image) when exposed to a flux of X' or gamma photons. This is the photo-stimulation phase. This generates luminance falling within the visible spectrum. After exposure, the screen is "read" by

scanning with a high-resolution laser beam to stimulate the trapped electrons. The number of light photons measured is proportional to the number of trapped electrons which is proportional to the number of X' or gamma photons which have interacted with the screen. The level of energy is measured and amplified through a photo multiplier, then digitised and stored as data tags in the image file, a DICONDE file. Because of the proportional nature of these physical mechanisms, the characteristic curve of the photo-stimulated screens is a linear straight line, unlike that of a silver film which is shaped like an S'. This characteristic explains in particular the considerable latitude in exposure times

Screens are re usable after being erased by an intense source of light bringing phosphor molecules at their initial energy level.

After the digitizing of the image, the operator uses measurement software tools capable of improving the contrast, zooming, measuring the thickness etc. The digitized images are saved in their original raw form and all measurements and modifications of the images are saved as layers or presentation states, keeping the integrity of the raw image but allowing multiple views to be created. This is a key portion of the DICONDE file standard.

Essentially, DICONDE is a dictionary that describes all the necessary syntax, attributes and data elements to allow users to acquire, store, archive, transmit and receive image data in a way that is universally compatible. It is a system that allows images to be saved with its meta-data. All the technique information and information on location, date and inspector is saved with the image. Such information can then be included in any report generated, and since the metadata is stored with the image, it means that database searches can be carried out on a variety of criteria to search across modalities or points in time for the same asset.

Moreover, DICONDE images can be included on a disk with a standard DICONDE viewer, which allows them to be displayed on any standard PC.

Reviewing, Measuring, Archiving

Rhythm, a DICONDE based software data management platform that can assist inspectors in improving dramatically the communications through the inspection process (i.e. from pre- to post-inspection stages), perform on-going asset management and evaluation thru the life of the assets independent of its origins (i.e. modality source) as well as extend knowledge with users like experts or customers who are not on a DICONDE network, enabling you to bring in the data to the experts instead of taking the experts to the data. The FAC inspection for nuclear inspection is a perfect application to highlight the strengths of Rhythm. Key to the inspection is collecting all the pertinent parameters during the Acquisition phase and then transmitting these along with the images to the inspector for review. As with all inspections; data integrity is key and Rhythm ensures that one will always be able to view the raw image along with various views of the same image, capturing notes and measurements as layers within the image. Overtime as more inspection data is collected within Rhythm the facility will be able to drive more conclusions from the trending and analysis of the asset data over time.

Important note:

It is important to note that the use of the CR considerably reduces the exposure time and/or the source activity but in no case allows testing on greater thicknesses than conventional radiography. The penetration power of the 'X' or gamma rays depends on the energy of the rays and not on the activity of the source.

The CR application limit for thickness measurements is linked directly to the energy of the radiation source being used ('X' ray tubes, sources of Se, Ir or Co).

Validation Methodology

For the validation of the CR technique, a test programme has been drawn up. This programme consists in measuring thicknesses of test tubes and comparing the results obtained with real values. The determination of the precision of the method is carried out by tests on various test tubes, depending on the range of use. Supplemental tests on real components are then performed to check the test parameters on components with realistic defects and the limits of use.

Description of test tubes

Test tubes for demonstrating the performance of Computed Radiography testing are tubes with stepped thicknesses. To cover diameters and thicknesses that can be tested by Computed Radiography, 2 stepped tubes have been manufactured with an outside diameter of 220 and 150 mm (see diagrams in annex 1).

Tube 1 has an outside diameter of 150 mm and an overall length of 150 mm. This tube is machined on the inside and the outside to obtain 3 different thicknesses.

The internal diameters are, successively: 140, 142 and 146 mm. The length of each step is 50 mm. The step thicknesses are: 2, 4 and 5 mm.

Tube 2 has an outside diameter of 220 mm and a total length of 150 mm. The tube is machined on the inside and the outside to obtain 3 different thicknesses.

The internal diameters are, successively: 190, 200 and 210 mm. The height of each step is 50 mm. The step thicknesses are: 5, 10 and 15 mm.

Description of real components

Diagrams of the two components used are given in annex 3.

Component No. 1 has one end of a valve welded onto an expander, itself welded to a straight tube.

Component No 3 has an expander welded to a stainless steel flange.

Influencing parameters

To determine the measurement precision, we need to evaluate the influencing parameters. To measure the thickness by CR, the following parameters are taken into consideration in the tests:

- Detector - object distance
- Source – detector distance
- Resolution of detector
- Thickness of object
- Diameter of object
- Position of gauge
- Presence of heat insulation
- Presence of water

The size of the source can also be an influencing parameter but it is not taken into consideration during testing. The possible influence of the metallographic structure (consistent isotope / absorption capability), is not taken into consideration either because it is considered as negligible regarding the desired results. For the influencing parameters related to the equipment, the requirements of the EN 14785 standard are applied.

The influencing parameters are illustrated in the diagram of annex 2.

Detector - Object - Source distances

The distance from the detector to the object and to the source (cf diagrams in annexes 1 to 5) is an influencing parameter and is factored in during testing.

The Source – Object distance varies between the minimum firing position of 4 x the diameter of the object and 7 x the diameter of the object.

The ‘detector’ - object distance is varied between the position in contact with the object and in contact with the insulation. The thickness of the heat insulation used during testing is 100 mm.

Resolution of detector

The resolution or sensitivity of the detectors used is an influencing parameter. For these tests, 2 types of detectors are used. "Fast" detectors (type IPC2), and "high resolution" or slow detectors (type IPS) have been tried out during testing.

Calibration gauge

During the thickness measurements, a gauge is positioned visibly on the image. The position on the gauge varies depending on whether heat insulation is present or not. For all of the shots, the gauge is placed against the object or the insulation, in the same plane as the source.

Heat insulation

The presence of heat insulation is considered during the tests on the test tubes. The properties of the heat insulation used are identical to those used in the EDF facilities. The protective sheet metal is of aluminium.

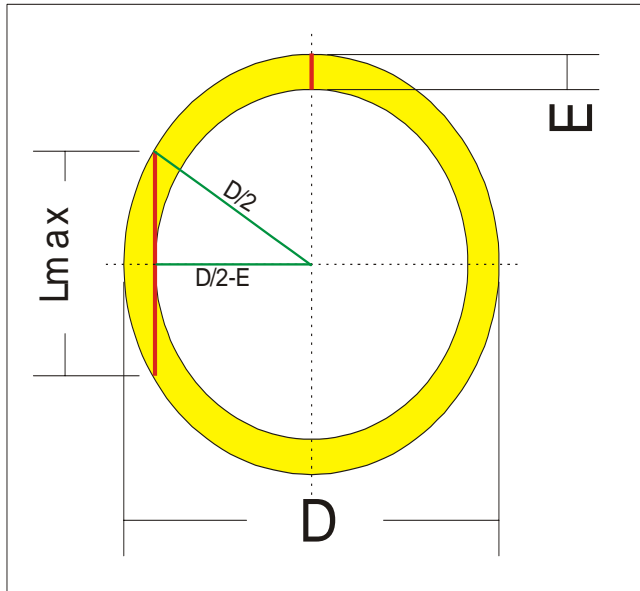
Water

The presence of water is considered in the tests by filling of component 1.

Geometry of parts to be tested

The diameter and thickness of the part to be tested influence the precision of the thickness measurement and are taken into account during testing by the use of a stepped test tube. The essential parameter for CR is the total length that the rays cover.

This parameter, known as L-max is determined as follows:



$$L_{\max} = 2 \times E \sqrt{\frac{D}{E} - 1}$$

Description of tests.

To demonstrate the performance of the CR method concerning the detection and sizing of faults due to a loss of thickness, two types of tests will be performed. The first tests will be performed on stepped test tubes and the second on removed components containing real defects.

The same tests were performed on the test tubes. For each tube, the exposure time is determined while allowing for the characteristics of the source, the thicknesses to be crossed, the various distances between the source, the object and the detector and the sensitivity and presence or absence of filters.

The tests are performed with the two types of detectors and in accordance with standard EN 14784-2. The various test configurations are indicated in the following table:

Configuration	Distance Screen to Object	Distance Source to Object Pipe OD 150 mm	Distance Source Object Pipe OD 220 mm	Source position	Calibration Gauge position	Heat Insulation (H.I.).
A	Contact	600	1100	Centred on object	Centred 5mm from object	No
B	Contact	900	1600	Centred on object	Centred 5mm from object	No
C	Contact	600	1100	Centred between gauge and object	Centred 5mm from object	No
D	Contact	900	1600	Centred between gauge and object	Centred 5mm from object	No
E	100 mm	600	1100	Centred on object	Centred 5mm from insulation	Yes

F	100 mm	900	1600	Centred on object	Centred 5mm from insulation	Yes
G	100 mm	600	1100	Centred between gauge and H.I.	Centred 5mm from insulation	Yes
H	100 mm	900	1600	Centred between gauge and H.I	Centred 5mm from insulation	Yes

Table 1: Configurations of shots on test tubes

For each of the test tubes, 16 shots were made, or a total of 32 shots on the test tubes.

For each shot, the thickness of the bank is determined by a system of acquisition and the results obtained are checked against the mechanical measurements on each stepped bank. Whenever possible, the thickness was measured on the right and the left side of the tube.

For the two real components, the shooting configurations are indicated in the following table.

Configuration	Distance Screen to Pipe	Distance Source to Pipe Component 1 Weld A	Distance Source to Pipe Component 1 Weld B	Distance Source to Pipe Component 2	Source position	Gauge position	Heat Insulation (H.I.)
A	Contact	700	900	650	Centred on object	Centred 5 mm from object	No
B	Contact	1200	1600	1600	Centred on object	Centred 5 mm from object	No
C	Contact	700	900	650	Centred between gauge and object	Centred 5 mm from object	No
D	Contact	1200	1600	1600	Centred between gauge and object	Centred 5 mm from object	No
E	100 mm	700	900	650	Centred on object	Centred 5mm from insulation	Yes
F	100 mm	1200	1600	1600	Centred on object	Centred 5mm from insulation	Yes
G	100 mm	700	900	650	Centred between gauge and H.I.	Centred 5mm from insulation	Yes
H	100 mm	1200	1600	1600	Centred between gauge and H.I.	Centred 5mm from insulation	Yes
A	Contact	700	900	/	Centred on object	Centred 5 mm from object	With water
B	Contact	1200	1600	/	Centred on object	Centred 5 mm from object	With water

Table 2: Configurations of shots on real components

For each shot, results are analysed and the values of the thickness measurements made by Wall Thickness Measurement (WTM) Rhythm tool are compared to those obtained by three-dimensional measurements.

Test implementation

Hardware and software below were implemented:

- Screens: IP C; IP C2 and IP S (IP C2 is the 2nd generation of IP C screens)*
- Scanners: CR50P and CR50XP*
- Software: Rhythm`*
- Gamma source: Ir¹⁹²
- Activity: 15Ci (555Gbq)
- Source size: 2x1 mm
- Calibration Gauges: 32mm and 30mm

*manufactured by GE Inspection Technologies

A level III radiographer as per the EN 473 standard supervised the tests.

A GE Inspection Technologies Engineer using Rhythm WTM tool carried out analysis of the results.

Determination of measurement uncertainty.

The uncertainty of the measurement by CR is determined solely by test results.

Measurements on real components are analysed to check the applicability of the technique on site.

Finally, uncertainty is expressed $I = \pm \sqrt{\frac{A^2}{3} + \sigma^2}$ with an enlargement factor of 1.

A = difference between the target value and the average measurements

σ = Standard deviation of the measurements.

I = Total uncertainty with $\sigma = 1$

There is a 68% "chance" that the measured quantity is included in a +/- I interval around the measurement result (normal law distribution).

With an enlargement factor of 2, meaning an uncertainty of +/- 2 x I, the probability is 95%.

With an enlargement factor of 3, meaning an uncertainty of +/- 3 x I, it is 99.7%.

Test results.

The measurements made on the tubes and components No.1 are indicated in annex 4. On the test tubes of 150 and 220 mm, 17 radiography shots were made, and on the 3 stepped tubes, 84 measurements were done.

The measurements made on component No. 1 are indicated in annex 4. On this component, 30 shots were carried out and several hundreds of measurements were made.

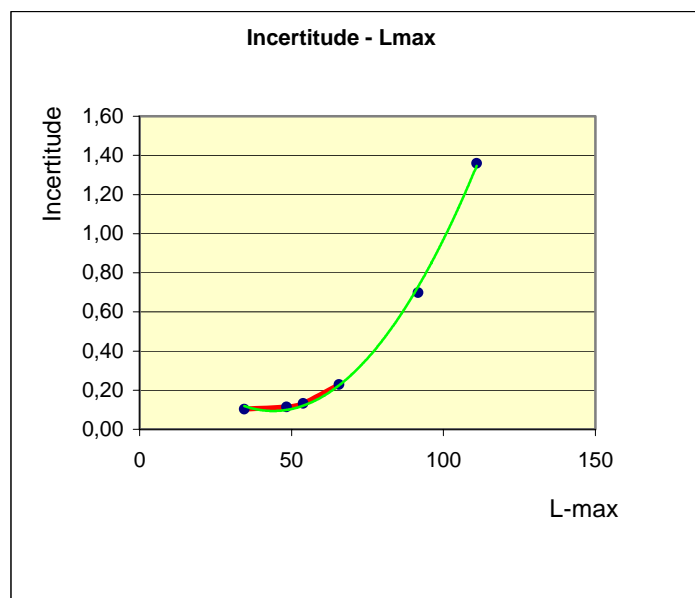
Test Tube Analysis.

Analysis of the results obtained on the test tubes in the test configurations indicated in § 20 lead to the following observations:

- The firing configuration (A to H) had little or no major influence on the measurement precision.
- The resolution of the detector has no major influence on the uncertainty.
- Firing in a centred position generates smaller errors than offset firing (remote point measurement)
- The uncertainty is linked directly with the value of L-max.
- The presence of the heat insulation does not interfere with the measuring process.
- The uncertainty of the measurements calculated according to the formula indicated in § 22, and all the configurations considered together, is indicated in the following table:

Dia. (mm)	Thickness (mm)	L-max (mm)	Qty of meas.	Avg. value (mm)	Std dev. (mm)	Min. dev. (mm)	Max. dev. (mm)	I (mm)
150	2	34	29	2.095	0.087	-0.03	0.34	0.10
150	4	48	29	4.02	0.115	0.17	0.28	0.12
150	5	54	29	5.03	0.13	-0.33	0.32	0.13
220	5	66	30	5.07	0.225	-0.28	0.84	0.23
220	8	82	*	*	*	*	*	*
220	10	92	30	10.22	0.69	-0.91	1.88	0.70
220	11	96	*	*	*	*	*	*
220	12	100	*	*	*	*	*	*
220	13	104	*	*	*	*	*	*
220	15	111	30	15.13	1.36	-2.49	3.74	1.36

* Tests not yet performed.



Real components Analysis

The results obtained with real components confirm those obtained with test tubes as regards uncertainties regarding the crossed length "L-max".

The graph of annex 10 depicts the error tendency curve for all the configurations considered together (not including tests in water). The graph indicates that the deviation between the metrological measurement and the measurement by CR increases with the increasing value of L-max. These results are consistent with the values obtained with the test tubes.

Note that it is extremely difficult to determine measurement uncertainties for real components because two measurements (CR and metrology) need to be compared and it is difficult to ensure their correspondence.

The tests also indicate that the measurement accuracy degrades as soon as we move more than 100 mm away from the source-positioning plane. Although this degradation has been observed, it is not estimated in detail.

Identification of limits

During a thickness test on a pipe, the following points must be checked:

Determination of length L-max. The L-max limit for tests with an Ir 192 source is approximately 95 mm. Beyond that value, the uncertainty becomes considerable (> 0.7 mm).

Degradation is not necessarily consistent on the diameter of the tested pipe. During inspection on site, 2 shots at 90° at the least need to be performed to evaluate the thickness along the 4 generating lines. The images also need to be analysed on greyscales to detect any other affected areas. Other shots may be necessary to make measurements in all of the affected areas.

Thickness measurements can be made with the precision announced in §24 in a zone of ± 100 mm on either side of the firing plane. Outside this zone, we recommend taking complementary shots.

Conclusion about CR

The test results reveal that thickness testing using the CR technique is possible in the configurations indicated by the EN 14785 standard.

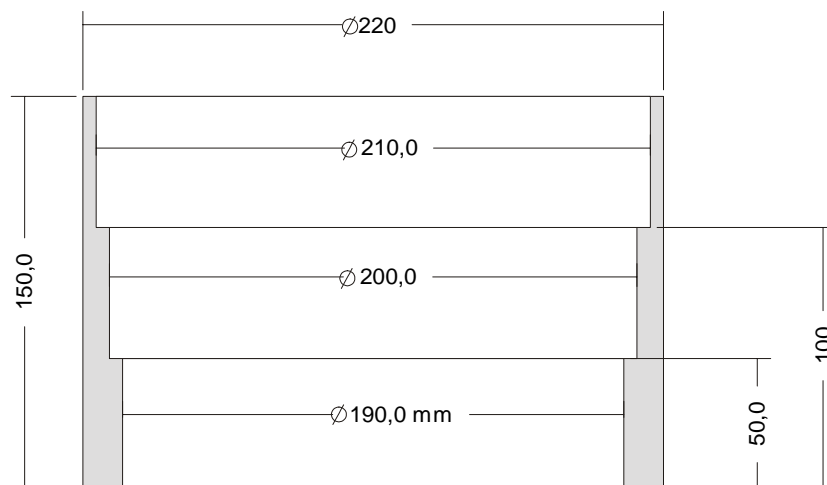
The essential parameter to be controlled for checks using this technique is the overall length of the material through which the rays pass. This length, known as "L-max" should be considered as an **essential parameter** making it possible to determine, on the one hand, the feasibility of the test compared to the diameter and thickness of the part to be tested according to the source being used and, on the other hand, the uncertainty of the measurement.

- The resolution of the detector has no major influence on the quality of the measurements and the use of "fast" detectors is suitable for thickness measurements without any restrictions.
- The shooting configurations (see annexe 3) only have a minor influence on the measurement uncertainty. However, to optimise tests on site, shots must be performed (whenever possible) in the following configurations:
 - Distance from source to object equal to 4 to 7 times the diameter.

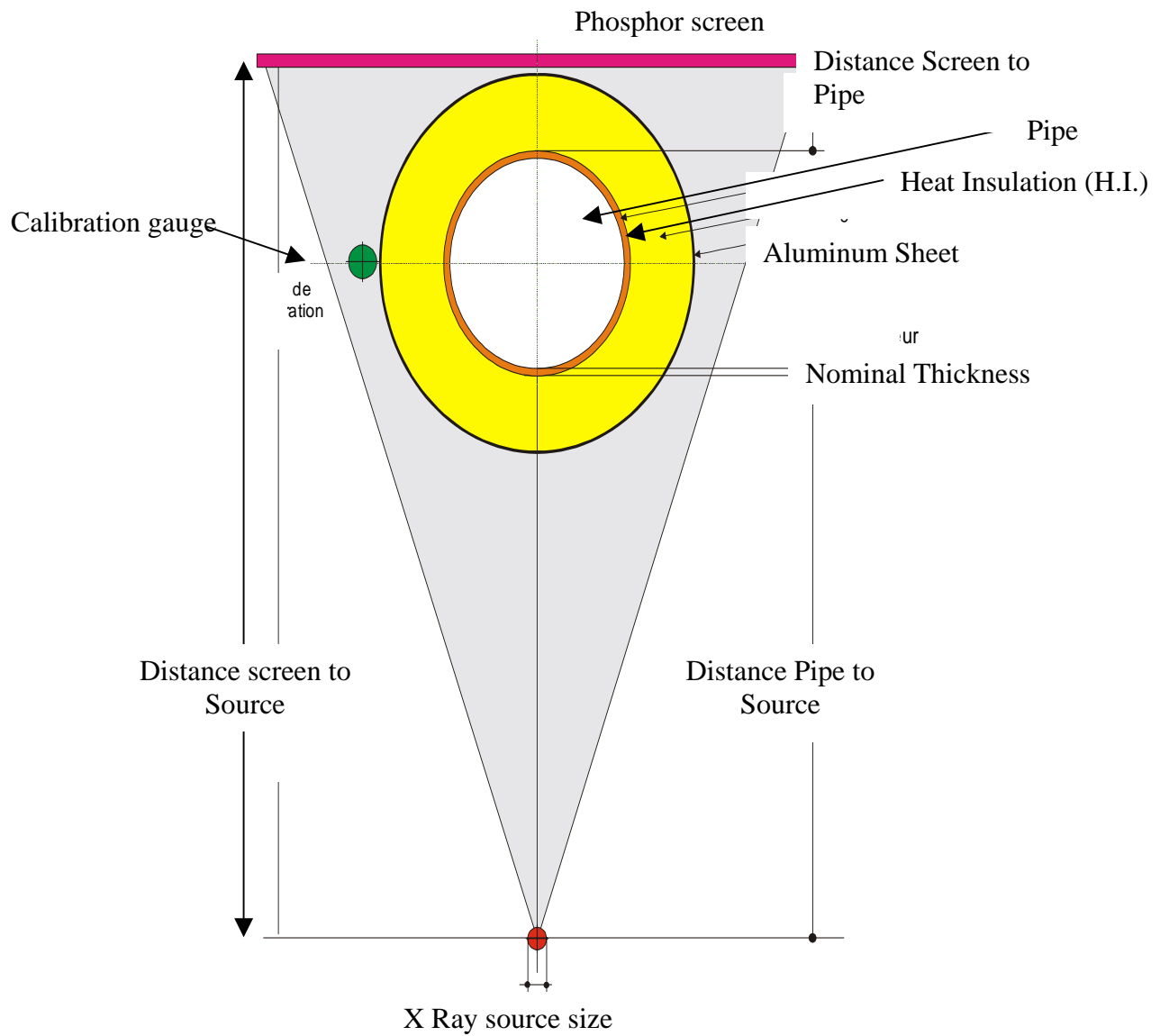
- Position of source centred with respect to the tube in order to be able to check the thickness on 2 walls at a time. This position will allow a decrease in the number of shots per element. (Configuration A, B, E and F)
- For each element, 2 shots must be fired at 90° at the least. If there is a doubt in a zone due to the interpretation of the grey scales, additional shots will need to be performed, for instance, at 45°.
- The presence or absence of heat insulation is not an obstacle to testing and its influence on the measurement uncertainty is negligible.
- The presence of water in the piping will not prevent testing but the influence on the measurement uncertainty and the limits requires complementary testing because of the energy absorbed by the water. The L-Max will decrease. Additional test will be performed on the test tubes filled with water.
- For smaller diameters (< 50mm), testing can be carried out using an x-ray tube (L-max depends on the power of the tube). The Table in annex 5 can be used for determining the source to be used with respect to L-max.
- The table in annex 6 indicates the measurement uncertainties obtained experimentally according to the values of L-max corresponding to each "diameter-thickness" couple. The Table is applicable for the use of an Ir192 source.

* Complementary tests are scheduled to better determine the limits of the method on heat insulated pipes and also pipe with water inside.

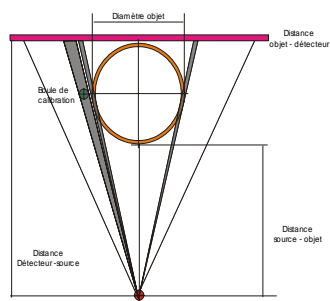
Annex 1: Test tubes



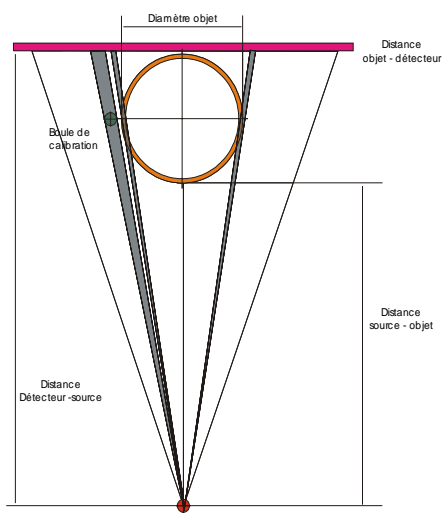
Annex 2 Influencing parameters



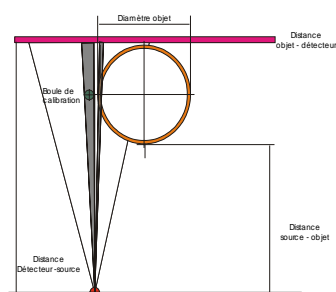
Annex 3: Shooting configurations



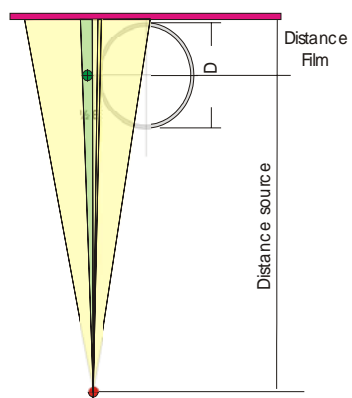
Configuration A



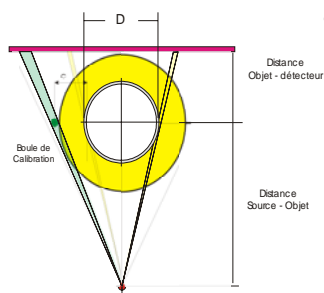
Configuration B



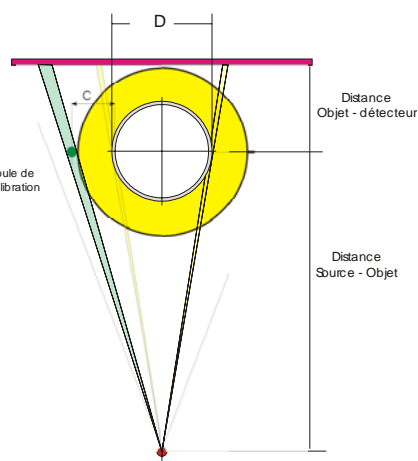
Configuration C



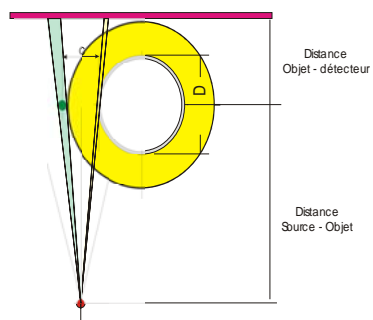
Configuration D



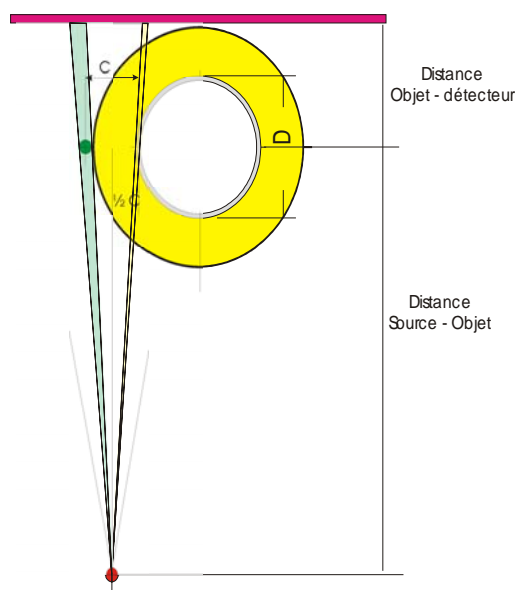
Configuration E



Configuration F

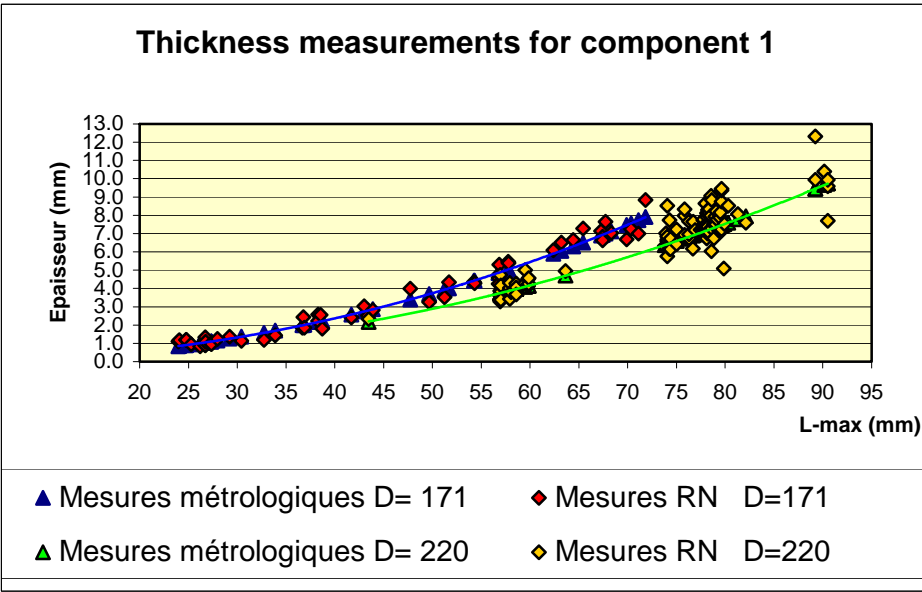
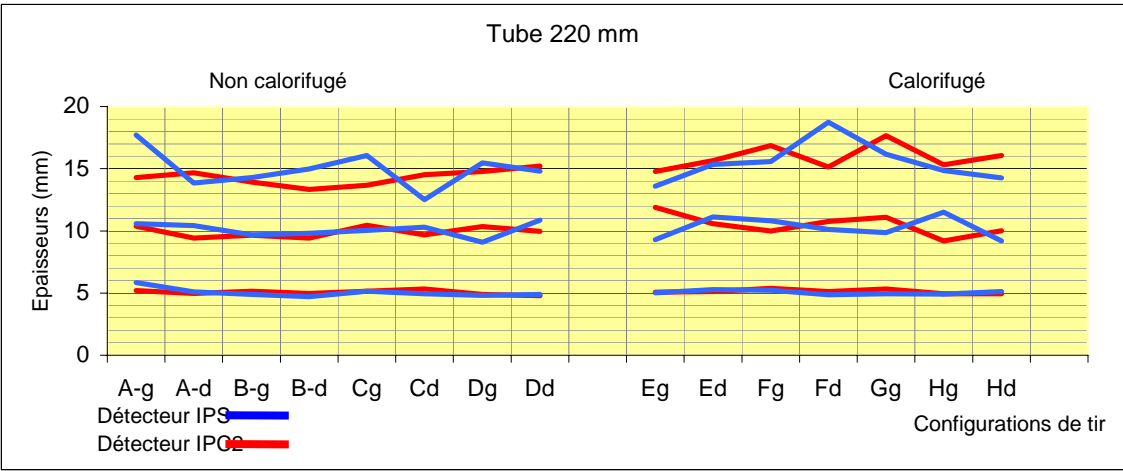
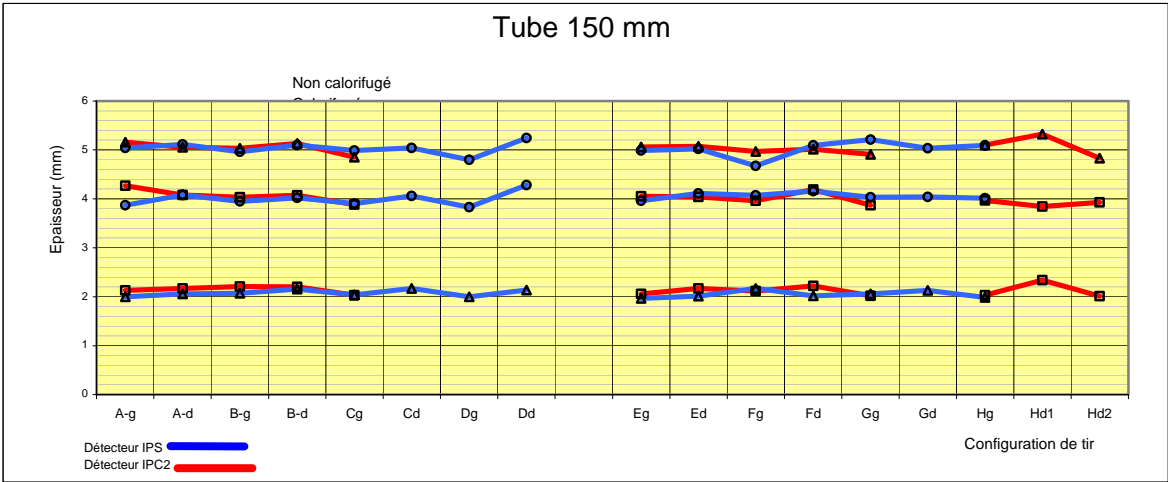


Configuration G



Configuration H

Annex 4 CR measurement results



Annex 5: Estimation of CR usability limits vs radiation sources

Source	Energy in kV	Limits L-max (mm)*	Estimated limits L-max
X-Ray	100	10	10
X-Ray	200	20	20
X-Ray	300	40	40
X-Ray	400	50	50
Selenium 75	~ 500	60	70
Iridium 192	~ 600	75	95**
Cobalt 60	~ 1400	120	145

D: Diameter at welds

* BAM tests

** DTG tests

Annex 6 / Application field of CR with Ir192 source.

Thickness (mm)

30.0	35	49	60	69	77	85	98	107	120	132	143	151	162	171	180	196	211	224	237	250
29.0	36	49	60	69	77	84	97	106	118	130	141	149	160	169	177	193	207	221	234	246
28.0	37	50	60	69	76	83	96	104	117	128	139	147	158	166	175	190	204	217	230	242
27.0	37	50	60	68	76	82	95	103	115	126	137	144	155	164	172	187	201	214	226	238
26.0	38	50	59	68	75	82	93	101	114	124	135	142	153	161	169	184	197	210	222	233
25.0	39	50	59	67	74	81	92	100	112	122	132	140	150	158	166	180	194	206	218	229
24.0	39	50	59	66	73	80	91	98	110	120	130	137	147	155	163	177	190	202	214	225
23.0	40	50	58	66	72	79	89	97	108	118	128	135	145	152	160	173	186	198	209	220
22.0	40	50	58	65	71	77	88	95	106	116	125	132	142	149	156	170	182	194	205	216
21.0	40	49	57	64	70	76	86	93	104	114	123	129	139	146	153	166	178	190	201	211
20.0	40	49	57	63	69	75	85	92	102	111	120	126	136	143	150	162	174	185	196	206
19.0	40	49	56	62	68	73	83	90	100	109	117	124	132	139	146	159	170	181	191	201
18.0	40	48	55	61	67	72	81	88	97	106	114	121	129	136	142	155	166	176	186	196
17.0	40	47	54	60	65	70	80	86	95	104	112	117	126	132	139	150	161	172	181	190
16.0	39	47	53	59	64	69	78	84	93	101	109	114	122	129	135	146	157	167	176	185
15.0	39	46	52	57	62	67	75	81	90	98	105	111	119	125	131	142	152	162	171	179
14.0	38	45	51	56	61	65	73	79	87	95	102	107	115	121	127	137	147	156	165	173
13.0	37	44	49	54	59	63	71	76	84	92	99	104	111	117	122	132	142	151	159	167
12.0	37	43	48	53	57	61	69	74	81	88	95	100	107	112	118	127	136	145	153	161
11.0	36	41	46	51	55	59	66	71	78	85	91	96	103	108	113	122	131	139	147	154
10.0	35	40	45	49	53	57	63	68	75	81	87	92	98	103	108	117	125	133	140	147
9.0	33	38	43	47	51	54	60	65	71	77	83	87	93	98	102	111	119	126	133	140
8.0	32	37	41	45	48	51	57	61	67	73	78	82	88	92	97	105	112	119	125	132
7.0	30	35	39	42	45	48	54	57	63	69	74	77	82	87	91	98	105	111	117	123
6.0	29	32	36	39	42	45	50	53	59	64	68	72	77	80	84	91	97	103	109	114
5.0	26	30	33	36	39	41	46	49	54	58	62	66	70	73	77	83	89	94	99	104
4.0	24	27	30	32	35	37	41	44	48	52	56	59	63	66	69	74	80	84	89	93
3.0	21	24	26	28	30	32	36	38	42	45	49	51	54	57	60	65	69	73	77	81
2.0	17	20	22	23	25	27	29	31	34	37	40	42	45	47	49	53	56	60	63	66
	40	50	60	70	80	90	110	125	150	175	200	220	250	275	300	350	400	450	500	550
	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.5	0.5	0.5	0.6	0.6	0.7	0.7	>0.7	>0.7	1.3	>1.3
	35.0	39.0	43.0	47.0	51.0	55.0	59.0	63.0	67.0	71.0	75.0	79.0	83.0	87.0	91.0	95.0	99.0	103.0	107.0	111.0

D = (mm)

Inc. = (mm)

Lmax (mm)