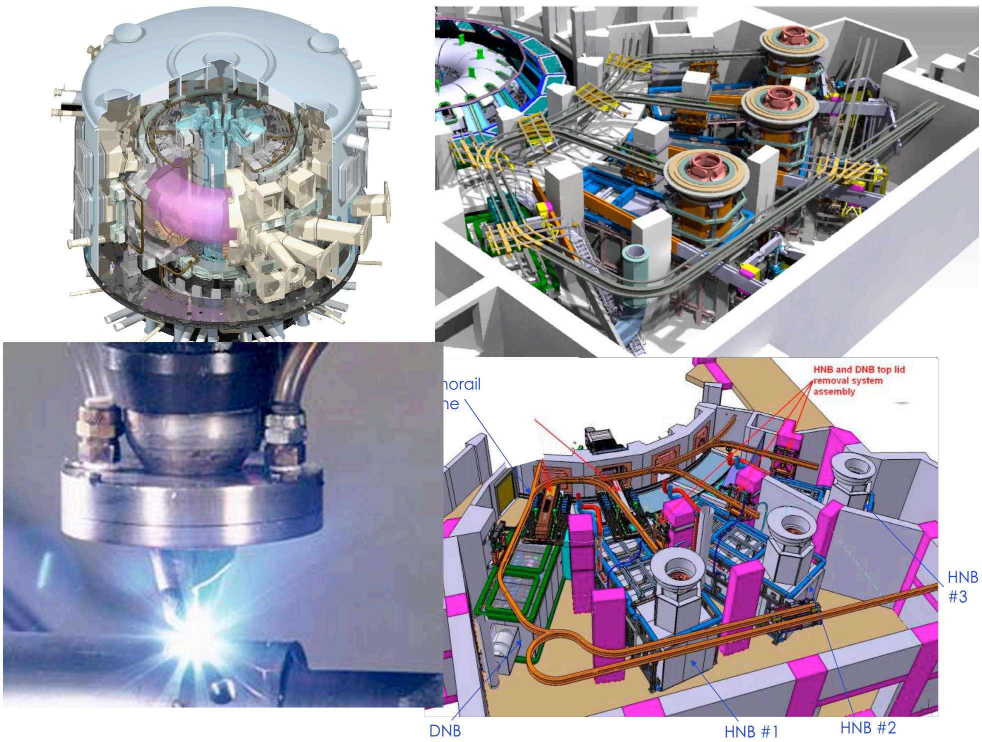
ITER Heating Neutral Beam Remote Handling System

Research & Development of Welding & Inspection technologies applicable for use in the ITER HNB Cell.



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Research & Development of Welding & Inspection technologies applicable for use in the ITER HNB Cell.

Table of Contents

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1 Introduction

The ITER tokamak will generate plasma temperatures in excess of 100 million degrees Celsius for up to one hour continuously. One of the key heating systems is the **Heating Neutral Beam** (HNB) which accelerates neutral particles into the plasma providing up to 15MW of energy per beamline.

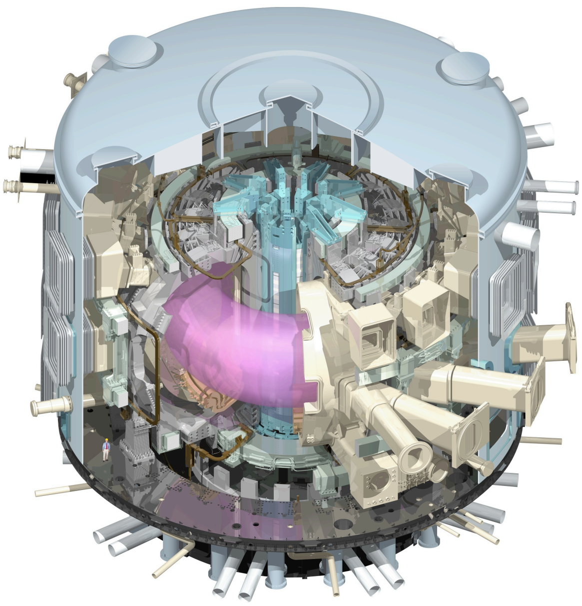


Figure 1 - ITER plasma (cutaway view)

Given the size of the plant, the background radiation and magnetic fields, the maintenance of the HNB components must be performed fully remotely by the Remote Handling System. This represents a greater challenge than anything experienced at JET and requires the adoption and development of new technologies to perform the necessary maintenance. Nearly every component in **Figure 2** has cooling pipes which must be welded and inspected upon installation.

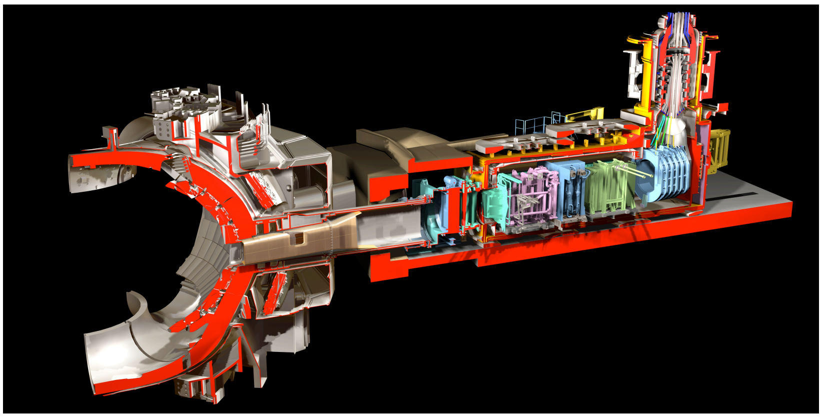


Figure 2 – Heating Neutral Beam Cell (cross section view)

The development of the NB Remote Handling System requires options for performing and inspecting welds in a remote and radioactive environment. The quality of the welds is of very high priority. For this reason, (an) NDT method(s) must be developed, to guarantee the required weld penetration and to reveal the eventual weld defects. It is unlikely that the processes used in JET can be applied in ITER so **a review of available and developing technologies for welding and Non-Destructive Testing (NDT) is required**.

2 Executive Summary

The two weld configurations investigated are **pipe welding and lip welding.** The first objective of this report is to provide a comparative study of the welding techniques and NDT techniques applicable to these two types of welds, based on literature review, CCFE experts, external experts and general internet search. The second objective is to propose a feasible inspection tool design of the selected NDT.

Indeed, during the maintenance operations, welded pipes and lip seals will be cut, to get access to the HNB components to maintain. As these joints will be re-welded and require a high quality because they are the ultra high vacuum boundaries, they must be inspected.

This report is only a first step to select the appropriate welding and NDT techniques. Consequently, further research and development must be made on the selected techniques to prove their feasibility.

To achieve the Welding/NDT techniques selection and come up with a feasible inspection tool design, four different subtasks were conducted:

1. Gather the expected environmental requirements during the ITER HNB remote handling and the expected NB welds dimensions.
2. Conducted a welding technique investigation, in three steps, to make a comparative study and select the best one according to the first subtask:
   - Welding techniques characteristics review
   - Literature review
   - Welding independent specialists opinions
3. Conducted a NDT technique investigation, in three steps, to select the one to investigate a feasible inspection tools design according to the first subtask:
   - NDT characteristics review
   - Literature review
   - NDT independent experts opinions
4. Conducted a more detail investigation about the NDT selected to come up with a feasible inspection tool design.

The subtask 1 has been conducted first as it gives the requirements that Welding/NDT must meet. The selection parameters of the subtask 2 and 3 are based on the requirements gathered in the subtask 1. Divided the investigation of the subtask 2 and 3 in three independent steps is a means to get independent information and consequently to have more confidence in the final results. The subtask 4 is the final step of this report and the inspection tool design proposed must be subjected to a research and development project to confirm and finalize it. These four subtasks are presented in the four Annex of this report.

Subtask 1

The subtask 1 is presented in the **ANNEX A** of this report.

Using CATIA models of the Neutral Beam (NB) Cell and NB components, the average space availability of the remote handling welding/NDT operations has been estimated. In the radioactive environment of the NB Cell man access is severely restricted, therefore all the maintenance operations are to be performed remotely. We have used the **SRD-*53-05*** (1) that gives the environmental conditions during the maintenance and the **ITER Remote Handling Code of Practice** (2) to find the standard HNB lip seals and pipes dimensions. CATIA models of the HNB lip seals were also used to determine precisely the space availability for the welding/inspection tools during the maintenance operations.

The two main restrictions that must be taken into account to make the selection of the welding technique and NDT are:

- the radioactive background of 1 Gy/h
- the space availability around the weld

The JET lip welded seals have never been inspected using a NDT (except by testing leaks). The main reason is the small weld dimension in a very constrained space. This will be exactly the same case for the ITER lip seals. To the HNB lip seals space availability challenging issue, the radioactive background provides several difficulties.

Subtask 2

The subtask 2 is presented in the ANNEX B of this report.

The TIG (Tungsten Inert Gas) welding technique has been used for the JET welding operations. This is a robust welding process that has the advantages to have been performed a lot of times on site. However, this last decade the YAG-laser welding technique has shown promising results. Even though, the ITER current welding technique is the TIG, the YAG-laser might be used as possible replacements if for any reason the TIG welding tool were unable to completely fulfil its function. Moreover, the YAG-laser is still at a research project and benefits from several improvements that could lead to be the first choice welding technique for ITER within a few years.

The TIG and YAG-laser welding processes are examined and compared, based on criteria such as complexity, reliability, welding parameters flexibility, ease of automation… To make this comparative study an investigation study was conducted in three steps by taking into account the results of the subtask 1:

- welding characteristics review
- literature review
- independent welding experts opinions

The comparative welding technique study results are summarized in a grid at the end of the **ANNEX B.**

As the space availability is more restricted for the HNB lip seals than pipes, the efforts were focused on the lip welding. This is why the literature review includes a welding technique study about lip seals. We have also reviewed a welding pipe study in a radioactive environment to determine the radioactive background impact.
Two independent welding experts were contacted:

- Ian Merrigan welding engineer Technology Welding Institute (TWI)
- Guillaume de Dinechin welding expert Atomic Energy Commission (CEA)

Mr Merrigan gave detailed information about the TIG and Mr de Dinechin about the YAG-laser and TIG welding techniques.

The conclusions of this comparative welding technique study are:

- the TIG welding technique is robust and benefits from decades of experience at the JET for pipes and lip seals welding
- the YAG-laser has more welding parameters and is more flexible
- it can also cut only by changing the welding parameters
- but it requires better alignment

However, the YAG-laser does not benefit from industrial applications and is still a research project. Even though is has a greater welding potential than TIG, at this stage the industrial and proved welding technique is the TIG. However, it is likely the YAG-laser will replace in several welding applications the TIG within a few years. The ITER first maintenance operation after being in use is not planned before at least a decade or more. At this time the YAG-laser might be the welding technique to use.

Subtask 3

The subtask 3 is presented in the **ANNEX C** of this report.

The Radiographic Testing (RT) was the preferred volumetric NDT performed at JET when it was possible to inspect the weld. However, the lip seals were not inspected with a NDT because of the small space availability. However, the ITER project requires a volumetric NDT to inspect the HNB welds during the maintenance. The two main limitations determined in the subtask 1 are:

- the space availability around the weld and its dimensions
- the radioactive background of 1 Gy/h

It is unlikely that RT used at JET can be performed in a radioactive background due to "fogging" to inspect the HNB lip welded seals. That is why we need to consider other NDT such as Ultrasonic Testing (UT), Eddy Current Testing (ECT), Visual Testing (VT), Leak Testing (LT), Liquid Penetrant Testing (LPT)…
These NDT are examined and compared based on criteria such as overall applicability to the HNB welded pipes and lip welded seals, ease of automation, resistance to the radioactive background, inspection tools dimensions, kind and size of defects detected, reliability etc.
As in subtask 2 a comparative NDT study has been made in three steps:

- NDT characteristics review
- Literature review
- NDT independent experts opinions

The comparative NDT study results are summarised in a grid at the end of **ANNEX C**.

The NDT characteristics review details the basic physics principles to understand how each NDT works and consequently, enables to determine what parameters (such as the available space, the radioactive background, the temperature etc) have an effect on the defects detection. It will lead us to an estimate overall applicability to both HNB weld types and the main limitations to investigate for each NDT.

The literature review and the NDT experts opinions are the data for the investigations of each NDT limitations due to the results of subtask 1.

We have investigated as much as possibly NDT literature applied to weld in an environment similar to the HNB during the maintenance in order to respect the main limitations determined in subtask 1. However, these mains constraints such as the radioactive background and the small space availability are not common and very particular to ITER. Consequently, most of the research articles that have been found do not meet all these requirements and the results must not be transposed directly.

Several NDT independent experts from companies and research institute have been contacted to get a current state of knowledge of industrial and research NDT applications. These opinions have been the most helpful because NDT specialists could answer directly about the overall applicability for each NDT to the both HNB weld type considering the constraints determined in subtask 1.

This NDT investigation in three steps allowed crossing each independent information from each step to get the most confidence in the final results. Finally, the Eddy Current Testing (ECT) has been selected for the next part of this study.

Indeed, the EC probes are resistant to the HNB radioactive background and have small dimensions that enable to use them in the very constrained space of the HNB lip seals. These capacities enable the ECT to meet the constraints of the subtask 1. But the ITER project requires a volumetric NDT and the ECT is said to be a surface inspection technique. This is the case but in fact the ECT can detect defect up to the standard EC depth of penetration. In our case the weld is made of austenitic stainless steel, by choosing a EC probe frequency of 20kHz, such probes exist, the EC probes can easily detect subsurface defects in the HNB welds (HNB welds dimensions are specified in the subtask 1). Moreover, the EC technology is very flexible and it is possible to develop specific EC probes adaptable to the weld geometry.

Subtask 4

The subtask 4 is presented in the **ANNEX D** of this report.

The ECT has been selected for further investigation to come up with a feasible inspection tool design for the HNB lip seals. In this part a more details investigation has been conducted about the EC probes technology to get an idea of the EC probes dimensions and geometry. A literature review about the EC probes technology has been made and experts on the subject have been contacted. Two of them have provided the necessary information to come up with confidence on a feasible EC inspection tools designed:

- Daniel Chauveau NDT experts at Institut de Soudure Industrie (French Welding Institute)
- Jean Marc Decitre NDT experts at the CEA LIST

The design adopted for the EC inspection tools is shown in subtask 4 and was made using CATIA models. This is a multi-elements EC flexible probe etched on kapton adaptable to the HNB lip welded seal. The carrying tools are the same as for the cutting/welding tools and consequently the EC probe is linked to it. The inspection and carrying tools are entirely automated and meet the ITER technical requirements.

However, this is only a feasible EC inspection tool design and the reader must bear in mind that it must be confirmed with Research and Development projects. With all the information I have at this stage of the ITER HNB project, this is the inspection tool that meets the most of the HNB maintenance requirements. With new developments and R&D it is likely to change within a few years.

3 Future Activities

At this stage of the ITER project the TIG welding process has been selected as the first remote welding technique. However, as shown in the ANNEX B of this report other welding technique such as the YAG-laser could be considered to replace it within a few years. An R&D project about the YAG-laser for the cutting and welding HNB operations should be considered because of its great potential.

Concerning the NDT for use in the HNB, the ECT has been selected and a feasible EC inspection tools designed proposed. However, a complete R&D about the ECT must be done to come up with a prototype and make tests on mock-up to confirm the selection or not of the ECT as a volumetric HNB welds inspection.

In addition, the other NDT must be considered in R&D projects because of the possibility to develop new capacities to overcome the HNB maintenance constrained details in the subtask 1.

4 References

(1)	**SRD-53-05 (Neutral Beam Remote Handling System)** 29 Oct 2009/2.0/ APPROVED
(2)	**ITER Remote Handling Code of Practice** 22 Dec 2009/1.2/APPROVED

ANNEX A
Neutral Beam Remote Handling Requirements

Contents

1. Introduction

The temperatures inside the ITER Tokamak must reach 150 million° Celsius—or ten times the temperature at the core of the Sun—in order for the gas in the vacuum chamber to reach the plasma state and for the fusion reaction to occur. The hot plasma must then be sustained at these extreme temperatures in a controlled way in order to extract energy.

The ITER Tokamak will rely on three sources of external heating that work in concert to provide the input heating power of 50 MW required to bring the plasma to the temperature necessary for fusion. These are neutral beam injection and two sources of high-frequency electromagnetic waves.

Neutral Beam Injectors are used to shoot uncharged high-energy particles into the plasma where, by way of collision, they transfer their energy to the plasma particles.

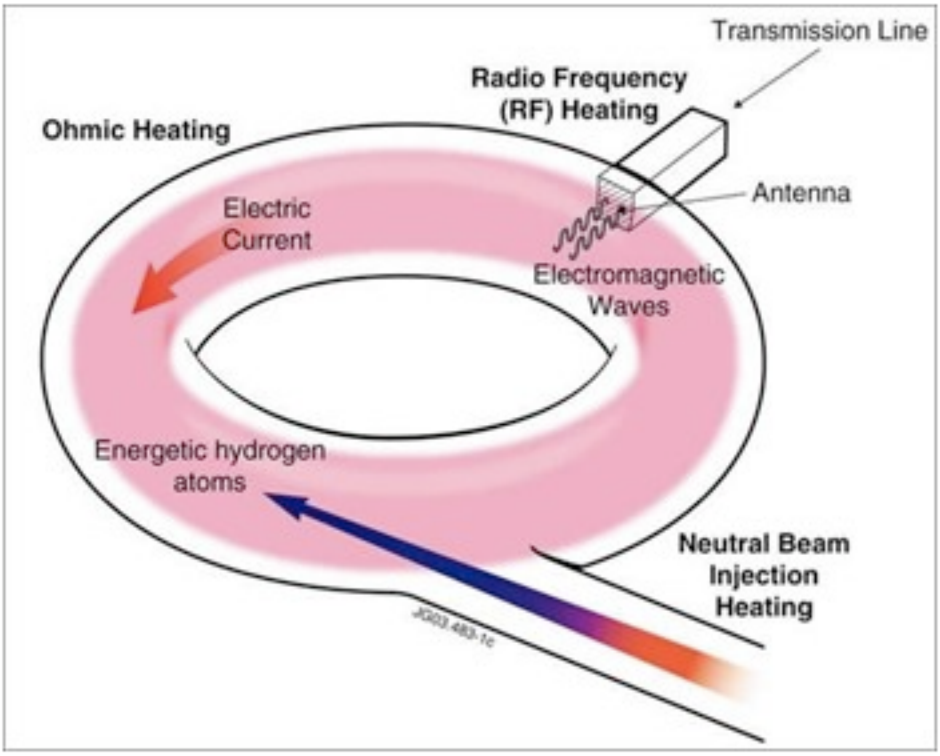


Figure 3 - A Neutral Beam Injector and two types of high-frequency electromagnetic waves will help bring the plasma to temperatures exceeding 150 million°C.

Given the size of the plant, the background radiation and magnetic fields, the maintenance of the HNB components must be performed fully remotely by the Remote Handling System. This represents a greater challenge than anything experienced at JET and requires the adoption and development of new technologies to perform the necessary maintenance.

2. Purpose and scope

The objective is to check the remote handling requirements for the welding and NDT operations during the ITER HNB maintenance. To achieve this objective we will divide the work into two steps:

- describe in detail the HNB environmental conditions during the maintenance
- describe in details the HNB joints characteristics

The HNB joints are composed of pipes joints and lip seals joints. We have found the HNB environmental conditions in the ***SRD-23-05 (Neutral Beam Remote Handling System)*** (1) and the standard HNB lip seals and pipes dimensions in the **ITER Remote Handling Code of Practice** (2). CATIA models of the HNB lip seals have also been used do determine precisely the space availability around the weld for the welding/inspection tools during the maintenance operations.

These features are critical for the next parts of the project as they will be some of the criteria selection for the welding technique and NDT comparative study.

3. Description of the Heating Neutral Beam Cells

Before injection, Deuterium atoms must be accelerated outside of the Tokamak to a kinetic energy of 1 Mega electron Volt (MeV). Only atoms with a positive or a negative charge can be accelerated by electric field; for this, electrons must be removed from neutral atoms to create a positively-charged ion. The process must then be reversed before injection into the fusion plasma; otherwise the electrically-charged ion would be deflected by the magnetic field of the plasma cage. In Neutral Beam Injection systems, the ions pass through a cell containing gas where they recover their missing electron and can be injected as fast neutrals into the plasma.

The large plasma volume at ITER will impose new requirements on this proven method of injection: the particles will have to move three to four times faster than in previous systems in order to penetrate far enough into the plasma, and at these higher rates the positively-charged ions become difficult to neutralize. At ITER, for the first time, a negatively-charged ion source has been selected to circumvent this problem. Although the negative ions will be easier to neutralize, they will also be more challenging to create and to handle than positive ions. The additional electron that gives the ion its negative charge is only loosely bound, and consequently readily lost.

Three Neutral Beam Injectors are currently foreseen for ITER. A third Neutral Beam will be used for diagnostic purposes.
The **Figure 4** below shows the three Heating Neutral Beam Cells that accelerates the neutral particles into the plasma. The Diagnostic NB is smaller than the Heating NB Cell and its purpose is to make measurements of different parameters such as temperature of the plasma.

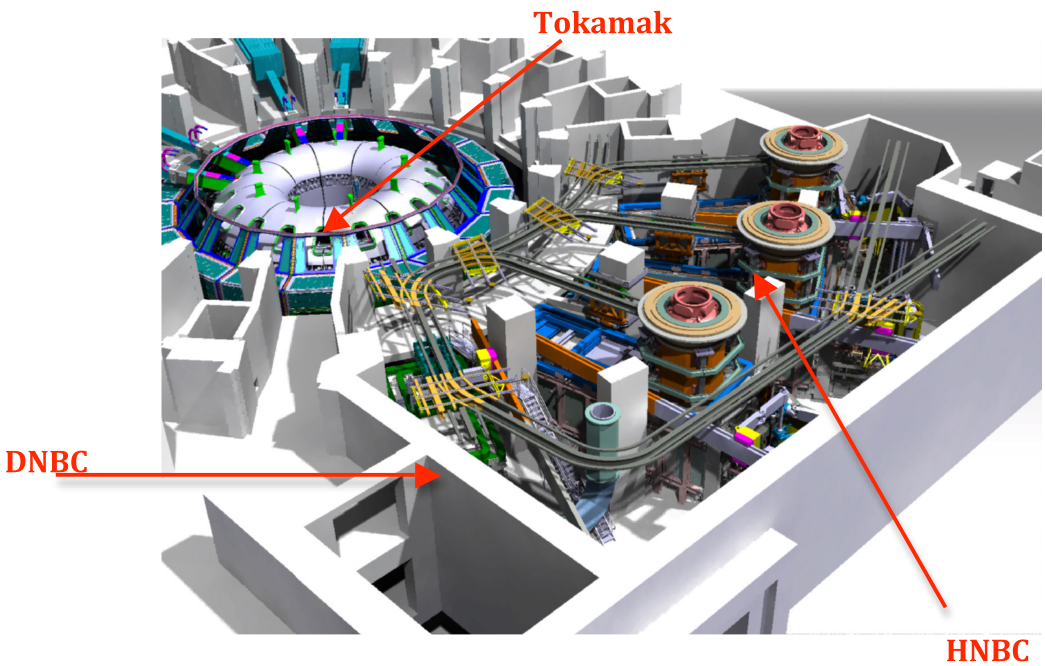


Figure 4 – Top view of the HNB

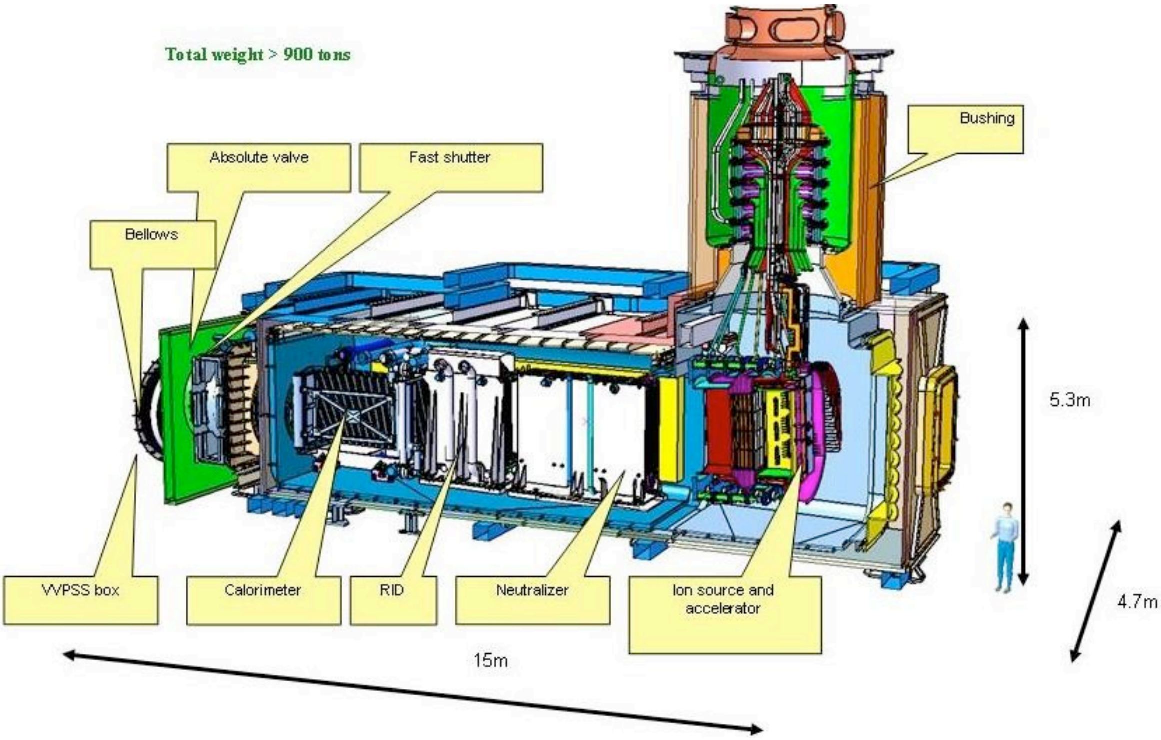


Figure 5 – Heating Neutral Beam (Side view)

The **Figure 5** gives an idea of the HNB dimensions and of its main components.

4. Environmental Conditions during NB Maintenance

The **paragraph 4.1.2.2** of ***SRD-23-05 (Neutral Beam Remote Handling System)*** gives the environmental conditions during NB maintenance.
The operating conditions for NB maintenance are describe in **Table 1**:

Atmosphere	Dry air
Pressure	1 bar absolute
Temperature	20 - 50°C
Relative Humidity	About 0 %.
Magnetic Field	**1 milli-Tesla**
Contamination	Mainly tritium, but possibly also activated dust (C, Be and W).
Gamma Radiation dose rate inside the NB vacuum vessel 10^6 s (~300h) after plasma operations	**1 Gy/hour**
Maintenance operations will demand high level of cleanliness because of the NB high vacuum requirements.	

Table 1 - Environmental conditions during HNB maintenance

As a consequence the Neutral Beam Remote Handling Equipment must be designed to be capable of operating with environmental temperature up to 50°C and environmental radiation dose rate up to 1Gy/hour.

5. Heating Neutral Beam Joints

5.1. Pipes

The **paragraph 9.2.1** of the **ITER Remote Handling Code of Practice**, gives the pipes sizes that have already been selected for ITER. However, the sizes are subject to ITER final design confirmation. They are summarised in the **Table 2** below.

Pipe Joint Location	Outside Diameter	Wall Thickness
HNB Source	20 mm	2.5 mm
HNB Source	40 mm	2.5 mm
HNB Neutraliser	100 mm	3.0 mm
HNB Residual Ion Dump	200 mm	3.0 mm
HNB Calorimeter	200 mm	3.0 mm

Table 2 - Standard Pipe Sizes

The **Figure 6** below shows one of the three HNB Cells with its vacuum vessel lid opened. The pipes inside the vacuum vessel must be cut to get an access for the manipulator to the different components to maintain. Then these pipes must be welded and inspected. **The available space between the pipes must be taken into consideration** for the design of the welding/cutting/inspection tools. Moreover, the maintenance will be fully automated as it is illustrated on the **Figure 6** where we notice a manipulator.

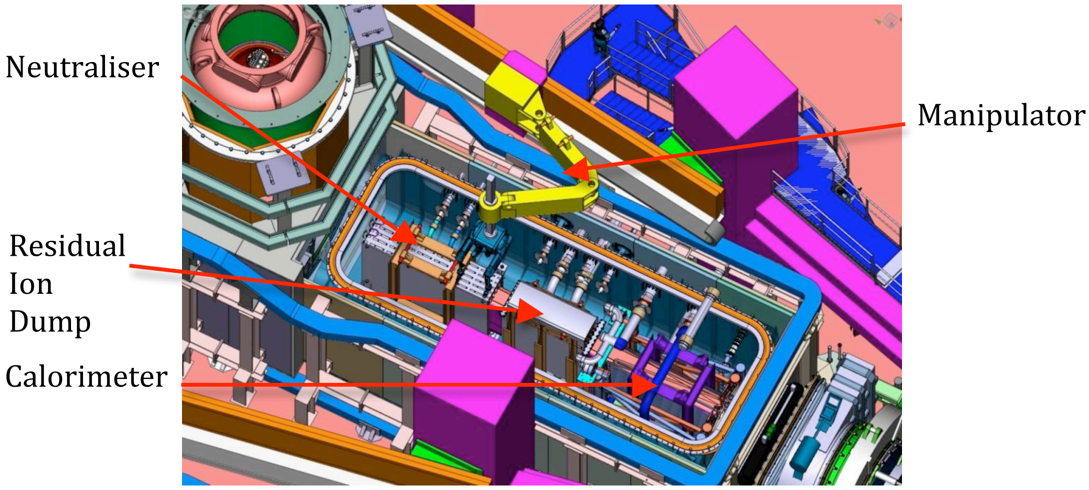


Figure 6 - Top view of one of the injector assembly with the vacuum vessel lid opened

The **Figure 7** below is an enlarged view of the pipes located the inside of the HNBC.

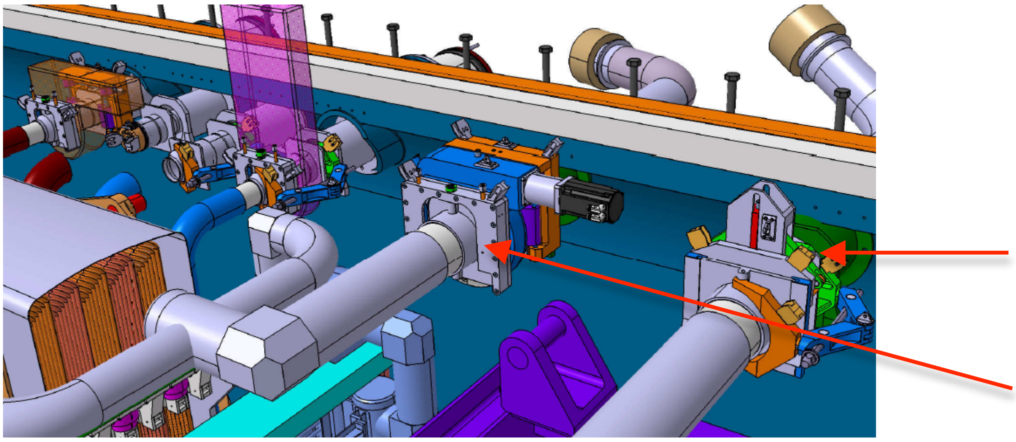


Figure 7 - Pipes to be cut/welded/inspected of the HNBC

The challenge is to make a design of the welding/cutting/inspection tools compatible with the restrained available space and the environmental condition during the maintenance.

5.2. Lip Seals

The **paragraph 9.6** of the **ITER Remote Handling Code of Practice**, describes the HNB lip welded seals. Here is an extract:

"The lip welded joint comprises **two 2 mm thick sheets** placed face to face and welded along their edge. This joint is used as a closure weld for vacuum vessel lids. It does not support internal pressure and only minor mechanical loads. Generally, mechanical bracing support is required to bridge the joint when the welding has been completed. It is suggested that swing bolts are used so that they can be progressively removed and replaced as the lip joint tool proceeds."

The **Figure 8** below shows the HNB lip seals sketch and its dimensions.
At this stage of the ITER project the TIG welding technique will be used to weld the top of the lips. The weld penetration required is 3 mm.

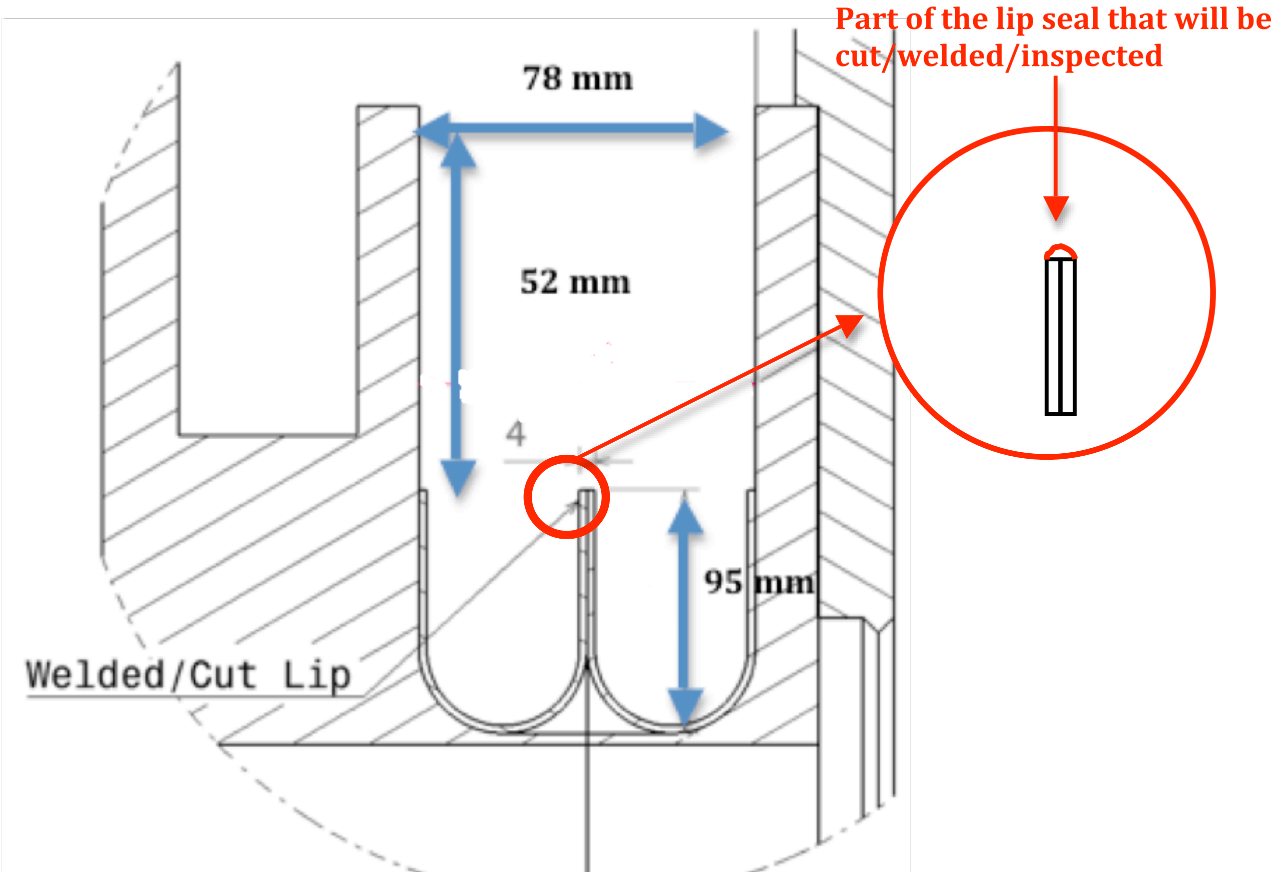


Figure 8 - HNB lip seal sketch

The lip seal joints are used as a closure weld for the vacuum vessel lid. The **Figure 9** below shows two of the HNB Cell vacuum vessel. The vacuum vessel displayed on the left contains the ion source and the one on the right contains the injector assembly. This is an exploded view of the lip seals, we notice the lid, the bolts and the sheets that are placed face to face in order to be welded.

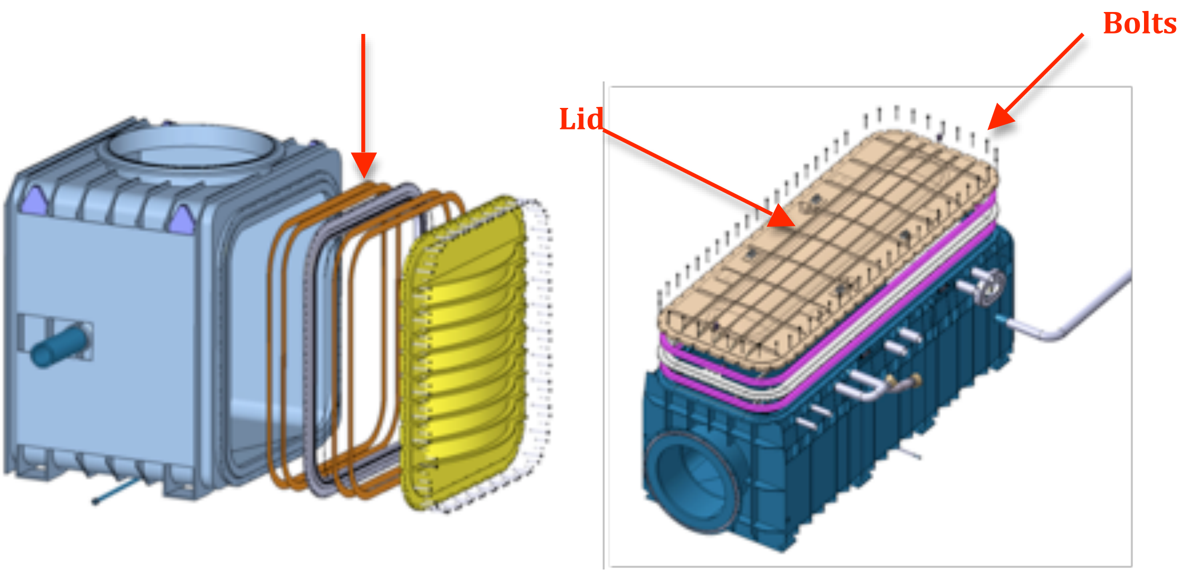


Figure 9 – HNB cell vacuum vessel where lip seals are used as a closure weld

The **Figure 10** is an enlarged view of the lip seal of these two vacuum vessels.

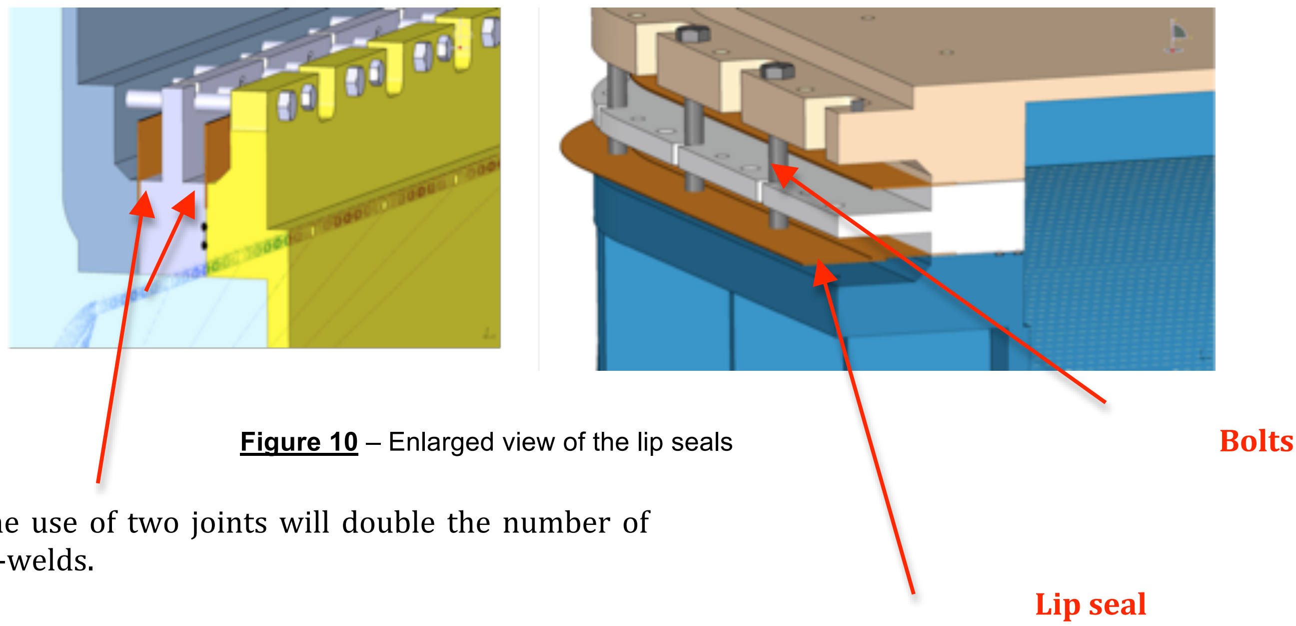


Figure 10 – Enlarged view of the lip seals

The use of two joints will double the number of re-welds.

As described on the **Figure 9** the HNB lip seal dimensions are small: width 78 mm, height 95 mm and a thickness of 4 mm. Due to these small dimensions this kind of joint has never been inspected in JET. In addition of the 1 Gy/h radioactive background, it will be challenging to find an applicable NDT to inspect this weld.

6. Summary and Conclusions

The environmental maintenance conditions have been determined and are presented in the **Table 1**.

The available space for the cutting, welding and NDT has been determined for the HNB lip seal and is illustrated in the **Figure 8**.

The HNB standard pipes sizes have been determined and are summarised in the **Table 2**.

These three documents will be used in the next parts of the report in the ANNEX B and C for the comparative welding technique and NDT study.

The most constraining requirements are:

- the radioactive background of 1 Gy/h
- the high level of cleanliness required for the welding and inspection operations
- the small HNB pipes thickness from 2.5 mm to 3 mm
- the small HNB lip seals dimensions and the small space available around the weld

At this stage we can already make the assumption that the main issue concerns the lip seals inspection. Indeed, the complex geometry, its small dimensions and the small available space around the weld are non usual. That is why they have never been inspected at JET so far.

7. References

(1)	**SRD-53-05 (Neutral Beam Remote Handling System)** 29 Oct 2009/2.0/ APPROVED
(2)	**ITER Remote Handling Code of Practice** 22 Dec 2009/1.2/APPROVED

ANNEX B
Investigation of Welding Techniques

Contents

1. Introduction

The characteristics of two welding techniques have been investigated:

- the TIG (Tungsten Inert Gas) welding technique
- the YAG laser welding technique

The TIG (Tungsten Inert Gas) welding process is robust and has been performed successfully many times during the past few decades at the JET. It benefits from several decades of experience in the industry in many different fields and has proved to be one of the best welding process.

The YAG laser is a new welding technique that has already shown very encouraging results. A lot of improvements have been made this last decade that enable the YAG laser to weld and cut. This is still a research process, none industrial company sell welding/cutting head laser, but it has some advantages over the TIG process.

At this stage of the ITER project the TIG welding technique has been selected as the first welding technique. However, considering the great potential and performances of the YAG laser welding technique, the YAG laser might be used as possible replacements, if for any reason the TIG welding tool were unable to completely fulfil its function.

2. Purpose and Scope

The objective is to make a comparative study between the TIG and YAG laser welding technique. Indeed, although the TIG welding technique is the current welding process for ITER, we are interested to know the performance of the YAG laser welding process. If the YAG laser welding technique has many advantages on the TIG welding technique, it might replace it for the ITER remote welding operations.

To achieve this objective the work has been divided into three steps taking into account the results of the ANNEX A:

- TIG and YAG laser welding characteristics review
- literature review
- independent welding experts opinions

Thanks to the results of this investigations, the TIG and YAG-laser welding processes are examined and compared, based on criteria such as complexity, reliability, welding parameters flexibility, ease of automation… The results are summarised in a grid at the end this part.

3. Welding Techniques Characteristics

3.1. TIG (Tungsten Inert Gas)

TIG welding also called as gas tungsten arc welding (GTAW), is a process where melting is produced by heating with an arc struck between a non-consumable tungsten electrode and the work piece. An inert gas is used to shield the electrode and weld zone to prevent oxidation of the tungsten and atmospheric contamination of the weld and hot filler wire.
Tungsten is used because it has a melting point of 3370°C, which is well above any other common metal.

TIG is most commonly used to weld thin sections of stainless steel and non-ferrous metals such as aluminium, magnesium, copper alloys. The process grants the operator greater control over the weld than competing processes such as shielded metal arc welding and gas metal arc welding, allowing for stronger, higher quality welds.

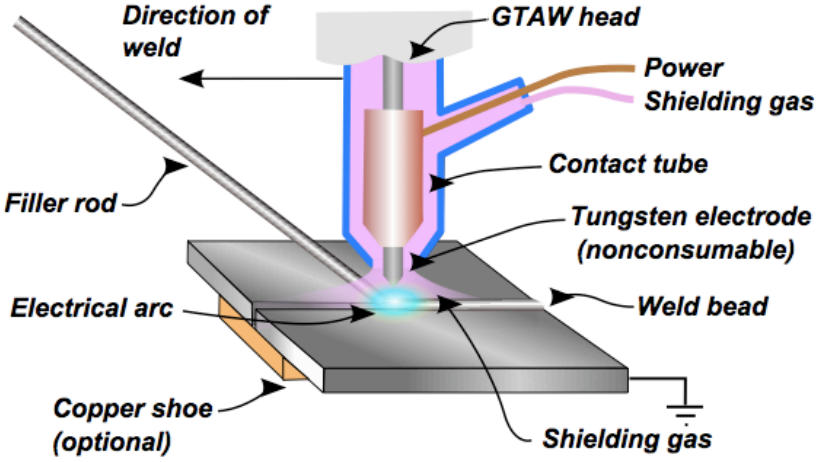


Figure 11 – Manual TIG welding

The main variables in TIG welding are:

- welding current
- current type and polarity
- travel speed
- shape of tungsten electrode tip and vertex angle
- shielding gas flow rate
- electrode extension

Welding current

The weld penetration is directly related to welding current:

- if the welding current is too low, the electrode tip will not be properly heated and an unstable arc may result
- if the welding current is too high, the electrode tip might overheat and melt, leading to tungsten inclusions

Current type and polarity

The best welding results are usually obtained with DC (Direct current) electrode negative, as illustrated in the **Figure 12** below.

DC Positive Electrode DC negative Electrode Alternative Current

Figure 12 – Electrode shape for TIG welding

Travel Speed

The travel speed affects both weld width and penetration but the effect on width is more pronounced:

- Increasing the travel speed reduces the penetration and width
- Reducing the travel speed increases the penetration and width

Tungsten electrode types

Different types of tungsten electrodes can be used to suit different applications such as:

- pure tungsten electrodes used when welding light metal with AC
- thoriated electrodes are alloyed with thorium oxide to improve arc initiation
- ceriated and lanthaniated electrodes wlloyed with cerium and lanthanum oxides for the same reason as thoriated electrodes
- zirconiated electrodes alloyed with zirconium oxide

Shielding gases

The following inert gases can be used as shielding for TIG welding:

- argon
- helium
- mixtures of argon and helium

For austenitic stainless steels (this is the case for the HNB welds) argon with up to 5% hydrogen may be used to improve penetration and reduce porosity.

The shielding gas rate has a deep impact during the welding:

- if the gas flow rate is too low, the shielding gas cannot remove the air from the weld area and this may results in porosity and contamination
- if the gas flow rate is too high, turbulence occurs at the base of the shielding gas column. It may lead to porosity and contamination.

Conclusion

The advantages of the TIG process are summarised in the **Table 3** below.

Advantages of the TIG process
Produces superior quality welds, with very low levels of diffusible hydrogen so there is less danger of cold cracking.
Does not give either weld spatter or slag inclusions which makes it particularly suitable for applications that require a high degree of cleanliness.
Can be used with filler metal and on thin sections without filler, it can produce welds at relatively high speed.
Enables welding variables to be accurately controlled and is particularly good for controlling weld root penetration in all positions of welding.
Support high temperature: more than 100°C
Robust and reliable process
Benefits from many years of industrial experience

Table 3 - Advantages of the TIG welding technique

3.2. YAG laser

The Nd:YAG (Nd is Neodymium) laser is one of the most versatile laser sources used in materials processing. The relative robustness and compactness of the laser and the possibility for the 1.06 micron light it produces to be transmitted to the workpiece via silica optical fibres, are two features which contribute to its success.

Nd:YAG lasers were first commercialised operating mainly in pulsed mode, where the high peak powers which can be generated were found useful in applications such as drilling, cutting and marking.

These pulsed lasers can also be utilised for welding a range of materials. More recently, high power (up to 10kW), continuous wave (CW) Nd:YAG lasers have become available. The Nd:YAG crystals in these lasers can be pumped either using white light flashlamps or, more efficiently, using laser diodes. The latter methods are used to produce high quality beams, which can be focused to smaller spots (and therefore produce higher power densities) than the flashlamp pumped lasers.

Because of the possibility of using fiber optic beam delivery, these lasers are often used in conjunction with articulated arm robots, in order to work on components of complex shape.

Different welding methods are possible:

- If the laser is in pulsed mode, and if the surface temperature is below the boiling point, heat transport is predominantly by conduction and a conduction limited weld is produced.
- If the applied power is higher (for a given speed), boiling begins in the weld pool and a deep penetration (deeper than with the TIG process) weld can be formed. After the pulse, the material flows back into the cavity and solidifies.

Both these methods can be used to produce spot welds. A seam weld is produced by a sequence of overlapping deep penetration 'spot' welds or by the formation of a continuous molten weld pool.
For the former, once the energy input is sufficient to ensure that the weld does not solidify between pulses, the 'keyhole' type weld normally associated with CO_2 laser welding can be formed. Pulsed laser welding is normally used at thicknesses below about 3mm.

The main variables in YAG laser welding are:

- the beam power, determined by the weld penetration required
- its power profile
- the focal distance and the focal position relative to the joint
- the beam travel speed

Advantages of the YAG laser
Capable of cutting and welding operations
Large choices of welding parameters enable to produce different kind of welds
Flexible welding parameters and very adaptable

Table 4 – Advantages of the YAG laser welding process

4. Literature Review

4.1. Pipes YAG Laser-Welding in a Radioactive Environment

Article of JAERI-Tech 99-048

Development of pipe welding, cutting and inspection tools for the ITER blanket (published in July 1999)

The objective of this study is to develop the remote bore tools for welding, cuttind and inspection of the blanket cooling pipe from inside. The bore tools has been designed to move at least 15 m along the cooling pipe so as to reach the position where the pipe is welded, cut and inspected. These tasks have to be performed under high gamma radiation dose rate of 3.10^6R/h(=350kGy/h).

The pipes sizes studied are :

- 100 mm diameter pipe with a bend radius of 400 mm and a for accessing from the 100 mm pipe a branch pipe with a diameter of 50mm.

The HNB pipes we considered have a diameter from 20 mm to 200 mm. The welding operations have been conducted inside a 100 mm pipe, we can assume it is feasible to make the same welding operations for HNB pipes with a diameter bigger than 100 mm. Concerning HNB pipes with a diameter smaller than diameter further research and develoment must be done.
This study has proved tthe feasibility of the YAG laser for pipes welding/cutting operations in an radioactive environnment.

Constitution of Welding tools

The proposed YAG laser welder/cutter is based on laser beam transmission using a flexible optical fiber installed inside the pipe. Therefore, welding/cutting by means of internal access can be performed even for the pipes with bends and branches. The YAG laser welder/cutter and weld inspection tools for the branch pipes have been designed to satisfy the following requirements :

- Axial traveling mechanism trough the cooling manifold with an inner diameter of 102.3 mm and the curved sections with a bend radius of 400 mm (minimum).
- Telescopic mechanism to access from the cooling manifold to the branch pipe with an inner diameter of 54.5 mm for welding and cutting.
- Position detection ; adjustment and fixing mechanism for welding and cutting.

Test pipe	Material	Inner diameter	Thickness	Maximum curvature
Manifold	SS316L	102.3mm	6mm	400mm
Branch pipe	SS316L	54.5mm	3mm	

Table 5: - Pipes sizes

Conclusion

The conclusion of the study is that the YAG laser type welding/cutting tool for branch pipes of module type blankets has been developed and tested under the various conditions (which are detailled in the article) and the realization of the branch pipe maintenance was confirmed. This system can be moved inside a 100-A pipe with a minimum curvature of 400 mm and the welding/cutting nozzle with telescopic mechanism can be extended into a branch pipe with a diameter of 50 mm for welding/cutting. With these welding, cutting, rewelding and repeat welding experiments using YAG laser, the optimum welding and cutting conditions including the effects of gaps and assist gas on the weldability and reweldability has been clarified.

From these tests, the optimum conditions of welding and cutting for the Branch pipe are :

	Laser Power	Frequency	Duty	Welding speed	Shield gas	Work distance	Defocus distance
Welding	1100 W	40 Hz	50%	0.5m/min	Nitrogen	2mm	0mm
Cutting	1000 W	40 Hz	5°%	0.8m/min	Nitrogen	2mm	0mm

Table 6 - Optimum conditions of welding/cutting for Branch pipe

YAG Laser results
Feasible under High Gamma Radiation: 350kGy/h
Feasible inside Orbital Pipes of 100 mm diameter with a minimum curvature of 400 mm
Feasible inside Orbital Pipes of 50 mm diameter
The **dimensions of the head laser are very flexible** and depend on the application
Flexibility of the welding parameters enable to weld and cut easily

Table 7 - Orbital Pipes YAG laser Welding Key points

5.1. Welding Technique Selection Study Part 1

ITER Lip Seal Cutting and Welding R&D Part 1

Evaluation of cutting and welding processes for Lip Seal maintenance work

The goal of the study is to select the welding processes applicable to the ITER vacuum vessels lips seals by making a comparative study.
The requirements for the maintenance work of the vacuum vessel are:

- The occupational radiation exposure access limitation. For this reason, it is inevitable to automate the cutting and the welding processes by using robot arm.

- The lip seal cutting and welding work is performed in the ambience of high vacuum area of the vessel. This sets high demands to the level of cleanliness.

- The quality of the Lip Seal Welds is of very high priority.

These requirements for maintenance work of the vacuum vessel are quite similar to the requirements for the HNB maintenance. In addition, the experiments have been performed with edge joint welding of 2 mm type austenitic stainless steel using plasma, TIG and laser welding.

This preliminary comparative study has shown that the YAG laser and the TIG welding technique has the best performances and were selected for the next phase of the project. Consequently, I have displayed only the preliminary results for the YAG laser and the TIG welding techniques.

4.2.1. TIG Preliminary Welding Tests

The experiments were started with edge joint welding of 2 mm type austenitic stainless steel using TIG welding. The specimens to be welded were designed from both welding and subsequent non-destructive testing (NDT) viewpoints. The 2 mm stainless steel sheets were shear cut into strips of 100 mm in width and 500 mm in length, which was regarded long enough for the welding processes to stabilise, and bent to a 90° angle, as shown in **Figure 13** below.

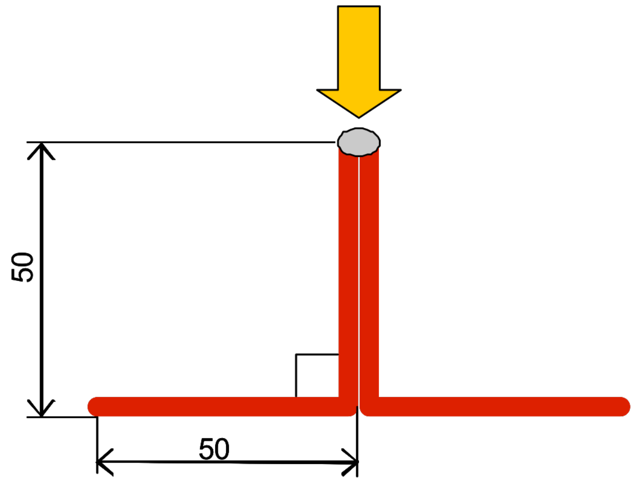
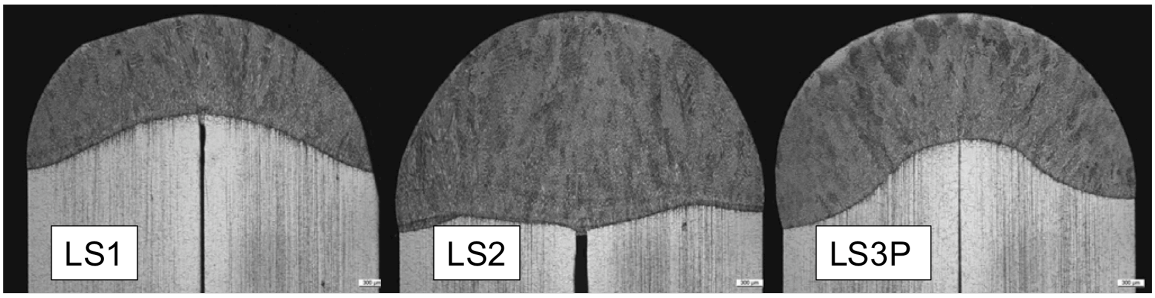


Figure 13 – Lip seals sketch

The weld pool behaviour was good and it could be controlled relatively easily. They had good reasons to expect that the required penetration can be realised in the next experimental programme.



a)
- v = 330 mm/min
- E = 0.17 kJ/mm
- Q = 0.10 kJ/mm
- Penetration 1.2 mm

b)
- v = 330 mm/min
- E = 0.21 kJ/mm
- Q = 0.13 kJ/mm
- Penetration 2.6 mm

c)
- v = 330 mm/min
- E = 0.18 kJ/mm pulsed
- Q = 0.11 kJ/mm pulsed
- Penetration 1.5 mm

Figure 14 - Macrographs from the preliminary TIG welding experiments: a) low heat input, no pulsing, b) high heat input, no pulsing, and c) low heat input, pulsing Ib/Ip = 90 A/120 A.

4.2.2. YAG laser Preliminary Welding Tests

Laser welding experiments were carried out by using the Nd:YAG laser process. Thickness of the test pieces was 4 mm, which was compounded of putting together two 2 mm thick 180 mm * 100 mm square sheets as illustrated in the **Figure 15** below.

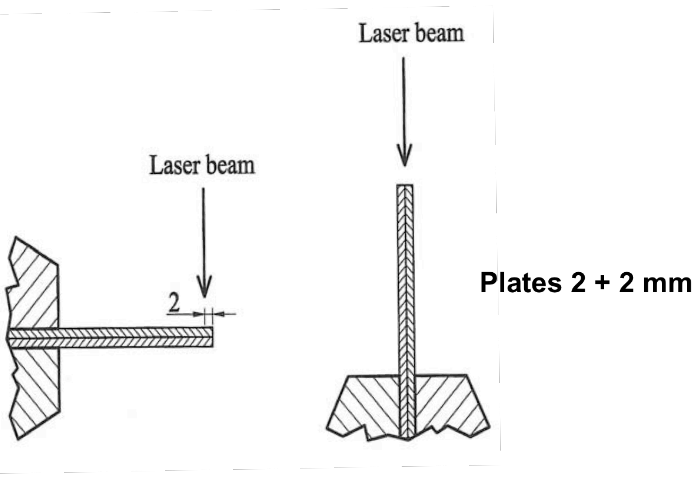


Figure 15 - Configurations of joint types. On the left: lap joint, on the right: edge joint.

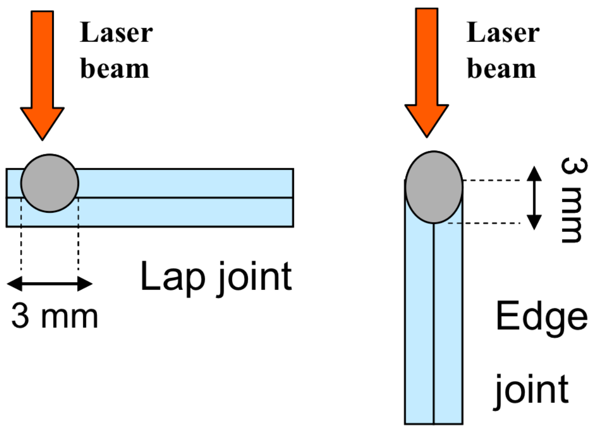


Figure 16 - A schematic presentation of the penetration requirement in lap joint and edge joint.

Preliminary Nd:YAG- laser welding tests with 3 kW laser power and in flat position showed that laser welding process seems to be a promising alternative for lip seal welding application. Deep and sound welds can be produced by properly selected parameters.

In welding of edge joints, penetration requirement (3 mm) can be achieved within a welding speed of ~ 1,2 m/min, and the welding energy input (E) can be kept around 0,15 KJ/mm. In lap joints, where width of the weld defines penetration, a penetration width of 1.3 mm could be produced. That is way too small compared to the penetration requirement of 3 mm.

In lap joint, the penetration requirement is difficult to achieve, because de-focusing and lowering the welding speed will cause excessive welding heat in-put, which may cause excess deformations and even sagging of the lip edge.

4.2.3. Preliminary Welding Tests comparison

Comparative TIG/ YAG laser preliminary results	
YAG laser	**TIG**
Promising alternative	Offer the best control for the welding process
3 mm penetration not achieved	3 mm penetration achieved
Plenty of potential for further improvements	Benefit from industrial background

Table 8 – Comparative TIG/YAG laser preliminary results

4.3. Welding Technique Selection Study Part 2

ITER Lip Seal Cutting and Welding R&D Part 2

Selection and development of the cutting and welding processes (published in December 2010)

In the second phase the potential welding processes selected in the preliminary study were studied and compared in practice.

The main objective of the Phase 2 was to define parameters for successful welding of Lip Seal Mock-up edge joints in each four basic positions (flat PA, vertical down PG, overhead PE and vertical up PF), and to study the sensitivity of the weld quality to the deviations from the optimum parameter set.

4.3.1. TIG Welding Tests Results

- Required penetration reached in PA (flat) position
  - Both with and without pulsing
  - Tolerances to welding parameter and misalignments screened
- Required penetration reached APPARENTLY in PE position (overhead) as well
  - To be confirmed
  - Both with and without pulsing
- Required penetration NOT reached in PF (vertical up) or PG (vertical down) positions
  - 3 mm penetration too demanding target
  - 2.0 – 2.5 mm would be more reasonable/possible

The main conclusion is that the 3mm of required penetration has not been reached in PF and PG positions.

4.3.2. YAG laser Welding Tests Results

Objectives of the advanced laser welding tests were in general to gain further confirmation about the suitability of the laser welding process for lip seal application and in specifically to establish parameter window for positional welding (PA, PF, PG and PE) of lip seal welding application.

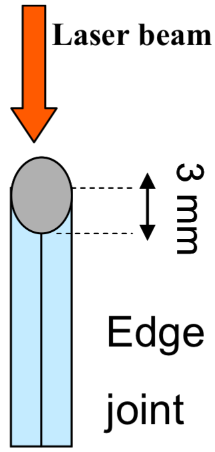


Figure 17 - A sketch from the joint configuration and penetration requirement.

Welding tests in flat position (PA): basic parameter research

Based on the results from the test weld C1, following basic parameters were chosen: Laser power P = 3 kW, welding speed v = 1.5 m/min and focal point position F = -3 mm.

Vertical up (PF) position

The results showed that the parameters used in PA position can be successfully applied to vertical up (PE) position welding.

Vertical down (PG) position

The results showed that the parameters used in PA position can be successfully applied to vertical down (PG) position welding.

Overhead (PE) position

The results showed that the parameters used in PA position can be successfully applied to overhead (PE) position welding.

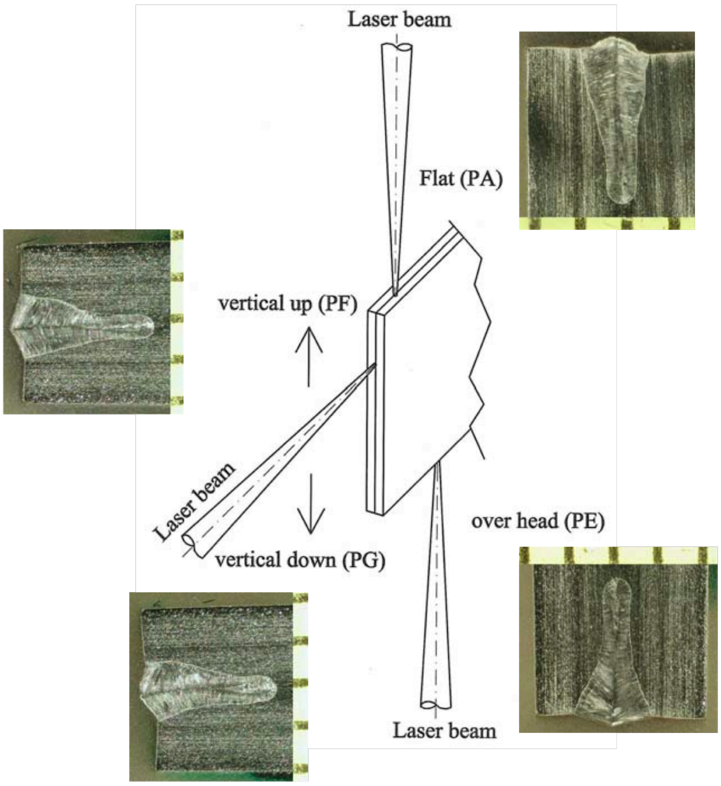


Figure 18 - Welding positions studied and the macro graphs of corresponding weld cross- section. Following parameters can be applied in all positions: Laser power 2.3 kW, welding speed 1.5 m/min and focal point position -3 mm.

Conclusion

Laser welding tests concerning Lip seal R&D project have been carried out. During these tests robotized Nd-YAG laser welding process showed its high potential for lip seal welding application. Welding process parameters have been successfully established as sound welds with 3 mm penetration can be demonstrated in all (PA, PF, PG and PE) welding positions.

4.3.1. Comparative Welding Study Part 2 Results

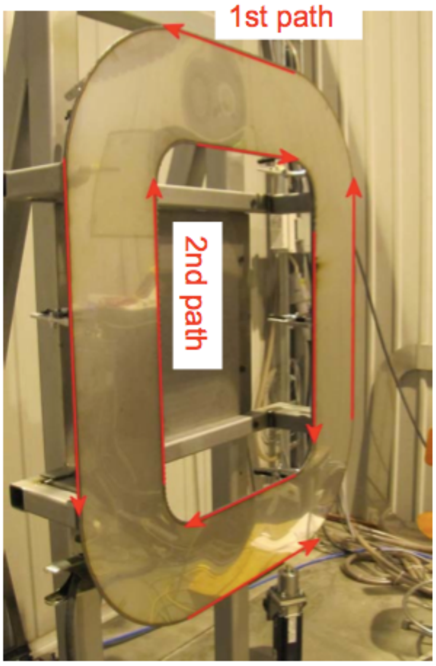
The 3 mm penetration required can be demonstrated in all welding positions with the YAG laser technique which is not the case with the TIG technique.
However, we don't know the weld penetration required for the HNB lip seals.

Comparative study TIG/YAG laser Part 2 results	
TIG	**YAG laser**
3 mm penetration achieved only in certain position	3 mm penetration achieved in all position and flexibility of the welding parameters
Reliable welding technique	Has shown high potential for lip seal welding
Welding tools are small	Flexibility of the laser head dimensions

Table 9 - Comparative study TIG/YAG laser Part 2 results

4.4. Welding Technique Selection Study Part 3

The final tests of this comparative study have been done on mock-up as illustrated in the **Figure 19** below.



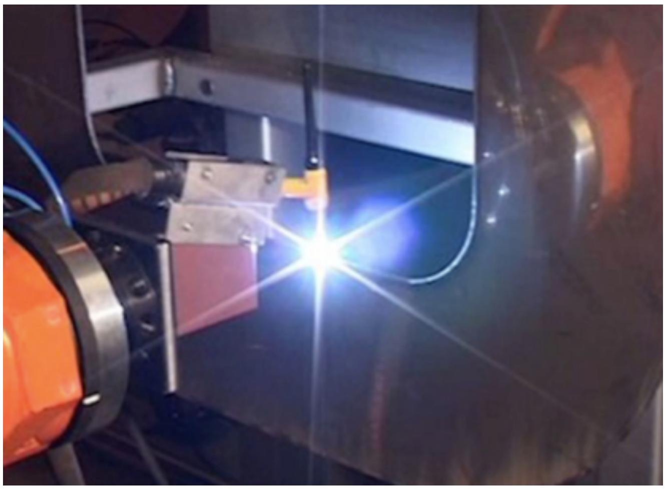


Figure 19 – Lip seal mock-up on the left and TIG welding of mock-up on the right

4.4.1. TIG Welding Final Tests Results

Final Results

- Weld melt to electrode contacts often in vertical positions (sagging) and on the third outer corner
- The best results achieved by increasing the welding speed according to the position (better melt control, but decreased penetration)
- Welding / cutting / re-welding of the mock-up lip seal was performed

Further Work

Increasing the penetration 2 →3 mm
Development of pulsing techniques to the specific joint type and configuration

- Peak current and duration to achieve the required penetration depth
- Base current and duration to allow the melt solidify before the next peak
- Welding speed adjusted to ensure sufficient overlapping of the successive peak penetration profiles

4.4.2. YAG laser Final Tests Results

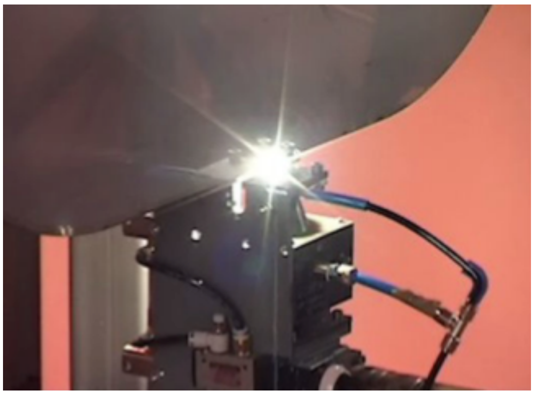


Figure 20 – YAG laser welding on the mock up

- Easy to perform, constant parameters can be used around the whole periphery of the Lip welds
- Relatively fast process, welding time less than 5 minutes
- Penetration depths of much more than 3 mm can easily be achieved
- Focus position in depth relatively tolerant (±2 -3 mm)

4.4.3. Final Comparative Welding Study Results

Comparative study TIG/YAG laser Part 3 Final Results	
TIG	**YAG laser**
Reliable welding technique	3 mm penetration achieved easily in all position and flexibility of the welding parameters
Weld penetration must be extended from 2 mm to 3 mm	Has shown high potential for lip seal welding
Welding and re-welding lip seal performed	Easy to perform

4.5. Literature Review Summary and Conclusions

Summary

In the **ANNEX A** we had determined the most constrain requirements during the HNB maintenance:

- the radioactive background of 1 Gy/h
- the high level of cleanliness required for the welding and inspection operations
- the small HNB pipes thickness from 2.5 mm to 3 mm
- the small HNB lip seals dimensions and the small space available around the we

To transpose the results of the studies must meet these requirements.

In the **Article of JAERI-Tech 99-048** *Development of pipe welding, cutting and inspection tools for the ITER blanket* the YAG laser welding technique has been performed in an radioactive environment with a level of radiation high than 1Gy/h, for the pipes welding. These pipes have a thickness from 3 mm to 6 mm and a diameter from 50 to 100 mm similar to the HNB pipes.

Even though the pipes thickness and the diameter are not exactly the same as in the HNB, the constrains of the ANNEX A are very similar to the constrains of this study. Consequently, this study proves encouraging results for the YAG laser welding technique about the pipes welding.

The **ITER Lip Seal Cutting and Welding R&D Part 1, 2, 3** *Selection and development of the cutting and welding processes* conducted several tests for the TIG and YAG laser welding technique in order to determine their performances. The lip seal mock up they have used to perform their tests has the same dimensions as the HNB lip seal. However, the space availability due to the environment and the radioactive background are not taken into account.

Consequently we cannot transpose directly the results of this study to the HNB. But this study has shown encouraging and promising results for the YAG laser welding technique. It has also shown that the TIG welding technique is reliable and has great capacities but it cannot reach a weld penetration of 3 mm.

Conclusion

The literature review provides encouraging and promising results for the YAG laser welding technique. However, it is difficult to transpose the results because the experimental welding conditions of the laboratory are not exactly the same as the environmental condition during the HNB maintenance. Moreover, the pipes and lip seals used by these studies are not exactly the same as the HNB one.

Consequently, we have to be careful with these results and only considering them as possibilities. The welding independent experts opinions will provide us more useful information because of the possibility to ask them what they think of the applicability of the TIG and YAG laser welding technique to the HNB joints in its very specific environment during the maintenance.

5. Independent Welding Experts Opinions

5.5. Ian Merrigan Welding Engineer Technologic Welding Institute (TWI)

***Ian Merrigan** has many years of experience about welding technique and especially TIG welding technique. He has been in charge of the welding operations at JET that makes him a reference in his field.*

The TIG process is robust and very accurate. This is a welding process on which we can rely on without any doubt. It has been performed for many years and has shown its great potential.

The TIG process has been performed in the JET several times and is a reference. The TIG process in every position can perform the pipes and lip seal welding. In addition, the welding tools are very small and enable to use the TIG process in very tiny spaces. At this stage of the ITER project **Mr Merrigan** thinks the TIG welding technique is the most reliable due to his great performances and years of experience.

Mr Merrigan has done for me a demonstration of the TIG welding technique on lip seals. I have noticed the welding process is entirely automated and very accurate.

The **Figure 21** below shows the TIG welding tools for the lip seals. It is obvious that the dimensions of the tools are small that enable them to weld in very tiny spaces.

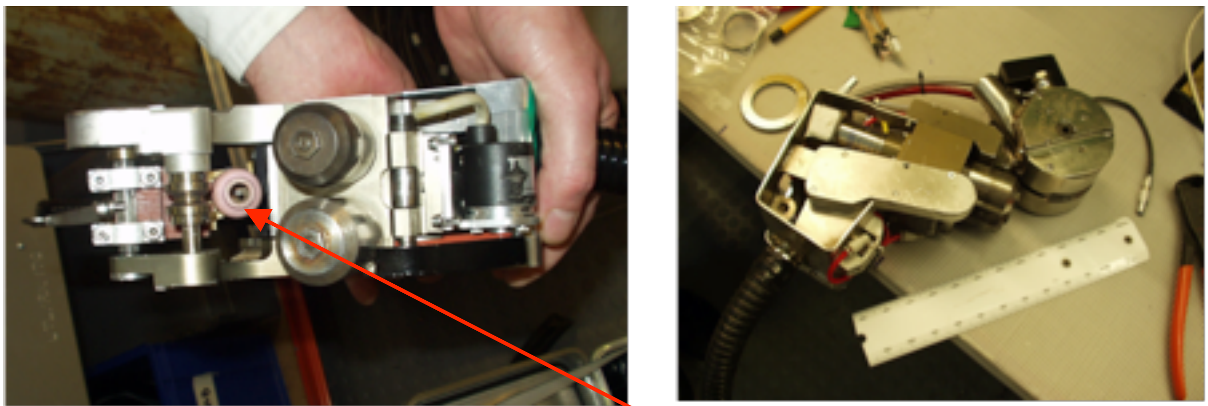


Figure 21 – TIG welding tools for the lip seals

5.2. Guillaume de Dinechin Welding Expert Atomic Energy Commission (CEA France)

He has with his team made severals developments with COGEMA (which is the former name of AREVA) for remote handling in the plants of the Hague (the place where all the radioactive waste are recycled and stocked) and more precisely for maintenance operations about orbital pipes. He has also worked for the CEA and more precisely for the maintenance operation of the nuclear power plant Phenix (which was a prototype nuclear power plant of the 4th generation).

The YAG laser is a new welding technique that is still in development. Since the last decade, the power is enough powerfull to weld and the great improvements that have been made provide a few advantages in comparison with the TIG welding technique.

Mr de Dinechin described the YAG laser welding tools that he and its team have developped :

- The head laser can be removed of more than 100 meters from the welding zone and is manipulated with a remote controlled arm. The laser power is transmitted via a flexible optic fiber.
- The YAG laser enables both the welding and cutting operations and to control the laser power with great accuracy.
- The welding parameters can be chosen with a lot of confidence and enables to make different type of welding.

Laser head compsitions and dimensions

The head laser dimensions are variable and can be adaptable to the space available without almost any technical restrictions. Indeed, the only limitations of the dimensions are :

- the laser power
- the rigid connector dimensions

The rigid connector is the component which links the optic fiber to the laser head and has dimensions that cannot be reduced. This is infact the component which gives the average laser head dimensions.
Consequently the laser head has approximatively the dimensions of a cube side of 10 cm. This is enough small to weld and cut in the HNB restriced environement.

As the head laser is almost contitued only of optics mirrors, it is possible to develop specific head laser for specific application such as weld and cut inside pipes. In addition, the head laser and the fiber optic are resistant to a high radioactive background (higher than 1 Gy/h). Indeed, in France, the YAG laser has already been used to dismantle irradiated structures.

6. Welding Technique Comparative Study

6.1. Grid parameters

The parameters selected for the comparative study are presented below.

Automated process
Is it possible to automate the welding processand operate at distance with a manipulator.

Head flexibility
If the room around object is limited, it has to be taken into account.
Is it possible to change the dimensions of the welding head easily to fit to the room around?

Process reliability
Is the welding process robust and reliable? It is important to be confident in the process to avoid errors. Does the welding process have a experience background?

Process flexibility
Is it possible to adapt the welding process to a specific application? Is it possible to do other things than just welding?

Welding parameters
Does the welding process have large variable welding parameters? Is it possible to change the welding parameters easily in order to control the shape of the weld?

Welding head dimension
Does the welding head have the required dimensions to weld in the tiny environment of the HNB?

Welding penetration
Does the welding process reach the required welding penetration for the joints of the HNB? Is it possible to change easily the welding penetration?

Radiation Resistant
Is the welding process resistant enough to be not affected in an radioactive environment?

Temperature
Is the welding process resistant enough to be not affected in an environment with high temperature?

6.2. Welding technique grid

Welding Techniques	HNB Overall applicability		Automated process	Head flexibility	Process Reliability	Process Flexibility	Welding Parameters	Welding Head Dimension	Welding Penetration	Radiation Resistance	Temperature
	Pipes	Lip seals									
TIG	Yes[4,5,9]	Yes[1,4,5,9]	Yes[1,3,5,9]	good[1,3,5,9]	very good, robust process tested many times[1,5,9]	Only welding[1,4,5,9]	less variable than YAG laser[1,9]	flexible and small[1,4,5,9]	good[1,4,5,9]	Feasibility proved>1Gy/h[9]	Feasibility proved <100°C[1,4,5,9]
YAG laser	Yes[2,9]	Yes[1,9]	Yes[1,2,9]	very flexible only by changing mirror configuration[2,9]	good but recent[9]	Very flexible capable of welding/cutting[2,9]	very large welding parameters[1,2,9]	flexible depending on the operation (max 100mm)[9]	flexible can be more than TIG[1,2,9]	Feasibility proved>1Gy/h[2,9]	Feasibility proved <50°C[2,9]

References

[1]Based on : ITER Lip Seal Cutting and Welding R&D Part 1,2 and 3 Selection and development of the cutting and welding processes
[2]Based on : Article of JAERI-Tech 99-048 : Development of pipe welding, cutting and inspection tools for the ITER blanket
[4]Based on : Introduction to Welding and Non Destructive Testing (WTC17)
[5]Based on : Ian Merrigan welding engineer TWI
[9]Based on : Mr De Dinechin welding expert CEA France

7. Summary and Conclusions

TIG

The TIG is a reliable and robust welding technique that benefits from many years of maintenance operations experience. **Mr Merrigan** confirms that the TIG welding technique works in all position and the welding tools are well adapted for both lip seal and pipes welding. He has no doubt concerning its applicability to the ITER welds.

The TIG welding technique has nothing to prove except the possible failure of the stuck electrode, this is why is has been selected at this stage for the ITER welding applications. Let us focus now on the YAG laser that seems a promising welding technique for the replacement of the TIG.

YAG laser

A lot of studies are focused on the YAG laser because it has some advantages in comparison with the TIG process.

YAG laser advantages
More welding parameter than TIG (by controlling the size of the laser beam)
Flexible tool that can be implemented as well as welding, cutting, surface preparation or even scour.
The head laser can be moved away from the energy source (more than 100m)
The laser power can be very well controlled
Laser head dimensions are very flexible (can be adaptable to the space available)
Possibilities to develop specific head laser for specific welding applications
Does not suffer from radiation (1Gy/h does not cause any problem)

Table 10 - Advantages of the YAG laser process

The laser field is still developing. Thus, now the laser source can be removed from the working area of over one hundred meters. The laser power is transported to the work area by an optical fiber.

With regard to the work area, what matters is actually the size of the particular carrier and the laser head which shapes the laser beam. The laser head dimensions depend on the laser power required. It is possible to reduce it by using mirrors, which has already been made to work on developments such as ITER by the team of **Mr de Dinechin** (for welding and cutting through the inside of pipes).

He is at the CEA in possession of a 8 kW laser capables of carrying the laser power over at least one hundred meters with a 300 mm radius of curvature for the optical fiber. There is only the fiber connector on the laser head which is rigid (rougly 10cm^3). The laser head dimensions are very flexible and small (rougly 10 cm^3), they depend almost only of the space available for the welding operations.

At this stage the main disadvantages of the YAG laser are that it is only on research development and that it requires a better alignment of lips/pipes for the welding operations. There are no heads laser sold by specialist suppliers. But **Mr de Dinechin** assures that it is possible to develop specific laser heads for a specific application.

All these promising results lead me to conclude that it might be possible the YAG laser replace the TIG welding technique for several applications in the coming years.

8. References

Experts	**Contact**
5.1 Ian Merrigan TWI	Ian Merrigan The Welding Institute Ian.merrigan@ccfe.ac.uk +44 123546 48 51
5.2 Guillaume De Dinechin CEA	Guillaume De Dinechin CEA Guillaume.dedinechin@cea.fr + 33 1 69 08 19 57
Part	**Reference Literature**
3.1 3.2	Introduction to Welding and Non Destructive Testing (WTC17) TWI Techniques de l'ingénieur TI-b7740 and TI-b7730 www.techniques-ingenieur.fr
4.1	**Article of JAERI-Tech 99-048** *Development of pipe welding, cutting and inspection tools for the ITER blanket (published in July 1999)*
4.2 4.3 4.4	**ITER Lip Seal Cutting and Welding R&D Part 1, Part 2, Part 3** Evaluation of cutting and welding processes for Lip Seal maintenance work Research Report VTT VTT's contact address VTT, PO Box 1000, FI 02044 VTT, Finland

ANNEX C
Non-Destructive Testing (NDT) Investigation

Contents

6.3. Conclusion of the NDT comparative study: overall applicability and main ways of R&D

7. Summary and Conclusions

8. References

1. Introduction

During the maintenance operations, welded pipes and lip seals will be cut, to get access to the HNB components to maintain. As these joints will be re-welded and require a high quality they must be inspected.

It is unlikely that RT used at JET can be performed in a radioactive background to inspect the HNB lip welded seals. That is why we need to consider other NDT such as Ultrasonic Testing (UT), Eddy Current Testing (ECT), Visual Testing (VT), Leak Testing (LT), Liquid Penetrant Testing (LPT)…

This report is only a first step to select the appropriate welding and NDT techniques. Consequently, further research and development must be made on the selected techniques to prove their feasibility.

We have determined in the **ANNEX A** the two main restrictions that must be taken into account to make the NDT selection:

- the radioactive background of 1 Gy/h
- the space availability around the weld

The JET lip welded seals have never been inspected using a NDT (except by testing leaks). The main reason is the small weld dimension in a very constrained space. This will be exactly the same case for the ITER lip seals. To the HNB lip seals space availability challenging issue, the radioactive background provides several difficulties.

This represents a challenge and some possible solutions given the information gathered have been provided in this report.

2. Purpose and Scope

The objective is to select the NDT applicable for the HNB welded pipes and lip welded seals inspection compatible with the maintenance requirements. To achieve this objective a comparative NDT study has been made in three steps:

- NDT characteristics review
- Literature review
- NDT independent experts opinions

This NDT investigation in three steps allowed crossing each independent information from each step to get the most confidence in the final results.

Then the NDT are examined and compared based on criteria such as overall applicability to the HNB welded pipes and lip welded seals, ease of automation, resistance to the radioactive background, inspection tools dimensions, kind and size of defects detected, reliability …

The results are summarised in a grid at the end.

3. NDT Characteristics Review

In this chapter the basic principles of each NDT are described and the advantages and disadvantages of each NDT are summarised at the end of each subpart.

3.1. Visual Testing (VT)

Surface inspection only

Visual examination is the first process control, the simplest and the most general NDT. VT is a low cost method, which is usually performed before the application of other NDT methods. In preliminary inspection, visual inspection of an object, a structure, an assembly such as welding will guide an experienced observer in the selection of another NDT and to fix its parameters: choice of shooting angle X-ray, magnetization direction ultrasonic frequency.

On-line visual testing enables fast detection of anomalies in the manufacturing process. Weld defects such as misalignment, toe overlap, surface pores, oxidation and cracks can be detected by using VT. Magnification can be used to make the inspection more effective. Remote VT using (a) camera(s) and a robot can be performed on line right after the welding process.

Steve Booth: working at CCFE in the Health Physics Department

Concerning the feasibility of VT in a radioactive environment, **Steve booth** said that the camera itself is not a problem where radiation is concerned. It is more the exposure media and internal circuitry that will need to be shielded from the source of radiation. A radiation dose rate 1Gy/h is significant and may prove too difficult an ambient background radiation to shield against.

In addition, we need to consider the effect of ionizing radiation on the camera electronics that would need to be quantified. Radiation hardened chips are available so it might be possible to develop a camera that has a lead glass lens and radiation hardened electronics.

3.2. Liquid Penetrant Testing (LPT)

Liquid penetrant testing (LPT) is a commonly used surface inspection method, which is used usually when the material is nonferrous causing that magnetic particle inspection cannot be used. There are two LPT methods : a coloured and a fluorescent method. The fluorescent method performed with black ligth is slightly more sensitive.

The main weak point of LPT is the use of chemicals. The inspected surface has first to be cleaned with solvent and then the liquid penetrant is spread on the surface. After penetration the excess penetrant is removed often with solvent and finally the developer is spread on the surface. Automation is possible but residues are a serious problem.

This technique is applicable to small parts with complex geometry but the main problem is that you need a penetrant liquid. This liquid has a high viscosity and is very hard to clean. The penetrant must meet the HNB components high vacuum requirements.

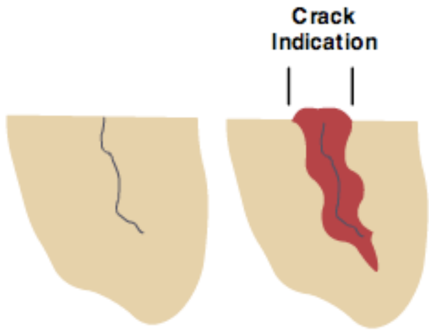


Figure 22 - LPT

LPT Advantages
High sensitivity to small surface discontinuities
Few material limitations: metallic and non metallic, magnetic and nonmagnetic, and conductive and nonconductive materials may be inspected
Large areas and large volumes of parts/materials can be inspected rapidly and at low cost.
Complex geometric shapes are routinely inspected
Indications are produced directly on the surface of the part and constitute a visual representation of the flaw
Aerosol spray cans make penetrant materials very portable
Penetrant materials and associated equipment are relatively inexpensive

Tableau 11 – LPT Advantages

LPT Disadvantages
Only surface breaking defects can be detected
Only materials with a relatively nonporous surface can be inspected
Pre-cleaning is critical since contaminants can mask defects
The inspector must have direct access to the surface being inspected
Surface finish and roughness can affect inspection sensitivity
Multiple process operations must be performed and controlled
Post cleaning of acceptable parts or materials is required
Leaks can be temporarily blocked by the penetrant
Difficult to apply remotely

Tableau 12 – LPT Disadvantages

3.3. Ultrasonic Testing (UT)

UT can perform volumetric and surface inspection

Ultrasonic Testing (UT) uses high frequency sound energy to conduct examinations and make measurements. Ultrasonic inspection can be used for flaw detection/evaluation, dimensional measurements, material characterization, and more.

A typical UT inspection system consists of several functional units, such as the pulser/receiver, transducer, and display devices. A pulser/receiver is an electronic device that can produce high voltage electrical pulses. Driven by the pulser, the transducer generates high frequency ultrasonic energy. The sound energy is introduced and propagates through the materials in the form of waves. When there is a discontinuity (such as a crack) in the wave path, part of the energy will be reflected back from the flaw surface. The reflected wave signal is transformed into an electrical signal by the transducer and is displayed on a screen.

3.3.1. Basic UT principles

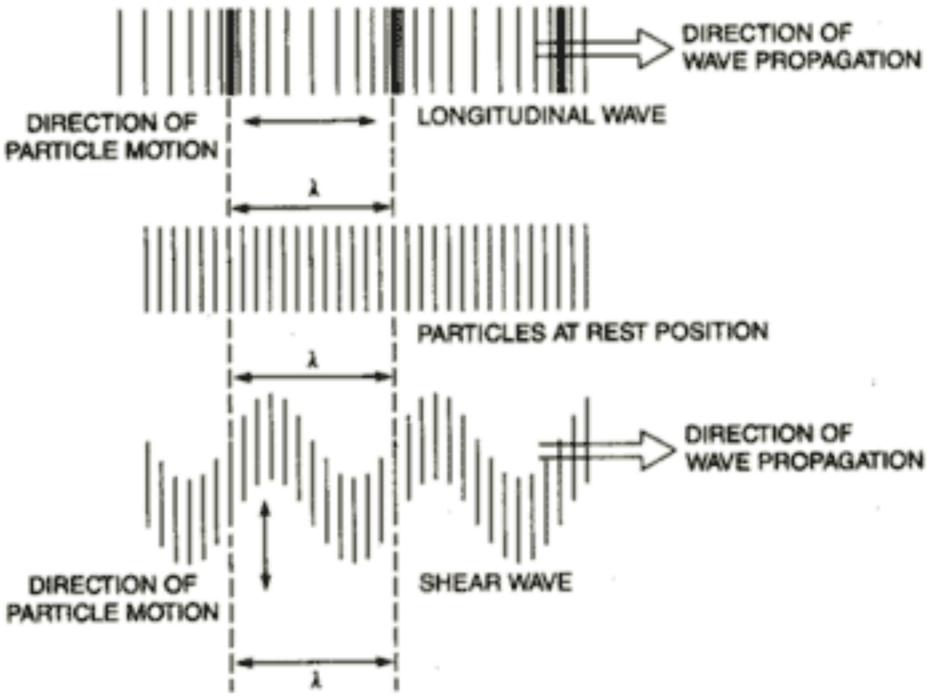
Wave Propagation

UT is based on time-varying deformations or vibrations in materials, which is generally referred to as acoustics. All material substances are comprised of atoms, which may be forced into vibrational motion about their equilibrium positions. Many different patterns of vibrational motion exist at the atomic level, however, most are irrelevant to acoustics and ultrasonic testing.

In solids, sound waves can propagate in four principle modes that are based on the way the particles oscillate. Sound can propagate as:

- longitudinal waves
- shear waves
- surface waves
- in thin material as plate waves

Longitudinal and shear waves are the two modes of propagation most widely used in ultrasonic testing.



Wavelength and Defect Detection

The wavelength of the ultrasound used has a significant effect on the probability of detecting a discontinuity. A general rule of thumb is that a discontinuity must be larger than one-half the wavelength to stand a reasonable chance of being detected.

Two different parameters must be taken into account for the defects detection:

- Sensitivity is the ability to locate small discontinuities. Sensitivity generally increases with higher frequency (shorter wavelengths).

- Resolution is the ability of the system to locate discontinuities that are close together within the material or located near the part surface. Resolution also generally increases as the frequency increases.

- The wave frequency can also affect the capability of an inspection in adverse ways. Therefore, selecting the optimal inspection frequency often involves maintaining a balance between the favourable and unfavourable results of the selection.

- The material's grain structure and thickness, and the discontinuity's type, size, and probable location should be considered.

As frequency increases, sound tends to scatter from large or course grain structure and from small imperfections within a material. Cast materials often have coarse grains and other sound scatters that require lower frequencies to be used for evaluations of these products. Wrought and forged products with directional and refined grain structure can usually be inspected with higher frequency transducers.

Since more things in a material are likely to scatter a portion of the sound energy at higher frequencies, the penetrating power (or the maximum depth in a material that flaws can be located) is also reduced. Frequency also has an effect on the shape of the ultrasonic beam.

Couplant

A couplant is a material (usually liquid) that facilitates the transmission of ultrasonic energy from the transducer into the test specimen. Couplant is generally necessary because the acoustic impedance mismatch between air and solids is large. Therefore, nearly all of the energy is reflected and very little is transmitted into the test material. The couplant displaces the air and makes it possible to get more sound energy into the test specimen so that a usable ultrasonic signal can be obtained. In contact ultrasonic testing a thin film of oil, glycerin or water is generally used between the transducer and the test surface.

When scanning over the part or making precise measurements, an immersion technique is often used. In immersion ultrasonic testing both the transducer and the part are immersed in the couplant, which is typically water. This method of coupling makes it easier to maintain consistent coupling while moving and manipulating the transducer and/or the part.

Figure 23 – Couplant required

3.3.2. Electromagnetic Acoustic Transducers (EMATs)

One of the essential features of ultrasonic measurements is mechanical coupling between the transducer and the solid whose properties or structure are to be studied.

Electromagnetic-acoustic transducers (EMAT) acts through totally different physical principles and do not need couplant. When a wire is placed near the surface of an electrically conducting object and is driven by a current at the desired ultrasonic frequency, eddy currents will be induced in a near surface region of the object. If a static magnetic field is also present, these eddy currents will experience Lorentz forces of the form:

$$\boldsymbol{F} = \boldsymbol{J} \times \boldsymbol{B}$$

F is the body force per unit volume,
J is the induced dynamic current density
B is the static magnetic induction.

The most important application of EMATs has been in Non-Destructive Evaluation (NDE) applications such as flaw detection or material property characterization. Couplant free transduction allows operation without contact at elevated temperatures and in remote locations. The coil and magnet structure can also be designed to excite complex wave patterns and polarizations that would be difficult to realize with fluid coupled piezoelectric probes. In the inference of material properties from precise velocity or attenuation measurements, using EMATs can eliminate errors associated with couplant variation, particularly in contact measurements.

The EMAT offers many advantages based on its couplant-free operation. These advantages include the abilities to operate in remote environments at elevated speeds and temperatures, to excite polarizations not easily excited by fluid coupled piezoelectrics, and to produce highly consistent measurements.

These advantages are tempered by low efficiencies, and careful electronic design is essential to applications.

3.3.3. Application to welded joints

The most commonly occurring defects in welded joints are porosity, slag inclusions, lack of side-wall fusion, lack of inter-run fusion, lack of root penetration, undercutting, and longitudinal or transverse cracks.

With the exception of single gas pores all the defects listed are usually well detectable by ultrasonics. Most applications are on low-alloy construction quality steels, however, welds in aluminium can also be tested. Ultrasonic flaw detection has long been the preferred method for NDT in welding applications. This safe, accurate, and simple technique has pushed ultrasonics to the forefront of inspection technology.

The conventional ultrasonic contact pulse-echo has many benefits. The method is well known and can be well mechanized or automated. The biggest limitation is the probe which have only one nominal angle so in many cases several probes are needed. Conventional ultrasonic transducer cannot achieve both detection and characterisation.

Besides of technical benefits of the conventional ultrasonic testing, phased array ultrasonic testing avoids the problem of one nominal angle of a probe, with only one scan the whole variety of needed angles is possible to achieve. Phased array probes are well adapted to shape the beam in order to optimise detection and characterisation in the same process.

Both the conventional and phased array testing methods require coupling medium but direct water feed is sufficient and no harmul chemicals are needed.

EMAT (Electro-Magnetic Acoustic Transducer) testing has the benefit of no contact medium needed and no liquid couplant.

The sound velocity of longitudinal and transversal ultrasonic wave in austenitic steel is approximately 5900 m/s and 3150 m/s respectively. The smallest detectable defect size range is approximately half of the used ultrasonic wave length.

Smallest detectable defect size for Austenitic Steel				
Frequency MHz	Compression wavelength mm	Smallest detectable defect with longitudinal wave mm	Transversal wavelength mm	Smallest detectable defect with transversal wave mm
0.5	11.8	5.9	6.3	3.2
1	5.9	3	3.2	1.6
2	2.95	1.48	1.6	0.8
4	1.5	0.7	0.8	0.4
6	1	0.50	0.5	0.3

Table 13 - Smallest detectable defect size for Austenitic Steel

The shorter the wavelength is, the smaller the flaws that can be discovered. On the other hand, the shorter the wavelength is, the less the ultrasound will penetrate the test material.

Conclusion

UT is a sensitive method to detect internal flaws. The inspection of thin wall welds is not standardized. With some restrictions, ultrasonic method can also be used to measure the depth of the weld penetration. In the lip seal inspection, the method compares to thickness measurement. The penetration measurement requires that the side of the lip seal weld is even.

The ultrasonic equipment is portable and also the probes are small. When using pulse-echo method, only one-side access is required. The inspection can be automated but the interpretation of the results requires experienced personnel.
Irregular shape of the weld causes geometric indications. A coupling medium such as water is needed.
Linear defects which are oriented parallel to the sound beam may not be detected. Both conventional and phased array method can be applied.

UT Advantages
Sensitive to both surface and subsurface discontinuities
Depth of penetration for flaw detection or measurement is superior to other NDT methods
Only single-sided access is needed when the pulse-echo technique is used
Highly accurate in determining reflector position and estimating size and shape
Minimal part preparation is required
Electronic equipment provides instantaneous result
Detailed images can be produced with automated system
As other uses, such as thickness measurement, in addition to flaw detection

Table 14 – UT Advantages

UT Disadvantages
Surface must be accessible to transmit ultrasound
Skill and training is more extensive than with some other methods
Requires a coupling medium to promote the transfer of sound energy into the test specimen (except EMAT)
Materials that are rough, irregular in shape, very small, exceptionally thin (a few mm) or not homogeneous are difficult to inspect
Cast iron and other coarse grained materials are difficult to inspect due to low sound transmission and high signal noise
Linear defects oriented parallel to the sound beam may go undetected

Table 15 – UT Disadvantages

3.4. Radiographic Testing (RT)

3.4.1. Basic physics principles

X-rays and gamma rays differ only in their source of origin and by their different wavelengths. X-rays are produced by an x-ray generator and gamma radiation is the product of radioactive atoms. They are both part of the **electromagnetic spectrum.**

Properties of X-Rays and Gamma Ray
They are not detected by human senses (cannot be seen, heard, felt, etc.).
They travel in straight lines at the speed of light.
Their paths cannot be changed by electrical or magnetic fields.
They can be diffracted to a small degree at interfaces between two different materials.
They pass through matter until they have a chance encounter with an atomic particle.
Their degree of penetration depends on their energy and the matter they are travelling through
They have enough energy to ionize matter and can damage or destroy living cells.

Table 16 – X ray and Gamma ray properties

X-rays

X-rays are just like any other kind of electromagnetic radiation. They can be produced in parcels of energy called photons, just like light. There are two different atomic processes that can produce X-ray photons. One is called Bremsstrahlung and is a German term meaning "braking radiation." The other is called K-shell emission. They can both occur in the heavy atoms of tungsten. Tungsten is often the material chosen for the target or anode of the x-ray tube.

Gamma rays

Gamma radiation is one of the three types of natural radioactivity. Gamma rays are electromagnetic radiation, like X-rays. The other two types of natural radioactivity are alpha and beta radiation, which are in the form of particles. Gamma rays are the most energetic form of electromagnetic radiation, with a very short wavelength of less than one-tenth of a nanometer.

Ionization

Gamma-rays, x-rays, and neutrons are referred to as indirectly ionizing radiation since, having no charge, they do not directly apply impulses to orbital electrons as do alpha and beta particles. Electromagnetic radiation proceeds through matter until there is a chance of interaction with a particle. If the particle is an electron, it may receive enough energy to be ionized, whereupon it causes further ionization by direct interactions with other electrons. As a result, indirectly ionizing radiation (gamma, x-rays, and neutrons) can cause the liberation of directly ionizing particles (electrons) deep inside a medium. Because these neutral radiations undergo only chance encounters with matter, they do not have finite ranges, but rather **are attenuated in an exponential manner**. In other words, a given gamma ray has a definite probability of passing through any medium of any depth.

A monochromatic radiation of intensity I_0 which travels through a homogeneous material of thickness x (cm), is attenuated in an exponential manner to an intensity I :

$$I = I_0 \exp(-\mu x)$$

μ (cm^{-1}) is a linear attenuation coefficient depending on the incident radiation wave length and the absorbent material.

Even when they have the same energy, photons travel different distances within a material simply based on the probability of their encounter with one or more of the particles of the matter and the type of encounter that occurs. Since the probability of an encounter increases with the distance travelled, the number of photons reaching a specific point within the matter decreases exponentially with distance travelled.
This phenomenon is illustrated in the **Figure 24** below.

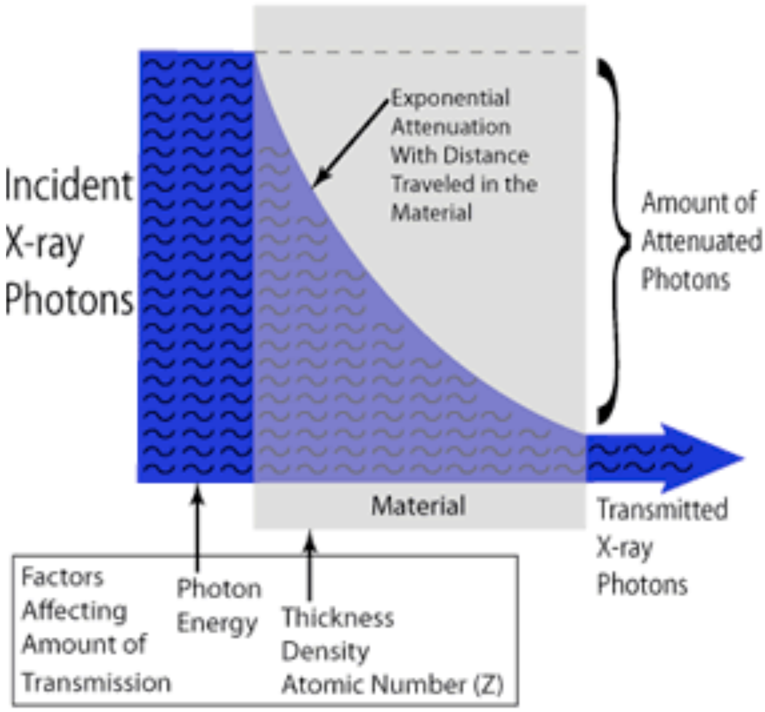


Figure 24 – Interaction between penetrating radiation and matter

Use of Linear Attenuation Coefficients

One use of linear attenuation coefficients is for **selecting a radiation energy that will produce the most contrast between particular materials in a radiograph**. Say, for example, that it is necessary to detect tungsten inclusions in iron. It can be seen from the **Figure 25** of linear attenuation coefficients versus radiation energy, that the maximum separation between the tungsten and iron curves occurs at around 100keV. At this energy the difference in attenuation between the two materials is the greatest so the radiographic contrast will be maximized.

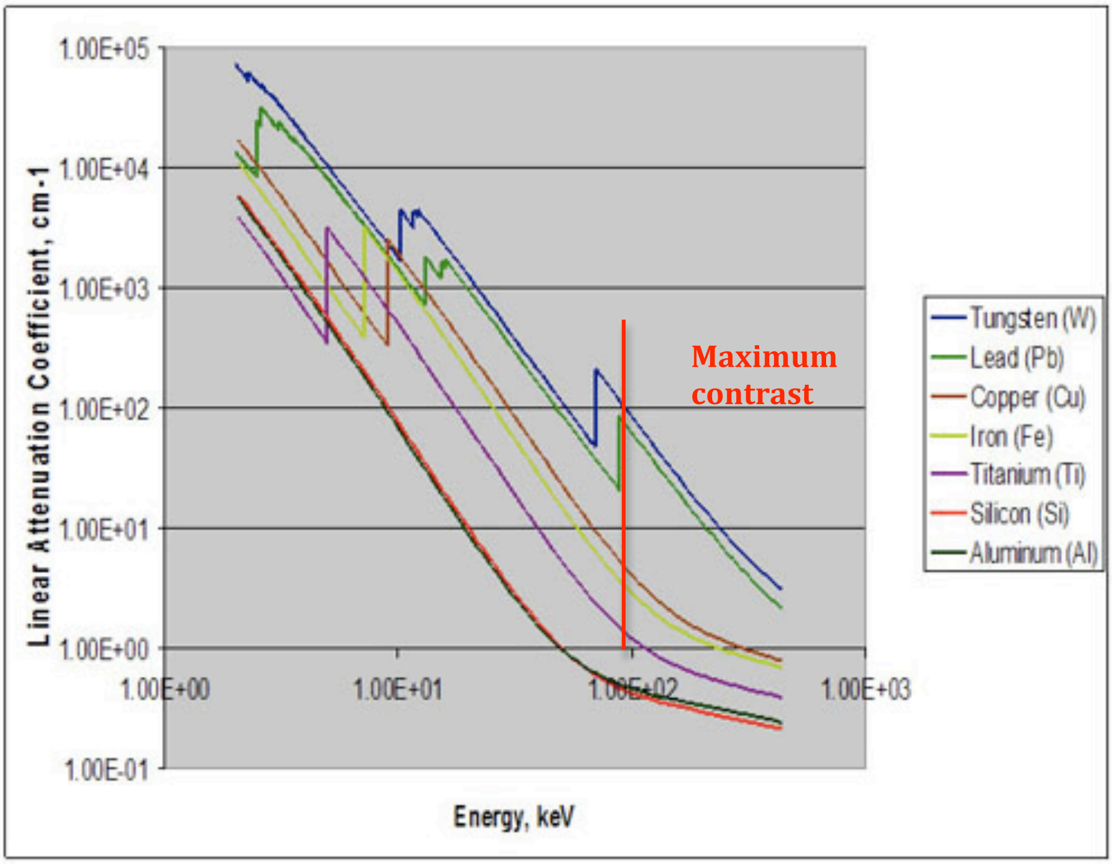


Figure 25 – Linear Attenuation Coefficient

Absorption characteristics will increase or decrease as the energy of the x-ray is increased or decreased. Since attenuation characteristics of materials are important in the development of contrast in a radiograph, an understanding of the relationship between material thickness, absorption properties, and photon energy is fundamental to producing a quality radiograph. **A radiograph with higher contrast will provide greater probability of detection of a given discontinuity**.

3.4.2. Radiographic films

X-ray films for general radiography consist of an emulsion-gelatin containing radiation sensitive silver halide crystals, such as silver bromide or silver chloride, and a flexible, transparent, blue-tinted base. The emulsion is different from those used in other types of photography films to account for the distinct characteristics of gamma rays and x-rays, but X-ray films are sensitive to light. Usually, the emulsion is coated on both sides of the base in layers about 0.0005 inch thick. Putting emulsion on both sides of the base doubles the amount of radiation-sensitive silver halide, and thus increases the film speed. The emulsion layers are thin enough so developing, fixing, and drying can be accomplished in a reasonable time. A few of the films used for radiography only have emulsion on one side which produces the greatest detail in the image.

When x-rays, gamma rays, or light strike the grains of the sensitive silver halide in the emulsion, some of the Br- ions are liberated and captured by the Ag^{+} ions. This change is of such a small nature that it cannot be detected by ordinary physical methods and is called a "latent (hidden) image." However, the exposed grains are now more sensitive to the reduction process when exposed to a chemical solution (developer), and the reaction results in the formation of black, metallic silver. It is this silver, suspended in the gelatin on both sides of the base, that creates an image.

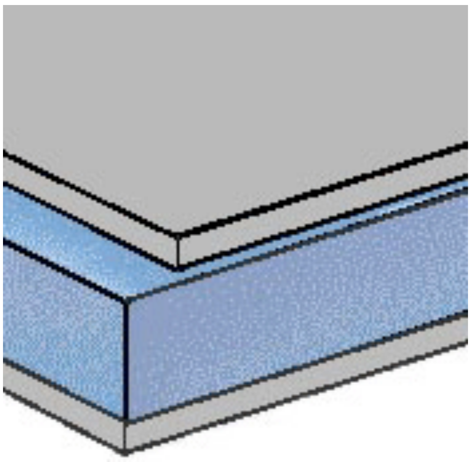


Figure 26 – Radiographic film

Image Considerations

The usual objective in radiography is to produce an image showing the highest amount of detail possible. This requires careful control of a number of different variables that can affect image quality. **Radiographic sensitivity** is a measure of the quality of an image in terms of the smallest detail or discontinuity that may be detected. Radiographic sensitivity is dependant on the combined effects of two independent sets of variables. One set of variables affects the **contrast** and the other set of variables affects the **definition** of the image.

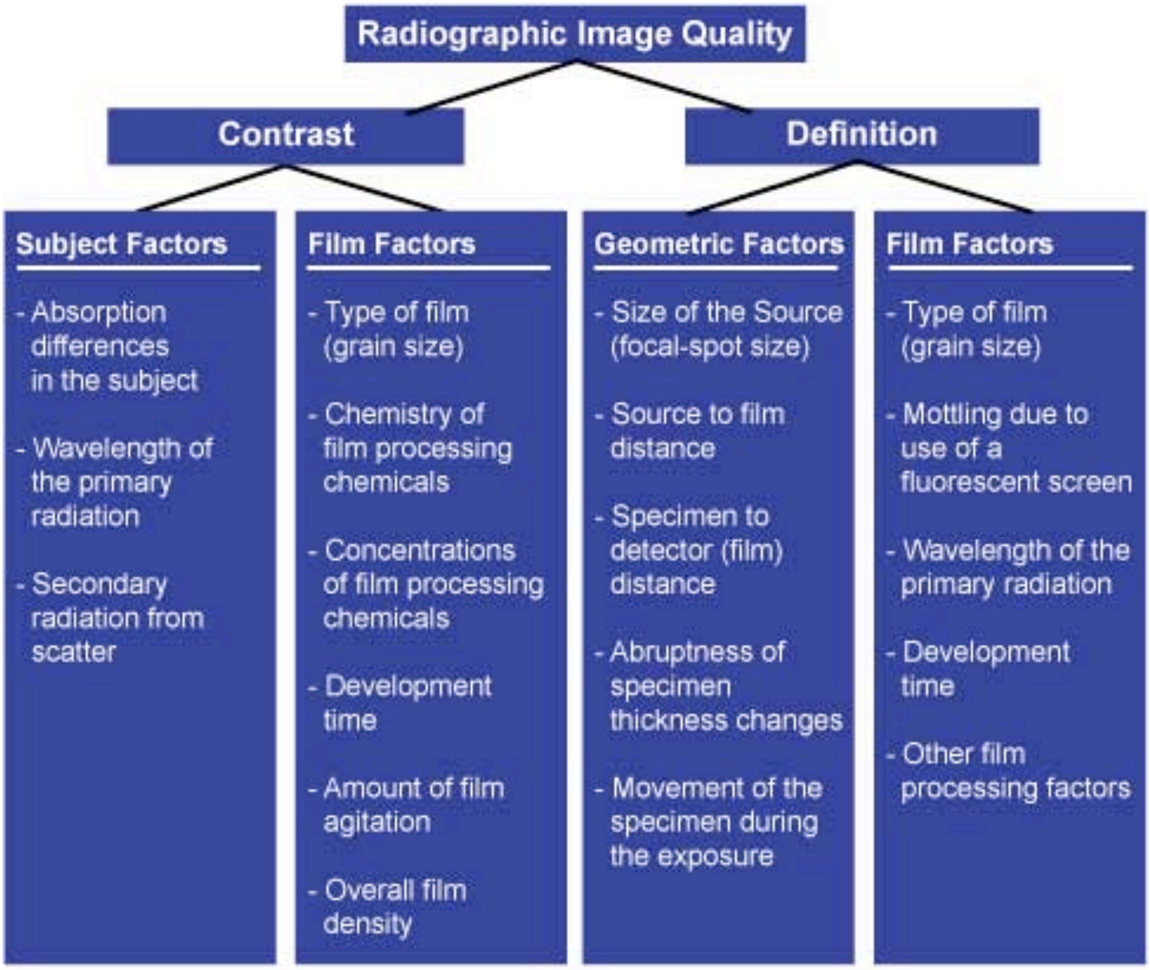


Figure 27 – Image considerations

Radiographic contrast is the degree of density difference between two areas on a radiograph. **Contrast makes it easier to distinguish features of interest, such as defects**, from the surrounding area. The **Figure 28** below shows two radiographs of the same step wedge. The upper radiograph has a high level of contrast and the lower radiograph has a lower level of contrast. While they are both imaging the same change in thickness, the high contrast image uses a larger change in radiographic density to show this change.

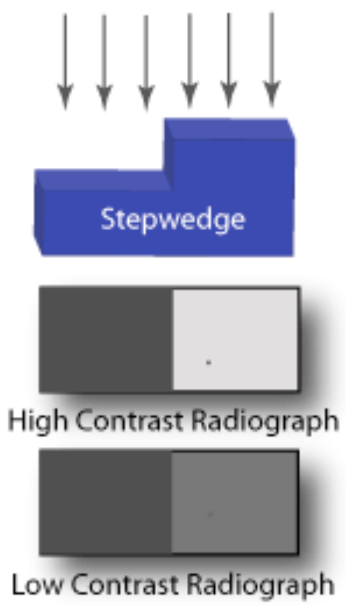


Figure 28 – Radiographic contrast

Radiographic definition is the abruptness of change in going from one area of a given radiographic density to another. Like contrast, **definition also makes it easier to see features of interest, such as defects**, but in a totally different way. In the **Figure 29** below, the upper radiograph has a high level of definition and the lower radiograph has a lower level of definition. In the high definition radiograph it can be seen that a change in the thickness of the step wedge translates to an abrupt change in radiographic density.

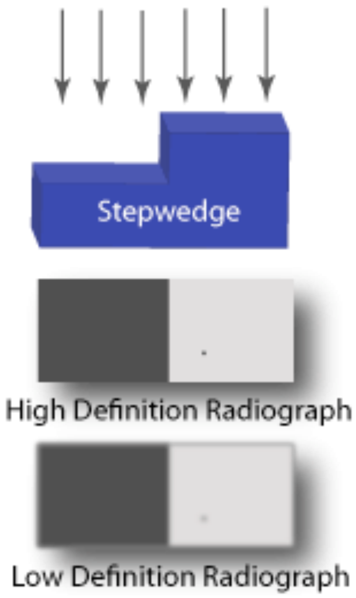


Figure 29 – Radiographic definition

Exposure Calculations

Properly exposing a radiograph is often a trial and error process, as there are many variables that affect the final radiograph.

Variables that affect the density of the radiograph
The spectrum of radiation produced by the x-ray generator.
The voltage potential used to generate the x-rays (KeV).
The amperage used to generate the x-rays (mA).
The exposure time.
The distance between the radiation source and the film.
The material of the component being radiographed.
The thickness of the material that the radiation must travel through.
The amount of scattered radiation reaching the film.
The film being used.
The concentration of the film processing chemicals and the contact time.

Table17 – Exposure Calculations

The current industrial practice is to develop a procedure that produces an acceptable density by trail for each specific x-ray generator. This process may begin using published exposure charts to determine a starting exposure, which usually requires some refinement.

Steve Rowe: working at CCFE and in charge of the implementation of radiographic operations on site.

Steve Rowe has provided some details about the procedure to perform RT on site.
As I said above there are two ways of produce radiation for radiographic testing :

- a high voltage that produce X ray
- a radioactive source that produce Gamma ray, alpha and beta particules

A radioactive source is very dangerous because it produces radiation in all directions. Instead of X ray which are focused on a target. In addition, a radioactive source cannot be switched off after exposure, this is a permanent source. That is why, X ray are almost always prefer to gamma radiography.

Generally speaking for safety reasons, **Steve Rowe** told me they avoid performing RT as much as possible, except if there is really no other way to do it. Indeed, each time you want to perform RT you have to reach the highest level of safety. That is why, you have to work when there is the less people on site (during the night), you have to evacuate people around the examination area. The safety requirements are very strict.

3.4.3. Conclusions

Radiographic testing is sensitive method for **subsurface inspection**. The weld inspection is standardized. It is possible to estimate the weld penetration if the radiation penetration through the weld material differs enough from the penetration through the parent material or if the weld is thicker than the parent material.

Concerning radiographic examination X-ray, gamma-ray and real-time X-ray radiography are potential testing methods. Radiographic inspection **requires a both side access** because the film or detector has to be located on the other side of the test object than the radiation source. This technique allow to **detect internal flaws and volumetric flaws** that are parallel to the radiation or **volumetric defects** like pores and inclusions.

The X-ray examination is the most commonly used radiographic method. Conventional film or digital film can be used. The benefit of the conventionnal film is the better image quality.

In gamma-ray radiography radiation source is radionuclide instead of X-ray tubes of X-ray radiography. **The benefit of this method is the small size of radiation source**, but the weak point is the radiation protection because radiation cannot be switched off after the exposure.

Sophisticated digital imaging systems have been developed for industry usage. **Digital images can be enhanced for more accurate inspection results** with tools such as integration to reduce noise or by introducing complex mathematical algorithms. State of-the-art digital imaging for X-ray inspection systems enable automatic defect recognition.

However, there are some limitations inherent to the RT and due to the HNB welds, summarized in the **Table 18** below.

The main issue we will have to deal with is the radioactive background of 1 Gy/h that will reduce the contrast of the radiographs
The second main issue is the X ray source dimensions that will have to be compatible with the HNB lip seals dimensions.

RT Advantages
Volumetric NDT
Detect multiple different kinds of defects: cracks, inclusions, lack of weld penetration…
Spatial resolution can reach ≈ 0.2 mm
Reliable NDT

Table 18 - RT Advantages

RT Disadvantages
Legislation, procedures protection against radioactive radiation
Many variables affect the sensitivity of the radiograph (**Figure 25**)
Background radiation of 1 Gy/hour is likely to affect the sensitivity of the radiograph
Do not detect defects parallel to the X ray beam
X ray source dimensions
Time consuming and expensive process to inspect a lot of welds

Table 19 - RT Disadvantages

3.5. Eddy Current Testing (ECT)

3.5.1. Basic Physics principles

Eddy currents are created through a process called **electromagnetic induction**. When alternating current is applied to the conductor, such as copper wire, a magnetic field develops in and around the conductor. This magnetic field expands as the alternating current rises to maximum and collapses as the current is reduced to zero. If another electrical conductor is brought into the close proximity to this changing magnetic field, current will be induced in this second conductor. **Eddy currents are induced electrical currents that flow in a circular path**.

One of the major advantages of eddy current as an NDT tool is **the variety of inspections and measurements** that can be performed. In the proper circumstances, eddy currents can be used for:

Main uses of the eddy current
• Crack detection
• Material thickness measurements
• Coating thickness measurements
• Conductivity measurements for: ○ Material identification ○ Heat damage detection ○ Case depth determination ○ Heat treatment monitoring

Table 20 – Main uses of the eddy current

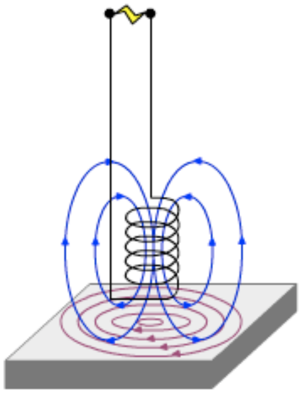


Figure 30 – When an electrically conductive material is placed in the coil's dynamic magnetic field electromagnetic, induction will occur and eddy currents will be induced in the material.

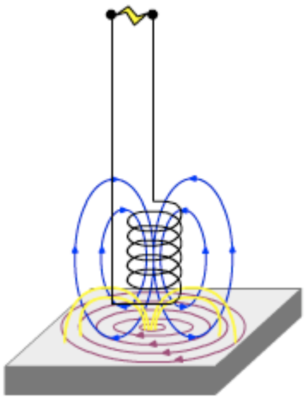


Figure 31 – Eddy currents flowing in the material will generate their own "secondary" magnetic field which will oppose the coil's "primary" magnetic field.

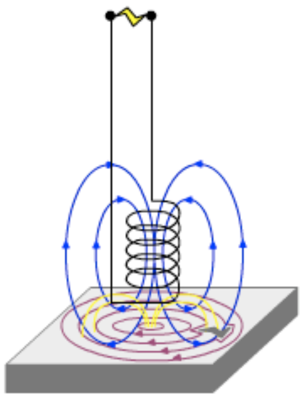


Figure 32 – When a flaw is introduced to the conductive material, the eddy currents are disrupted. This is how we can detect cracks and defects in the material.

Lenz's Law

Basically, **Lenz's law states that an induced current has a direction such that its magnetic field opposes the change in magnetic field that induced the current**. This means that the current induced in a conductor will oppose the change in current that is causing the flux to change.

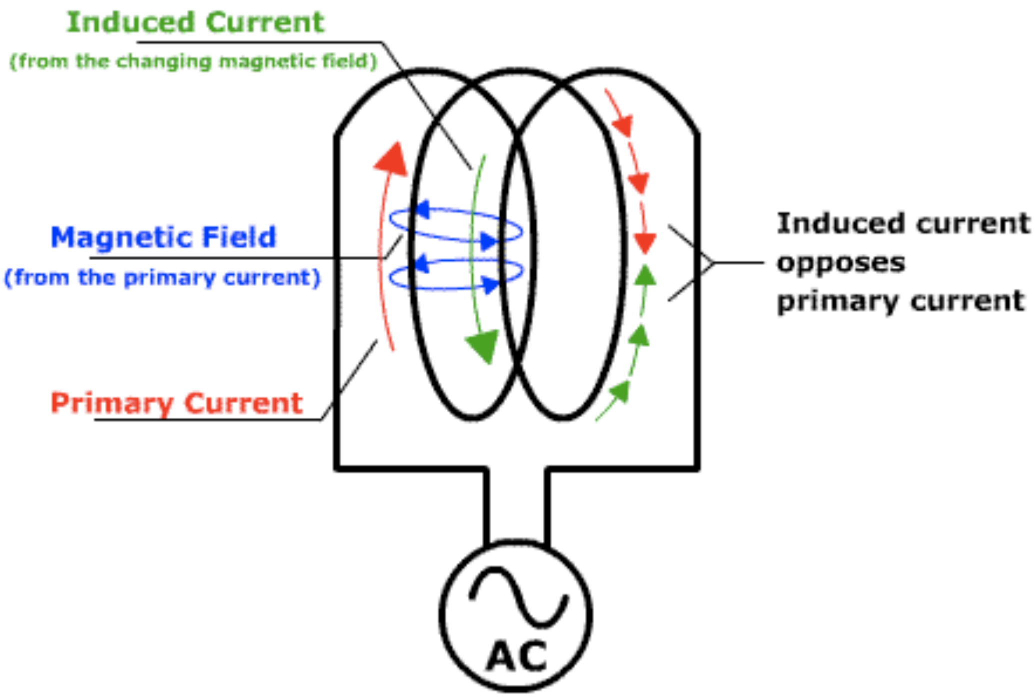


Figure 33 – Illustration of the Lenz's law

The induced current working against the primary current **results in a reduction of current flow in the circuit.**
In an AC circuit that contains only resistive components, the voltage and the current will be in-phase, meaning that the peaks and valleys of their sine waves will occur at the same time. When there is inductive reactance present in the circuit, the phase of the current will be shifted so that its peaks and valleys do not occur at the same time as those of the voltage.

3.5.2. Depth of Penetration & Current Density: the skin effect

Eddy currents are closed loops of induced current circulating in planes perpendicular to the magnetic flux. They normally travel parallel to the coil's winding and flow is limited to the area of the inducing magnetic field. Eddy currents concentrate near the surface adjacent to an excitation coil and **their strength decreases with distance from the coil** as shown in the **Figure 35**. **Eddy current density decreases exponentially with depth**. This phenomenon is known as **the skin effect**.

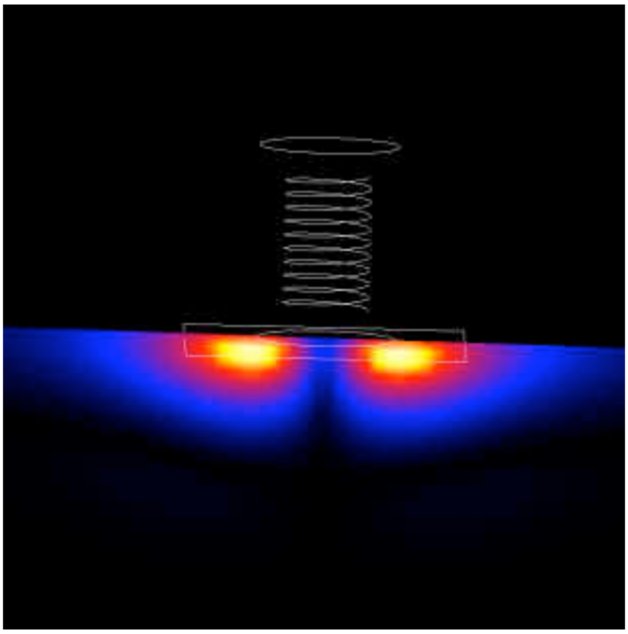


Figure 34 – EC density

The depth that eddy currents penetrate into a material is affected by the frequency of the excitation current and the electrical conductivity and magnetic permeability of the specimen. **The depth of penetration decreases with increasing frequency (f) and increasing conductivity (σ) and magnetic permeability (μ).** The depth at which eddy current density has decreased to 1/e, or about 37% of the surface density, is called **the standard depth of penetration (δ)**. The word 'standard' denotes plane wave electromagnetic field excitation within the test sample (conditions which are rarely achieved in practice).

For a plate infinite piece which is submitted to a f frequency current sheet parallel to the plane, the modulus of the current density at a depth z is:

$$J(z) = J_s \exp\left(-z\sqrt{\pi f \sigma \mu}\right) = J_s \exp\left(-\frac{z}{\delta}\right)$$

With J_S the modulus of the current density at the surface of the piece.

The depth of penetration δ is:

$$\delta = \frac{1}{\sqrt{\pi f \sigma \mu}}$$

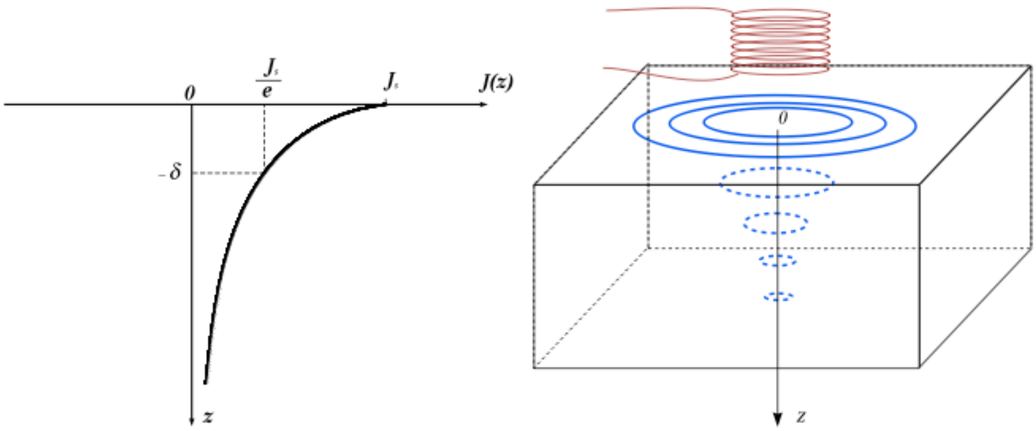


Figure 35 – Distribution of eddy currents for a piece

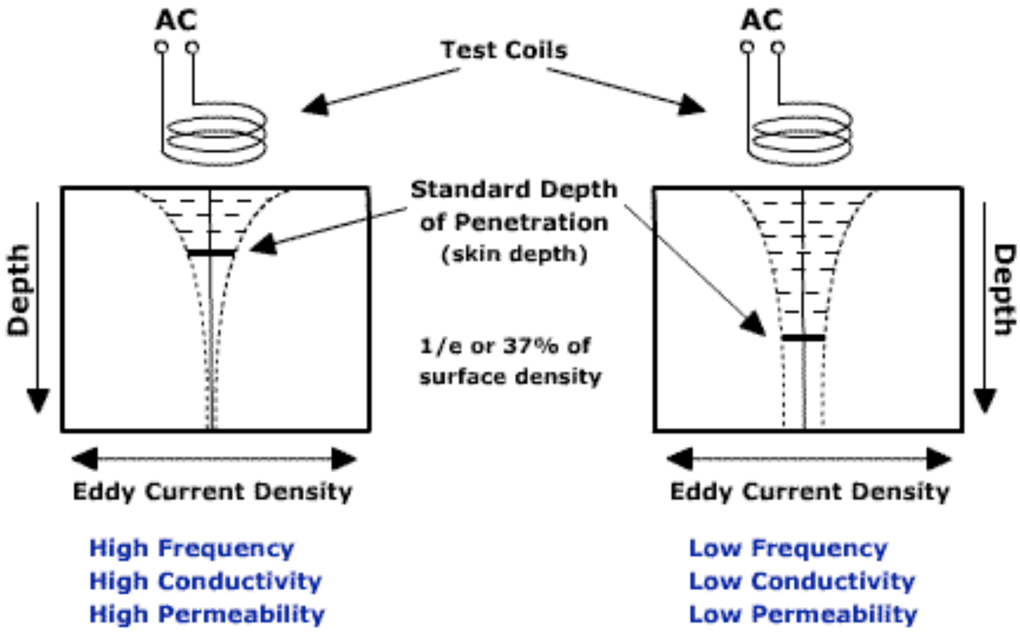


Figure 36 – Eddy current depth of penetration

The depth of penetration is an essential parameter for the inspection of the welds. Indeed, in the case of the lip-welded seals of the HNB, the weld has a thickness of 3 mm. The thickness of the pipes varies from 2.5 mm to 3 mm. The material of the weld is the same as the joint because the welding process is autogenous. Consequently, we are capable of calculating the depth penetration in the austenitic stainless steel given the frequency.

The **Figure 38** below gives different standard depth of penetration. Our concern is to reach a depth penetration of 3 mm in austenitic stainless steal. This is possible with a **frequency of 20 kHz, the depth penetration is roughly 3 mm.**

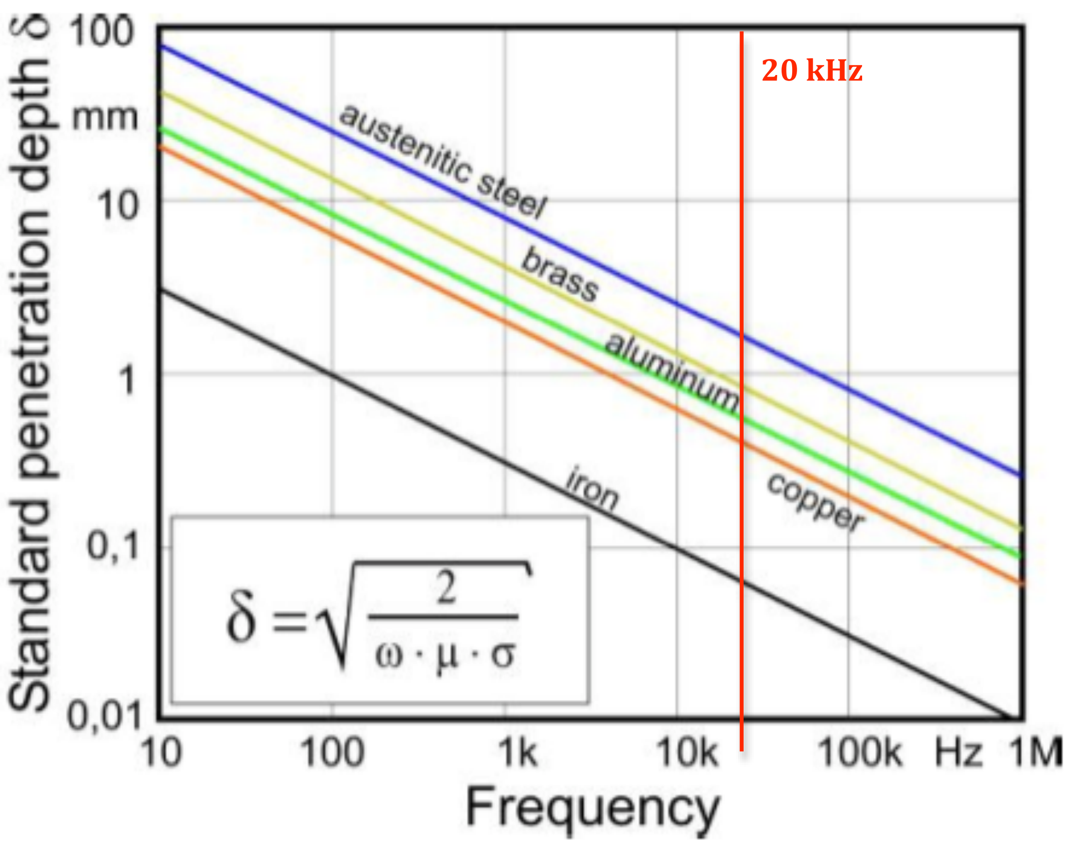


Figure 37 – Standard penetration depth

3.5.3. Conclusions

To complete the surface inspection of the weld, ECT is a fast method **inspection**. The method is **sensitive to small cracks and other defects on the surface and through up to the penetration depth**. It does not require heavy instruments, the probes are small and the inspection can rather easily be automated. However, ECT **requires smooth surface to avoid misinterpretation**, so reliable weld inspection in the lip seal case is demanding. In addition, the depth of penetration decreases when the frequency increases. For high sensitivity for small defects, the frequency should be as high as possible.

Advantages of the eddy current inspection
• Sensitive to small cracks and other defects
• **Detects surface and near surface defects: depth penetration of 3 mm reached for austenitic stainless steel.** Resolution at 3 mm depth will be determined in the ANNEX D
• Inspection gives immediate results
• Equipment is very portable
• Method can be used for much more than flaw detection
• Test probe does not need to contact the part
• Inspects complex shapes and sizes of conductive materials

Table 21 - Advantages of the eddy current inspection

Limitations of the eddy current inspection
• Only conductive materials can be inspected
• Surface must be accessible to the probe
• Skill and training required is more extensive than other techniques
• Surface finish and roughness may interfere
• Reference standards needed for setup
• **Depth of penetration is limited**

• Flaws such as delaminations that lie parallel to the probe coil winding and probe scan direction are undetectable

Table 22 - Limitations of the eddy current inspection

3.6. Conclusions

As a conclusion of the NDT basic physics principles, the **Table 23** summarizes the defects sizes detectable by the different NDT considered.

Method	Spatial Accuracy
Eddy current testing	- ~ 0.1 mm linear defect on a planar surface - Detect defects through the surface up to 3 mm
Penetrant testing	- Linear defect size : 0.001<depth<0.002 mm, 0.0002<width<0.001 mm, 1mm < length - Non-linear defect with a diameter of 0.025 mm.
Radiographic examination	- In optimum conditions spatial resolution can reach 0.2 mm
Ultrasonic testing	- Half of the used ultrasonic wave length
Visual testing	- Non-linear defect : width approximately 0.1mm

Table 23 - NDT detectable sizes comparative

At this stage of the study, the basic information about the NDT characteristics enables us to have an idea about the HNB welded pipes and lip welded seals overall applicability.
The NDT basic principles also allow us to consider the mains issues we are going do deal with. This is summarised in the **Table 24** below.

NDT	Overall applicability		Main issues
	HNB welded pipes	HNB lip welded seals	
Ultrasonic Testing (UT) Surface and volumetric inspection	Seems Feasible	Feasibility must be investigated	- Defects size - Results interpretation Background radiation impact
Radiographic Testing (RT) Surface and volumetric inspection	Seems Feasible	Feasibility must be investigated	- Background radiation impact - X ray Probe dimensions
Visual Testing (VT) Surface inspection	Seems Feasible	Seems Feasible	- Background radiation impact
Eddy Current Testing (ECT) Surface and volumetric inspection up to the depth penetration	Seems Feasible	Feasibility must be investigated	- Defects size - Background radiation impact
Liquid Penetrant testing (LPT) Surface inspection	Feasibility must be investigated	Feasibility must be investigated	- High vacuum requirements

Table 24 – Results of the NDT basic physics principles investigation

4. Literature Review

A literature review has been made about the NDT inspection of welds. I have found most of them on the Internet (scopus…) or sent by NDT specialists. In this chapter only the main studies about NDT that provide more information about the main issues to deal with have been displayed, summarised in the **Table 25** above. We encourage the reader to have a look on them if he wants more details information.

Literature References	Interesting points
ITER Lip Seal Cutting and Welding R&D Part 1 and Part2 *Selection and development of the cutting and welding processes*	Comparative study of all NDT for lip welded seals inspection.
Article of JAERI-Tech 9 *Development of pipe welding, cutting and inspection tools for the ITER blanket* **9-048**	Pipes EMAT inspection in a radioactive environment
Article of Fusion Engineering and Design 55 (2001) Manufacturing and maintenance technologies developed for a thick-wall structure of the ITER vacuum vessel	UT inspection of the ITER vacuum vessels joints in a radioactive environment.
Article of Fusion Engineering and Design 82 (2007) *Demonstration tests for manufacturing the ITER vacuum vessel*	LPT inspection of the ITER vacuum vessel.
FEED BACK OF EXPERIENCE ON CLOSE-RANGE GAMMAGRAPHY TECHNIQUE APPLICATIONS Institut de Soudure Industrie (French Welding Institute)	Development of a protection system against radioactive radiation.

Table 25 – References and interesting points of the literature review

The reader can go directly to the conclusion of this chapter where are summarized the most useful and important results given by this literature review. And then if he wants more details he should have a look on the details conclusion made for each study.

4.1. EMAT welded pipes in a radioactive environment

Article of JAERI-Tech 99-048

Development of pipe welding, cutting and inspection tools for the ITER blanket (published in July 1999)

For surface crack detection of pipe welds, Electro-Magnetic Acoustic Transducer (EMAT) was **selected in terms of radiation hardness, high temperature application and no couplant requirement.** The EMAT, is conventionnally used for the non-destructive inspection of nuclear power plants welds. The main technical issue for ITER applications is to increase the radiation hardness and the detectability of defects for pipe welds within a constrained space.

The irradiation tests of EMAT units were conducted at a dose rate of about **10kGy/hr** with no significant degradation observed up to **10MGy**. This is to be compared with a dose rate of about 1Gy/hr in the HNB.

EMAT specifications for tests

Frequency	700kHz	Beam angle	About 64.4 °
Wave mode	SH ultrasonic wave	Heat proof T	150 °C
Magnet Material Height Width	 SmCO, 7 elements 7.5 mm 5.0 mm	Coil Material Length Width	 Polyamide based 30 mm 12mm

Table 26 - EMAT specifications for tests

The prototype EMAT for pipes **has been designed to move inside a 100-A pipe (6mm of thickness) with a minimum of curvature of 400 mm** and the inspection nozzle with telescopic mechanism can be extended into a branch pipe (3mm of thickness) with a diameter of 50 mm for the non-destructive inspection.

The non-destructive tool for the welding pipe has been successfully fabricated and **the applicability to the branch pipe inspection has been demonstrated**.

The EMAT can detect 10% depth of pipe thickness defect on a base metal and 20% defect across a weld region.

Conclusion

This study is particularly interesting because they have conducted irradiation tests at a **very high dose rate: 10kGy/hour**, much higher than the radiation background inside the HNB: 1Gy/hour. It proves that EMAT can be used during the HNB maintenance.

This study is also interesting because the joints are orbital. In addition, the pipes diameters are 50 mm and 100 mm and the inspection technique can be used in a 100-A pipe with a minimum of curvature of 400 mm. The HNB pipes have a diameter from 40 to 200 mm. If it is possible to use EMAT in 50 mm diameter pipes, we can make the assumption it is possible to inspect bigger pipes. As the inspection has been conducted inside the pipes, it gives confidence about the feasibility to develop small EMAT inspection tools compatible with the restricted HNB environment.

EMAT pipes inspection
Feasible under high Gamma Radiation: 10kGy/h
Feasible under high temperature: 100°C
Feasible inside 100 mm diameter pipes with a minimum curvature of 400 mm
Feasible inside 50 mm diameter pipes
Detect 10% depth of pipe thickness defect on a base metal and 20% defect across a weld region.

Table 27 – EMAT pipes inspection

4.2. ITER vacuum vessel LPT

Article of Fusion Engineering and Design 82 (published in 2007)
Demonstration tests for manufacturing the ITER vacuum vessel

The LPT application is the most economical and practical method for the VV (Vacuum Vessel) fabrication. However, in general LPT solutions have been thought to be unfavorable for ultra-vacuum surfaces in fusion application because of unfavorable chemical contents for the plasmas. LPT applicability to the surface examination of the interior surface (ultra-vacuum side) of the ITER VV was investigated. The LPT solutions with low sulphur and halogen (fluorine and chlorine) contents and with the short evaporation times were selected to avoid adverse affect on the VV structural materials. Candidate LPT solutions were analyzed in detail including mass analysis and outgas measurements.

Based on the findings (see the article to see the main test results), it is considered that the candidate PT solution in particular could be used for the VV.

Conclusion

Candidate LPT solutions were analyzed, including mass analysis and outgas measurements. **It was found that the selected LPT solutions have sufficient low outgas rates and are applicable to the VV.**

Even though this study is **not about the pipes and lip seals**, it shows that it might be possible to use LPT in a vacuum environment that was impossible before. However encouraging these results may be, R&D must be made to prove the LPT applicability to HNB pipes and lip seals.

VV LPT results
Some LPT solutions are applicable to the VV
Encouraging results

Table 28 - VV LPT results

4.3. ITER vacuum vessel field joint UT

Article of Fusion Engineering and Design 55: *Manufacturing and maintenance technologies developed for a thick-wall structure of the ITER vacuum vessel (published in 2001)*

The NDT technique selected for **field joint** welds is UT. This was selected because access to the backside of the joint is not required with this technique.
However, flaw detectability for austenitic stainless steels is generally poor due to the large attenuation and anomalous propagation of elastic waves in stainless steels. Detectable flaw size is typically 20% of plate thickness. To improve detectability, and identify the flaw size and location more accurately, two types of UT systems have been investigated. One system (called '**Augur'**) uses multiple ultra-sonic waves with a coherent data processing system. The other uses **a phased array system**, which can control the focusing depth of the waves and steer them three-dimensionally.

The main feature of the **Augur system** is high-resolved defect visualization using coherent processing of the echo signals, allowing the defects to be located and the size determined independently from the plate thickness.
It was demonstrated that artificial **defects as small as 2 – 3 mm (in diameter) × 5 mm (in length) can be detected for the 60 mm thick austenitic stainless steel plates**.

As for **the phased array UT system**, preliminary tests have been carried out using a prototype circular phased array probe. **Notches of 5 – 15 mm (in height) × 20 mm (in length) in 35 mm thick material were successfully observed** even in the case where incident waves penetrate the weldment. Further optimization of the probe design and wave conditions (such as frequency and polarity) is in progress to improve the flaws detectability.

Results of the study

Conventional UT probes used for nuclear power plants generally withstand the gamma-radiation dose rate of up to 7.2×10^{-5} C/kg/s (=0.033Gy/h). However, in ITER a more intense dose rate: 7.2×10^{-2} C/Kg/s (=**120 000Gy/h**) is expected at the VV after operation. Using radiation-resistant materials (such as polyimide) and minimizing the use of epoxy resin, radiation-resistant UT probes have been developed. The probes were tested for 1000 h at a dose rate of 7.5×10^{-2} C/kg/s (**120 000Gy/h)** in a 60Co irradiation test facility. The probes also showed stable performance after irradiation without degradation of the sensitivity and the materials used. **Radiation hardening of the probes has been shown to be feasible**.
In addition, the probes were tested at elevated temperatures, which are expected for the VV structure due to nuclear heating. It was found that the sensitivity of the probes was significantly decreased at more than 100°C. Thus, the VV temperature should be kept low during UT inspection.

Two EMAT sets, one conventional operating at 730 kHz and the other radiation resistant operating at 1.1 MHz, were fabricated and tested. The test results using weld samples of 70 mm thick plate with artificial notches showed that the detectable flaw sizes using the conventional and the radiation-resistant EMATs were **7 and 14 mm in depth**, respectively. To identify the flaw sizes accurately, phased array type EMAT can be used.

NDT tests results and comparison of the different methods			
NDT (radiation resistant)	UT Phased Array	UT Augur	EMAT
Sampled Plate Thickness mm	35	60	70
Detectable notch depth mm	5	4	14
Detectable notch size (% from plate thickness)	14	7	20
Charaterization capability of flaw	Confirmed	Confirmed	Development required
Radiation Resistance	**Feasible**	**Feasible**	**Confirmed**

Table 29 - NDT tests results

Conclusion of the study

Based on the development results, all the investigated methods have an improved **capability to detect notch- type defects with sizes of about 10% of the inspected plate thickness**. The ability to characterize flaws can be developed for the EMAT with no problem foreseen. Although the detectability may decrease, radiation-resistant probes were found to be feasible.

This study proves that it is possible to use the UT in a radioactive environment. The radiation resistance of the EMAT has been confirmed and the UT phased array and UT augur have been proved feasible.

The problem with this study is that they **consider only field joints** and not pipes or lip seals. The detectability and the capability to characterize flaws may change with different type of joints. Especially with lip seals which are very thin. However, this study shows that it is possible to detect flaw and notch in plate with the UT.

Field Joints UT results		
Phased Array	**Augur**	**EMAT**
Feasible under 120kGy/h	Feasible under 120kGy/h	Feasible under 120kGy/h
Detect notch- type defects with sizes of about **10% of the inspected plate thickness**		
Tests on welded pipes and lip welded seals in the HNB environment maintenance must be made to confirm and get more results		

Table 30 - Field Joints UT results

4.4. Lip seal NDT selection

ITER Lip Seal Cutting and Welding R&D Part 1 and Part 2

Selection and development of the cutting and welding processes (published in July 2010 and December 2010)

When reading the results and conclusions of this study, you have to bear in mind that no radioactive background was taken into account and the inspection tests were performed on samples with no space restriction. The access to the HNB lip welded seals is very restricted due to the other components, the room to inspect the welds is a critical parameter. That is why we cannot transpose directly these results even if they are very encouraging.

The requirements for the lip weld NDT **were penetration verification and defects detection**. The requirements for the inspection method were cleanliness, restriction of residuals and the automation possibility.

As a result of the screening matrix Applicable NDT Methods for Lip Seal Inspection (for further details see the study Part 1), **visual testing, ultrasonic testing, radiographic examination and eddy current testing were selected for further research**.

Results of the study

VT Results

Visual testing was performed for all the test specimens. Surface pores, misalignment, toe overlap and irregular weld surface were detected. The results of the visual testing were as expected **and validate the method as the one NDT method to be used when evaluating lip welded seal.**

RT Results

Defect Detection

Some tenth of a millimeter sized pores were detected. Also some inclusions (tungsten) were detected.

Results for RT using digital films

The main problem in the use of digital film for the inspection of **especially thin welds** is **the lower sensitivity compared to conventional film**. The inspection is difficult to perform. That was noticed when using image quality indicator: not enough wires could be seen.

Penetration Verification

Penetration verification of TIG weld **is unreliable if the weld has been sagging to the**

side of the lip. To examine different occurrences, three TIG specimens were machined and the radiographic testing was re-performed. The penetration can **still mostly be estimated**.

The results show that the penetration verification of the **laser weld using radiographic inspection is unreliable**.

UT

Defect Detection

Defect detection of a TIG weld **proved to be challenging and the results somehow confusing both with conventional and phased array ultrasonic techniques**. When using the angle beam technique, the thin material and varying shape of the weld causes such a complicated combination of geometric echoes and their multiples. These factors combined with mode conversion make interpretation challenging and a flaw indication may fuse into other signals.

Penetration Verification

Penetration verification of a TIG weld without machining proved to be **unreliable.**

Laser weld differs from the TIG weld with its even sides. That enables using straight beam ultrasonic inspection for the penetration verification and defect detection. The penetration verification **can well be performed** using conventional dual probe, which relates to thickness measurement. But that requires that the side of the seal weld is even.

Conclusions of the study

VT results

Visual testing of the weld is performed before volumetric inspection to ensure acceptable shape and defect-free surface of the weld. The testing can be performed using two or more cameras to achieve more than one angle of view.

Visual testing is cheap and easy to perform but it **might not be possible** to perform it in a **radioactive environment**. It will need to make the camera with other material which are resistant to radiation. It is possible but it is more expensive.

UT results

The ultrasonic immersion testing of weld test plate showed promising results. In immersion testing, a focused sound beam can be used without problems of varying contact. Focused sound beam is essential to achieve sufficient resolution. **However, immersion testing cannot be applied for lip seal weld in practice because it means to immerge the UT probe in an couplant.** The tests performed with contact method both conventional and phased array ultrasonic examination **showed problems due to the thin material, varying contact and the shape of joint.**

It shows that it will be very challenging to use ultrasonic testing for lip welding to detect internal defects because of the very thin material and the lip welded geometry, where the waves reflect and the interpretation and the results becomes very hard.

It is commonly stated in literature that **the size of smallest detectable defect in ultrasonic examination is about half of the wavelength**. The wavelength of longitudinal wave in stainless steel for 5 MHz probe is 1.1 mm so the size of the smallest detectable defect is limited to about 0.5 mm.

This has to be compared with the lip seals dimensions, which are two sheets (2mm of thickness) of steel face to face. Ultrasonic examination is limited by the thickness of the lips seal and its geometry.

RT results

In this case, the weld volumetric inspection is based on radiographic examination because the achievable resolution is better than when using ultrasonic examination. Radiographic examination is standardized method for the inspection of thin plate welds but ultrasonic examination is not. The tests have shown **good performance of conventional film radiography**. For example, small pores can well be detected.

Radiographic examination tests have shown good performance for the lip welded seals inspection but the main problem is having enough space around the lip seal to perform the examination. In this study the tests have been performed on a sample, it does not take into account the environment that can force to work in tiny spaces. These tests may be not possible in the NHB environment because of the radiographic tools dimensions. In addition, this study does not take into account a radioactive background that affects the radiographic films.

The penetration measurement performance using radiography has been good for TIG weld test plates also after grinding of the weld. The penetration measurement of laser weld has proved to be possible in the case of about ≥ 3 mm of penetration.

ECT results

The eddy current testing could be possible for surface inspection but that **depends strongly on the surface condition of the weld.** The two laser weld test plates that were available for testing did not meet the surface requirements for a reliable eddy current testing. The mock-ups are assumed to have a better quality. Also the shape of TIG weld should be regular to make eddy current inspection reliable.

Unfortunately the eddy current tests have not been performed in this study. But if it depends strongly on the surface condition of the weld, it indicates that for further maintenance operation the welds may have to be cleaned.

4.5. Shielding possibility against the radioactive background

FEED BACK OF EXPERIENCE ON CLOSE-RANGE GAMMAGRAPHY TECHNIQUE APPLICATIONS

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Extract of the abstract

"The regulations applicable during the examination of a part or object using a portable ionising radiation emitting apparatus demand cordoning off of the operating zone with boundary markers. At the edge of the exclusion zone the average equivalent dose rate evaluated over the total duration of the operation, must remain less than 0.0025 mSv/h. This safety perimeter, whose access is restricted to personnel whose presence is essential (Category A), can reach major proportions.
In order to reduce this zone, Institut de Soudure Industrie has developed a device which is an adaptation of the Close-Range Gammagraphy concept, which is capable of operating with the gammagraphic apparatus approved for use in France. This device, known ***as "γ-Prox" provides enhanced protection for operators by reducing the ionising radiation dose rate whilst reducing the scanning exclusion zone.***
For example an X-ray examination using radioactive Iridium 192 source of 0.93 TBq (25 Curies) standard activity and for which the cumulative exposure times would be 2 hours for a total operation duration of 6 hours involves cordoning off an operating zone whose radius is equal to about 40 metres (this value is obtained using a 1/250th depleted uranium collimator, measured on its side – ***practical attenuation approximately 1/100th****). Under the same operating conditions (operating and exposure times), but using Selenium 75 source with γ-Prox, the radius of the exclusion zone is reduced to about 8 metres (this value is obtained using the optimised collimation system, and identical measurement conditions as those used above). "*

This ***"γ-Prox"*** system provides an enhanced protection by reducing the ionising radiation that come from the radioactive source. In our case for the inspection of the welds, we would like to protect the films against the background of radiation. If this system is capable of reducing the radiation that come from "inside", it is possible that it will reduce the dose rate radiation "inside" if the radiation come from "outside".

<u>Daniel Chauveau</u>: NDT Specialist of the Institut de Soudure Industrie (the French Welding Institute).

Mr Chauveau has already worked for the vacuum vessel of ITER and he is very skilled for teleoperation maintenance in the very particular environmental condition of ITER.

Mr Chauveau thinks that it is possible to adapt this system to protect the films from the radioactive background. However, R&D has to be done to confirm this assumption but it is a serious possibility to investigate.

Figure 38 – The “γ-Prox” in control situation of a welding pipe inspection

4.6. NDT Literature review main results

The literature review has provided a lot of very useful information about all NDT techniques except the ECT. The main results are summarized in the **Table 35** below, it displays the most important and useful results for the HNB both type of joints applicability and the missing information I have to investigate. This is the next part of the project and will be based on NDT specialists opinions. To get more details information about the results displayed below, we advise the reader to have a look on the detailed conclusion made for each study.

Literature review key points		
NDT	**Literature review main results**	**Missing information/ Ways of investigation**
UT	- Inspection tools can be radioactive resistant - Lip welded seals inspection applicability challenging with laboratory optimal conditions - EMAT has goods results for pipes inspection under high level of radiation	- UT HNB welded pipes and lip welded seals applicability
RT	- Possibility to develop a film protection system against the radioactive background - RT have shown encouraging results for lip welded seals inspection with laboratory optimal conditions - Weld penetration measurement limited	- Background radiation impact on films - X ray probe dimension - RT HNB lip welded seals applicability
VT	- Easy and cheap but inspection limited to surface defects	- HNB welds applicability - Background radioactive impact on camera
ECT	- No information	- Defect size - Background radioactive impact on EC probes
LPT	- Possibility to develop compatible penetrant with high vacuum requirements	- LPT HNB welds applicability

Table 31 – Literature review key points

5. NDT Independent Experts Opinions

The **Table 35** above indicates the main issues we need to deal with to decide the NDT HNB welds overall applicability.
To confirm the main results of the literature review and find the answers or investigations ways of the missing information several NDT specialists have been contacted.

In this chapter the main information issued from three independent NDT specialists have been gathered and summarised. The same questions have been asked to them to cross their answers to get the most confidence on the results.

5.1. Roger Davies (TWI)

Roger Davies : NDT Specialist of The Welding Institute (TWI).

Concerning the HNB lip welded seals volumetric inspection, **Mr Davies** thinks the RT is the only volumetric applicable NDT even if it has some limitations. Indeed, the UT inspection would give bad results because of the small thickness of the lip welded seal: 4 mm. Consequently, the results interpretation would be too challenging. About the ECT **Mr Davies** advised to ask more information to another NDT specialist.

RT overall applicability

Concerning the HNB lip welded seals, RT does not allow to measure and check the weld penetration. The reason is the impossibility to place the film such as in the position indicated in the **Figure 40** below. In addition, it is not possible to detect defects such as cracks parallel to the X ray beam. These two limitations are illustrated in the **Figure 40** below.

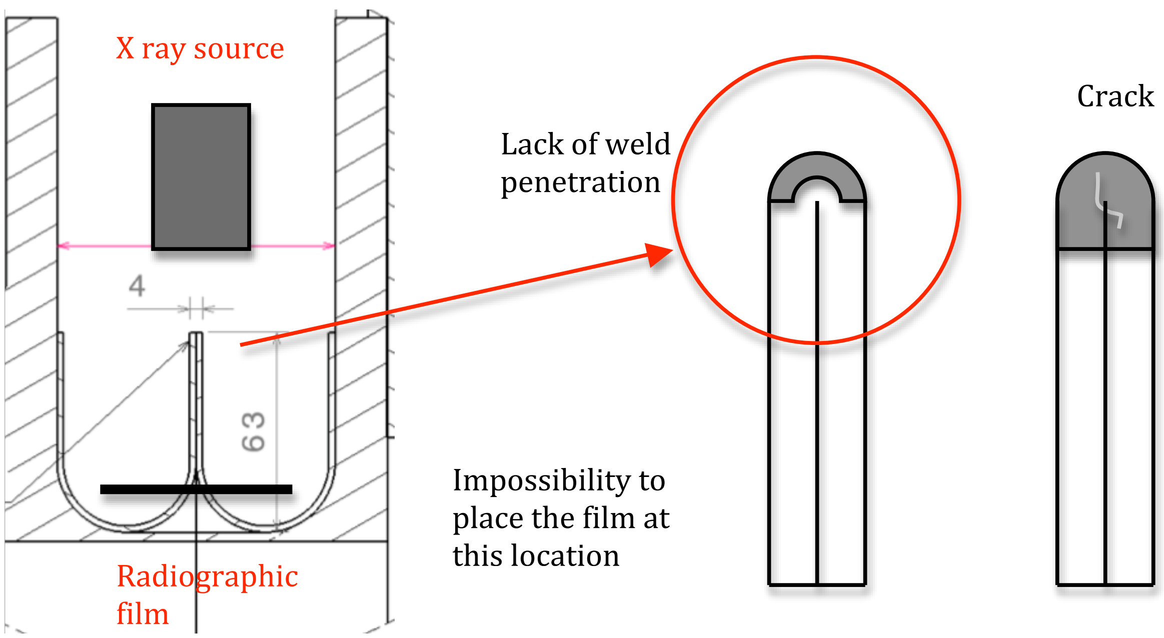


Figure 39 – RT limitations

Mr Davies thinks that concerning the HNB welded pipes, RT is the best volumetric NDT. Indeed, the limitations due to impossibility to locate the radiographic films will not occur for the HNB pipes. Consequently, the possibility to take different shots will enable to detect all the defects in the weld.

However encouraging this information may be, the main issue concerns the radioactive background that could affect the radiographic film and consequently the defects detection. **Mr Davies** did not know the effect of the radioactive background on the radiographic films.

Key points of the meeting with Roger Davies
HNB lip welded seals
RT inspection challenging
RT has its own limitations: lack of weld penetration and defects parallel to the X ray beam
HNB welded pipes
RT best volumetric NDT with it own limitations
Incertitude concerning the RT inspection feasibility in a radioactive environment for both lip welded seals and welded pipes.

Table 32 – Key Points of the meeting with Roger Davies

5.2. Paul Howarth Caparo Testing Technologies

Paul Howarth: NDT Specialist of Caparo Testing Technologies.

Concerning the HNB lip welded seals, **Paul Howarth** has provided almost the same information as **Mr Davies**: RT is the best volumetric NDT but has its own limitations on the HNB lip welded seals concerning the impossibility to detect a lack of weld penetration and defects parallel to the X ray beam.

However, **Paul Howarth** gave more information about the radioactive background effects on the radiographic films and the X ray source dimensions required to inspect the HNB lip welded seal.

HNB lip welded seals X ray source dimensions

As noticed in the **Table 17** (**3.4.2**), several parameters have to be taken into account to get exploitable radiographs such as the distance between the X ray source and the weld. This distance must be optimized given the weld thickness and the defects size searched. According to **Mr Howarth** in our case, the optimal distance would be 300 mm, which is impossible to reach given the HNB lip seals dimensions.

Concerning the X ray source dimensions, Mr Howarth made the assumption it could be feasible to develop a X ray source compatible with the HNB lip seals dimensions. But the X ray source dimensions cannot be smaller than the distance between the wall and the weld. This limitation means that the distance between the X ray source and the weld is almost null, instead of being 300 mm as required.
The impossibility to reach the optimised distance between the x ray source and the weld could have a deep impact about the defects spatial resolution.

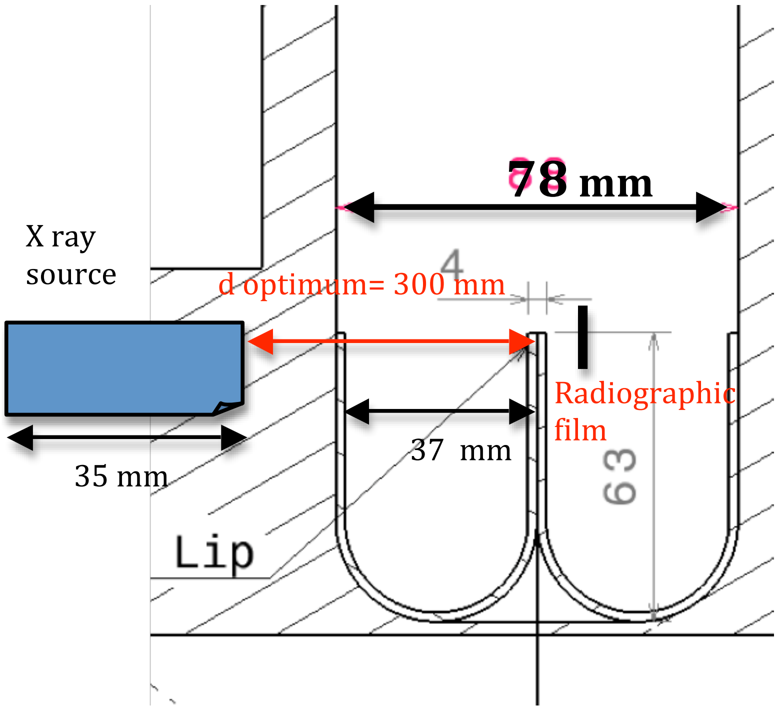


Figure 40 – Ideal X ray source dimensions with optimal distance

Impact of the radioactive background

The radioactive background of 1 Gy/h will affects the radiographic films sensitivity and contrast. Conventional film would be affected in a period of time far smaller than the time required to put in place the film, take the shot and remove it. According to **Mr Howarth,** an investigation to overcome this limitation could be to consider digital films. Even though digital films are 5-6 times more sensivitive to the radioactive exposure and consequently affected 5-6 times faster, as they are linked to a computer, it might be possible to change the contrast and the sensitivity to make up for the loss of them. But this is only an assumption.

Due to the radioactive background of 1 Gy/h and the small dimensions of the HNB lip seals, **Mr Howarth** has many doubts about the RT inspection applicability.

ECT

That is why he advised me to consider the ECT. Even though it is a surface inspection technique, by changing the EC probes parameters such as the frequency it is possible to detect defects through the surface inside the weld (to get more information see the **3.5.1 of this part**).
Mr Howarth confirmed that the EC dimensions probes can be very small such as a pen, that is why the HNB lip seals dimensions are not obstacle for the ECT.
In addition, the radioactive and magnetic background (1mT) does not affect the ECT.

Consequently, ECT could be the most suitable NDT to inspect the HNB lip welded seals. However, further developments and tests must be made to confirm these assumptions.

Key points of the meeting with Paul Howarth
HNB lip welded seals
RT
RT has its own limitations: lack of weld penetration and defects parallel to the X ray beam
Incompatibility to reach the optimised distance between the X ray source the weld
The radioactive background affects the films rapidly
At this stage **too challenging to perform RT**. R&D must be performed.
ECT
Small EC probes dimensions compatible with HNB lip seals dimensions
ECT not affected by the radioactive and magnetic environment
ECT can detect internal defects with some limitations.
ECT first NDT to investigate for the HNB lip welded seals inspection

Table 33 – Key points of the meeting with Paul Howarth

5.3. Daniel Chauveau Institut de Soudure Industrie

Daniel Chauveau: NDT Specialist of the Institut de Soudure Industrie (the French Welding Institute).

Mr Chauveau has already worked on the ITER vacuum vessel and consequently is very competent for teleoperation maintenance in the very particular ITER maintenance condition.

RT

As **Mr Howarth**, **Mr Chauveau** has many doubts about the possibility to perform RT in a radioactive environment. Indeed, as we have already said it many times, the radioactive background will affects the radiographic films sensitivity and contrast that leads the impossibility to notice them. He has also doubts the feasibility to develop a X ray source given the lip seal dimensions, the reasons are the same as **Mr Howarth** explained: impossibility to reach the optimised distance between the X ray source and the weld.

Mr chauveau recommends protecting the radiographic films against the radioactive background. Indeed, the digital films do not required as much energy as the conventional film to "print" the X ray as they are most sensitive. That is why it is possible to reduce the emission time by half and consequently the inspection by half. It means that in a radioactive environment the digital films will lose their sensitivity faster than the conventional films. A solution to shield the film against the radioactive background would be to **put the digital film in a lead box with a diaphragm**. The diaphragm would be opened only for the time of the X ray exposure. The use of digital film would allow us to reduce the time of the exposure and consequently the time of the inspection. This assumption is based on the study **FEED BACK OF EXPERIENCE ON CLOSE-RANGE GAMMAGRAPHY TECHNIQUE APPLICATIONS** Institut de Soudure Industrie (French Welding Institute), that I have considered in the literature review.

ECT

Given these two mains limitations, he deeply recommends to investigate first the ECT. Indeed, the EC probes are enough small to be used for the HNB lip welded seals inspection. In addition, ECT can detect defects inside the weld to a penetration depth of 5 mm, which is enough to inspect the entire weld. Concerning the defects size that we could detect, he advised me to consider the multi-elements EC probes etched on kapton that can reach a spatial resolution in surface of 0.1 mm.

Mr chauveau confirmed the EC probe resistance to the radioactive and magnetic background.

More information has been provided about the EC probes and we have noticed the possibility develop EC probes adaptable to a complex geometry such as the HNB lip welded seals. It is also possible to develop multi frequencies EC probes capable of investigating larger area and consequently reducing the inspection time. Time is an important parameter given the amount of welded pipes to inspect and the huge HNB components dimensions closed thanks to a lip joint.

UT mixed with ECT

Mr Chauveau recommends also investigating the UT probes. Indeed, they have already performed UT inspection for similar type of joint for space satellites components and have obtained good results. The main UT limitation would be the couplant but the EMAT does not require one. Consequently, on way of inspecting the HNB welded pipes would be to develop inspection tools that **mix EC and ultrasonic probes**. The EC probes would give information about surface defects and under the surface and ultrasonic probes would give information at the root of the weld.

Key points of the meeting with Daniel Chauveau
HNB lip welded seals
RT
RT has its own limitations: lack of weld penetration and defects parallel to the X ray beam
Incompatibility to reach the optimised distance between the X ray source the weld
The radioactive background damages the films. A solution could to develop a protection system against it.
ECT
ECT first inspection technique to investigate.
Small EC probes dimensions compatible with HNB lip seals dimensions
ECT not affected by the radioactive and magnetic environment
EC probes could detect internal defects up to **5 mm in depth**.
Multi-element EC probes etched on kapton adaptable to complex geometry
HNB welded pipes
Mix of UT and eddy current probes
Investigate the UT

Table 34 – Key Points of the meeting with Daniel Chauveau

6. NDT Comparative Study

6.1. NDT parameters selected for the comparative study

Overall applicability
The first thing to estimate is the overall applicability of a method. The material, circumstances and the test object form define some methods outside the estimation.

Operation
The inspection or scanning can be manually operated, mechanized or automated. Usually a method which can be mechanized can also be automated. Mostly automation is a question of costs and in many cases mechanizing is more reasonable. Sometimes circumstances and effectiveness require automated inspection systems. Manual inspection has the strongest human factor.

Equipment power supply
Nowadays equipment can well be battery-operated because of the development of batteries. The benefit of that kind of operation is that no electric conductor cable is needed.

Equipment size
The development of electric components has led to smaller equipment and many inspections can nowadays be performed with portable equipment. More complicated inspection systems may still require large and rather heavy equipment. If the room around the inspection object is limited, it has to be taken into account.

Flexibility
When inspection tasks are varying the flexibility of the equipment is important to reduce the amount of equipment to be maintained, calibrated etc. Sophisticated equipment nowadays offers many alternative choices for different kinds of inspection targets.

Defect type
The NDT methods are typically divided into two categories: surface and volumetric methods. The defect type defines the method to be used. For surface defects there are several efficient methods, such as eddy current testing and penetrant testing. For internal defects radiographic and ultrasonic testing are the most common methods. Another way to classify defects is to divide them into volumetric or linear defects. The orientation of different kinds of defects must also be taken into account when choosing a suitable method. Ultrasonic testing has the best performance in finding linear defects perpendicular to the sound wave. Radiographic inspection is most effective in finding linear defects parallel to the radiation and for volumetric defects, such as pores.

Penetration measurement capability
One of the main tasks required in the task definition for NDT inspection is the weld penetration measurement. It can be measured by volumetric methods.

Flaw locating capability
Flaw locating capability is one of the main issues when considering an NDT method; otherwise an inspection looses its purpose. Flaw locating is not always straightforward, especially when considering volumetric methods.

Flaw sizing
Flaw sizing is typically more challenging than locating the flaw. When considering thin wall materials and small defects, flaw sizing is even more challenging.

Reliability
The reliability of NDT inspection is affected by human factors, equipment performance and inspection procedure. By automating and mechanizing it is possible to reduce the human factors during the actual inspection but such inspection systems have to be verified beforehand just as carefully as methods operated by a human. The complexity of a system requires carefulness in settings, analysis etc. In many cases a rather simple inspection system is well enough to meet the requirements. It is not only important to detect the critical flaws but also to avoid false calls.

One side access
In some cases only one side access for the inspection is possible. While it reduces the scanning time it also limits the inspection reliability because defects may be orientated in a way that one may miss them which, for example, may happen in ultrasonic testing. For full coverage in surface and visual inspection a both side access is required.

Repeatability
Inspection has to be reproducible. In conventional and especially in manual inspection systems full repeatability is the more challenging the more complicated the inspection object is. Repeatability is essential when considering findings and in-service inspections. To achieve reproducibility, standardized methods, calibrating as well as calibration and verification blocks are used.

Preparation
It is quite typical that the inspection preparation may require more time than the inspection itself. Usually most of the preparation work can be performed outside the inspection site. That kind of preparation tasks includes, for example, calibration and the equipment setting. The equipment has to be mounted into the inspection place and all the adjustments for mechanized or automated system have to be done before the inspection. Sometimes also the inspection object requires preparation, like surface cleaning, etc. When the environment limits the time to stay on site, for example due to radiation, the preparation work has to be well planned to reduce the time required for it.

Inspection liquids/chemicals
With some methods it is not possible to avoid using chemicals or liquids. It has to be evaluated which kind of chemicals are harmful for the object or its environment and find substituting agents. The recovery of residues has to be organized. If no chemicals or liquids are allowed, some methods have to be rejected.

6.2. NDT grid details

6.2.1. Introduction

Literature References	Assigned number
ITER Lip Seal Cutting and Welding R&D Part 1 and Part2 *Selection and development of the cutting and welding processes*	1
Article of JAERI-Tech 99-048 *Development of pipe welding, cutting and inspection tools for the ITER blanket*	2
Article of Fusion Engineering and Design 55 (2001) Manufacturing and maintenance technologies developed for a thick-wall structure of the ITER vacuum vessel	3
Article of Fusion Engineering and Design 51-52 (2000) Advanced cutting, welding and inspection methods for vacuum vessel assembly and maintenance	4
Article of Fusion Engineering and Design 82 (2007) *Demonstration tests for manufacturing the ITER vacuum vessel*	5
www.ndt-ed.org	6
Introduction to Welding and Non Destructive Testing (WTC17)	7
FEED BACK OF EXPERIENCE ON CLOSE-RANGE GAMMAGRAPHY TECHNIQUE APPLICATIONS Institut de Soudure Industrie – 90 rue des Vanesses – 93420 Villepinte a.blettner@institutdesoudure.com	8
Opinions References	
Roger Davies NDT Specialist of the TWI	9
Paul Howarth NDT specialist of Caparo Testing Technologies	10
Daniel Chauveau NDT specialist of the French Welding Institute	11
Jean Marc Decitre NDT specialist in the instrumental and probes laboratory for NDT at the CEA in France.	12

Table 35 – References for the NDT comparative study

The results are based on the opinions of the NDT specialists and the literature review.

6.2.2. Ultrasonic Testing (UT)

1. **Overall applicability**

Welded pipes inspection

References: 2,9,10,11

It is feasible to perform all ultrasonic methods (conventional UT, phased array, augur and EMAT).

In general, ultrasonic methods are the most suitable for searching and sizing of **inner defects** and the most sensitive for **planar defects** perpendicular to the sound beam. Also the weld penetration measurement is possible. Surface inspection is possible but usually the surface methods are more reliable and sensitive.

Lip welded seals inspection

References: 1,3,7,9,10,11

It is very challenging to perform ultrasonic methods. The interpretation of the results would be challenging considering the small weld thickness and its very specific geometry. In addition, applying a couplant is very challenging to automate.

2. **Operation**

References: 9, 10, 11

Conventional ultrasonic contact pulse-echo, phased array, augur and EMAT can be all performed manually and automatically.

3. **Equipment**

Equipment Size

References: 2, 7

Concerning the conventional contact pulse-echo, the equipment size is enough small to enable the inspection on pipes. It would be approximately the same thing as for the phased array and augur methods. Indeed, there are no reasons why the equipment would be bigger, the technology does not differ.

Concerning the EMAT method, the **JAERI-Tech 99-048** *Development of pipe welding, cutting and inspection tools for the ITER*, has proved that it is possible to inspect pipes (diameter from 50 to 100 mm) from the inside. This provides us a good indication of the equipment size and allows us to make the assumption that it is feasible to develop small EMAT probe to inspect pipes. With further development it might be possible to perform it in 20 mm diameter pipes.

Size is not a fixed parameter. It is more important to know if it is possible to develop specific inspection tools for a specific application, so adapting the size of the inspection tools to the environment around the component which has to be inspected. This capability is measured by the parameter flexibility.

Equipment Flexibility

References: 1, 2

I have not found information about the equipment flexibility of the augur technique. However, for the conventional pulse echo and the phased array technique the equipment flexibility according the NDT screening matrix of **ITER Lip Seal Cutting and Welding R&D Part 1** *Selection and development of the cutting and welding* is good. Concerning the EMAT, the Japanese study has shown that it was possible to inspect pipes from the inside and that proves that EMAT technique can be adapted to a specific application.

However, to get more information about the equipment flexibility further tests are needed.

4. Defect type

All four ultrasonic inspection techniques are capable of detecting surface and internal defects. However, the accuracy varies according to the method and the dimensions of the inspected component.

Lip welded seals inspection

References: 1,3,4,7,9,10,11

It is very challenging to perform ultrasonic testing to lip welded seals because of its geometry that makes more difficult to interpret the results. I have found only one study about the inspection of the lip welded seals with the UT: **ITER Lip Seal Cutting and Welding R&D Part 1** *Selection and development of the cutting and welding.* The results are not encouraging and this is confirmed by the NDT specialists that told me it would be challenging to interpret the results.
Consequently, the defect type results in the grid are **only for the welded pipes**.

Welded pipes inspection

References: 2,3,4,7

If you consider the characteristics of the ultrasonic testing, it is likely to give good results for internal and volumetric defects on the HNB pipes. Especially for the EMAT according to the article of **JAERI-Tech 99-048**: *Development of pipe welding, cutting and inspection tools for the ITER.* Concerning the phased array and augur techniques, the article of **Article of Fusion Engineering and Design 55**: *Manufacturing and maintenance technologies developed for a thick-wall structure of the ITER vacuum vessel*, has shown good results.

5. Performance

Penetration measurement capability

References: 1

As it is very challenging to interpret the results using ultrasonic testing on lip welded seals, it is challenging to perform a penetration measurement. However, the article of **ITER Lip Seal Cutting and Welding R&D Part 1** *Selection and development of the cutting and welding*, has shown that for the conventional pulse echo technique the penetration verification for the laser weld can be well performed using conventional dual probe. But that requires that the side of the seal weld is even which might no be always the case. In addition, for TIG weld the penetration measurement is not possible. For the EMAT, phased array and augur I have not found information about this.

For the welded pipes, theoretically the penetration measurement is possible with ultrasonic testing but I have found no experimental results about this.

Flaw locating and sizing capabilities

References: 1,2,7

Due to the small dimensions of the lip welded seals it is very challenging to locate and size a defect. However, the capabilities are good for the welded pipes. The EMAT has shown good results in the article of **JAERI-Tech 99-048**: *Development of pipe welding, cutting and inspection tools for the ITER*. But I have not found such results on pipes for the three other ultrasonic techniques. However, we can assume that they are quite similar. But there might be substantial differences in the results depending on which UT technique you perform. Phased array and augur technique are said to be more accurate than the conventional echo pulse according to the article of **Article of Fusion Engineering and Design 55**: *Manufacturing and maintenance technologies developed for a thick-wall structure of the ITER vacuum vessel*. As the study is not about pipes this is only an assumption.

Further researches need to be done on the HNB pipes to get more results about flaw locating and sizing capabilities of UT.

Reliability

References: 1,2,3

The main challenging issue is the interpretation of the results. Given the UT techniques characteristics, we can be confident and rely on them for the welded pipe inspection. But it depends on the dimensions and the thickness of the component to be investigated. In the article of **Fusion Engineering and Design 55**: *Manufacturing and maintenance technologies developed for a thick-wall structure of the ITER vacuum vessel* and of **JAERI-Tech 99-048**: *Development of pipe welding, cutting and inspection tools for the ITER*, UT has shown good results. But it has to be confirmed by further tests on HNB welded pipes.

Repeatability

References: 2,3

It depends on the component complexity and its geometric dimensions. As we are considering only welded pipes (the overall applicability of UT inspection for lip welded seals is challenging), the main concern is the thickness. As the article of **JAERI-Tech 99-048**: *Development of pipe welding, cutting and inspection tools for the ITER*, has shown good results for the EMAT inspection technique we can assume that it would be the same as for the other UT techniques. In the article of **Fusion Engineering and Design 55**: *Manufacturing and maintenance technologies developed for a thick-wall structure of the ITER vacuum vessel* UT has shown good results concerning the repeatability but pipes are not considered. It has to be confirmed by further tests on HNB welded pipes.

Preparation

References: 7

UT techniques need a couplant (liquid for the UT) (exception for the EMAT that does not need a couplant) but you do not have to clean the welded pipes before the inspection. The use of a couplant means an after cleaning to meet the high vaccum requirements.

6. **Couplant**

References: 7

UT techniques need a couplant (liquid for the UT) (exception for the EMAT that does not need a couplant.

7. **Environnent**

Radiation background of 1 Gy/hour

References: 2,3,7

In the article of **Fusion Engineering and Design 55**: *Manufacturing and maintenance technologies developed for a thick-wall structure of the ITER vacuum vessel* and of **JAERI-Tech 99-048**: *Development of pipe welding, cutting and inspection tools for the ITER*, UT techniques have shown good performances under high dose rate (higher than 1Gy/hour). The radiation resistance of UT inspection tools have been proved, especially for the EMAT.

6.2.3. Radiographic Testing (RT)

1. **Overall applicability**

Welded pipes inspection

References: 7,8,9,10,11

It is feasible to perform X-ray for the inspection of welded pipes. For this goal this is the best volumetric NDT according to the NDT specialists.

Surface inspection is possible but usually the surface methods are more reliable and sensitive.

The main issue is to deal with the radiation background the affect the sensibility of the films (conventionnal or digital). One possiblity could be to shield the films with a system similar to the ***"γ-Prox"*** developped in the **FEED BACK OF EXPERIENCE ON CLOSE-RANGE GAMMAGRAPHY TECHNIQUE APPLICATIONS** by the French Welding institute.

Lip welded seals inspection

References: 8,9,10,11

Due to the small dimensions of the HNB lip welded seals, it is challenging to develop a suitable X ray probe. In addition, it is not possible to check the weld penetration with this technique. Concerning the background radiation the issue is the same as for the welded pipes inspection. Consequently, the overall applicability of RT on HNB lip welded seals is challenging, a lot of Research and Development has to be performed.

2. Operation

References: 7,9, 10, 11
RT can be performed manually and automatically.

3. Equipment

Equipment Size
References: 1,10,11
The equipment size is a limitation for the HNB lip welded seals inspection but the NDT specialists think that it could be possible to develop a specific X ray probe for this application. However, this is only an assumption at this stage such technology does not exist. In addition the films have to be shielded against the background radiation with a system similar to the ***"γ-Prox,*** this system requires a volume that has to be taken into account. At this stage it does not seem to be possible to inspect the HNB lip welded seals due to the equipment size.

Concerning the welded pipes the RT has already been performed many times at the JET and is the selected volumetric NDT for this application.

Equipment Flexibility
References: 10, 11
Possibility to develop a specific X ray probe for the HNB lip welded seals inspection.
Possibility to develop a similar system to the ***"γ-Prox"*** to provides a protection of the films against the background radiation.
These two ways of investigation need Research and Development.

4. Defect type

It is challenging to perform ultrasonic testing to lip welded seals because of its small dimensions that require a specific X ray probe. In addition the background radiation will affect the sensitivity of the films.
These are the main two RT HNB lip welded seals limitations.

Lip welded seals inspection
References: 1 ,7,9,10,11
If we ignore these two limitations, RT has very good capabilities to detect almost any kind of defects. The article **ITER Lip Seal Cutting and Welding R&D Part 1 and Part2** *Selection and development of the cutting and welding processes* have shown encouraging results but the inspection was performed in a laboratory that does not take into account the lack of room due to the other components.
In addition, due to the geometry of the lip welded seals it is not possible to check the weld penetration.

Welded pipes inspection

References: 7,9,10,11

If we ignore the background radiation, the RT has already been performed a lot of times at the JET and is the selected volumetric NDT to inspect the welded pipes.

5. Performance

Penetration measurement capability

References: 1,7,9,10,11

Impossible to check the weld penetration of the HNB lip welded seals.
Concerning the welded pipes, the penetration measurement has already been performed at the JET and has been proved.

Flaw locating and sizing capabilities

Lip welded seals inspection

References: 1,9,10,11

The article **ITER Lip Seal Cutting and Welding R&D Part 1 and Part2** *Selection and development of the cutting and welding processes* have shown encouraging results if we do not take into account the two RT limitations on HNB lip welded seals. However encouraging these results may be, R and D has to be done to take real conclusions.

Welded pipes inspection

References: 7,9,10,11

RT have shown very good results for JET welded pipes. The main issue is to find a way to protect the films against the background radiation.

Reliability and Repeatability

References: 7,9,10,11

RT has its own limitations and concerning the HNB lip welded pipes at this stage we cannot rely on this NDT.
Concerning the HNB welded pipes inspection, if we do not consider the background radiation we can rely on RT.

Preparation

References: 7

Do not need a pre-cleaning of the weld. However, there is a legislation to respect to use RT. film

6. Couplant

References: 7

No couplant.

7. Environnent

Radiation background of 1 Gy/hour

References: 9,10,11

The conventional and digital films are affected by the background radiation. If they are not shielded against it they lose all their sensibility.

The digital films are more sensitive than the conventional one, it means that for the same amount of radiation they have a smaller exposure time. In a radioactive environment the digital films are disadvantaged compared to the conventional one. But if there is a protection system, with the digital films the inspection is made faster. In addition, as the digital films are linked to a computer, it might be possible to change the contrast and enhance the sizing and locating capabilities.

6.2.4. Visual Testing (VT)

1. Overall applicability

References: 1

The VT is applicable for both the lip welded seals and welded pipes. The only limitation is the radioactive background that can affect the electronics of the camera. But cameras resistant to radiation are available, it is just a matter of price.

VT is the easiest and cheapest way to inspect weld but it allows only detecting defects on the surface. As ITER requires volumetric inspection, this NDT can only be complementary to a volumetric NDT.

2. Operation

References: 1

VT can be performed manually and automatically.

3. Equipment

Equipment Size

References: 1

Depending on the type of cameras needed but the equipment size is not a limitation. The only limitation is due to the necessity of protecting the camera against the radioactive background.

Equipment Flexibility

References: 1

Possibility to develop a camera shielded against the background radiation and radiation hardened cameras can be bougth.

4. **Defect type**

References: 1
The VT can only detect defects on the surface of the weld.

5. **Performance**

References: 1
Penetration measurement capability
Impossible.

Flaw locating and sizing capabilities
Depending on the spatial accuracy of the camera but VT allows detecting small surface defects.

Reliability and Repeatability
VT provides an acceptable reliability and repeatability for surface defects detecting.

Preparation
Do not need a pre-cleaning of the weld.

6. **Couplant**

References 1
No couplant.

7. **Environnent**

References 10
Radiation background of 1 Gy/hour
Possibility to shield the camera against the background radiation.

6.2.5. Eddy Current Testing (ECT)

1. **Overall applicability**

ECT is a surface NDT but it can also detect defects through the surface up to the standard depth of penetration that can be calculated knowing the characteristics of the weld materials, and the frequency of the EC.
We are considering austenitic stainless steel, and with a frequency of 20kHz the EC standard depth of penetration is about 3 mm. The maximum thickness of the pipes is 3 mm and the weld penetration of the weld for the lip welded seals is about 3mm. Moreover, it exists different kind of EC sensors and one of them called Giant magneto Resistance (GMR) enable to extend the depth of penetration to 7 mm.
Consequently, for the welds we are considering, the ECT provides a volumetric inspection. Spatial resolution at this depth is however unknown.

At this stage, thanks to the opinions the NDT specialists that bring us confidence, this is the first NDT to investigate for the volumetric inspection of the lip welded seals.

Welded pipes inspection

References: 6,7,10,11,12

It is feasible to perform ECT for the inspection of welded pipes.
The EC probes can be made of material resistant to the background radiation.

Lip welded seals inspection

References: 6,7,10,11,12

The most challenging issue is to deal with the small dimensions of the weld and its specific geometry but fortunately an EC probe has roughly the same dimensions as a pen. Moreover, the technology is very flexible and enables to make specific probe adaptable to the geometry of the weld. This is only a matter of Research and Development, such kinds of probes have already been made for other specific application.

2. Operation

References: 6,7, 10, 11, 12

ECT can be easily performed manually and automatically.

3. Equipment

Equipment Size

References: 6,7,10,11,12

The EC probes dimensions are very similar to a pen. It exists hundred of different probes specific to one application. It is possible to develop specific EC probes for specific geometry and application. That is why the EC probes dimensions are not a limiting factor.

Equipment Flexibility

References: 6,7,10,11,12

This is the main advantage of the ECT. This is the most flexible NDT because the technology provides huge possibilities of designing specific EC probes adaptable to a very complex geometry. According to the NDT specialists there are doubts that a EC probe adaptable to the weld geometry could be developed. It only needs Research and Development to set up the parameters such as the frequency of the probes and the EC probes technology.

4. Defect type

References: 6,7,10,11,12

ECT provides a volumetric inspection up to the standard penetration depth which is about 3 mm for austenitic stainless steel for a EC probe frequency of 20 kHz. The standard penetration depth can be extended up to 7 mm with GNR sensors.

5. Performance

Penetration measurement capability

It is possible to detect defects up to the standard penetration depth but I have not found information about the possibility to check the weld penetration. This point needs further investigation.

Flaw locating and sizing capabilities

References: 6,7,10,11,12

With a multi-elements EC probes etched on kapton it is possible to detect surface defects with a spatial accuracy of 0.1 mm. With GMR sensors it is possible to detect defects up to 7 mm. This point needs further investigations and research and development about EC probes. We will see in the ANNEX D the spatial resolution at the depth of 3 mm.

Reliability and Repeatability

References: 6,7,10,11,12

The interpretation of the results needs a skilled technician but this is a very reliable and repeatable NDT.

Preparation

References: 7

Do not need a pre-cleaning of the weld.

6. Couplant

References: 7

No couplant.

7. Environnent

Radiation background of 1 Gy/hour

References: 10,11

According to the NDT specialists the background radiation of 1 Gy/hour is not a limiting factor for the weld inspection. It is feasible to develop resistant EC probes.

6.2.6. Liquid Penetrant Testing (LPT)

1. **Overall applicability**

References: 5
The use of a liquid penetrant is the main disadvantage of this technique because it could not meet the high vacuum requirements of the HNB components. Finding a suitable penetrant liquid is the main issue. But encouraging results have been shown in the study of **Article of Fusion Engineering and Design 82:** *Demonstration tests for manufacturing the ITER vacuum vessel*, where a new liquid penetrant has been proved to be suitable for high vacuum area. However, a lot Research and Development remains to be done before having the possibility to rely on it.
In addition, LPT is a surface NDT inspection and does not provide volumetric inspection, and penetrant can temporarily block leaks that could give false results.

2. **Operation**

References: 11
LPT can be easily performed manually but due to the necessity of pre-cleaning, after-cleaning on the considerable surface to inspect, perform these operation automatically could take a very long time.

3. **Equipment**

Equipment Size and flexibility
However I have found no information about the equipment size and flexibility, the equipment consists mainly of the equipment for the pre-cleaning and the after cleaning.

4. **Defect type**

References: 7,11
LPT provides only a surface inspection.

5. **Performance**

Penetration measurement capability
Impossible.

Flaw locating and sizing capabilities
References: 7
The length of a surface breaking discontinuity can be determined readily, but the depth dimensions can only be assessed subjectively by observing the amount of bleed out.

Reliability and Repeatability

References: 7

Interpretation is sometimes difficult.

Preparation

References: 7

The preparation and pre-cleaning is an important part of the LPT. The majority of spurious indications and mistakes result from poor cleaning of the surface. Then the penetrant has to be applied and removed.

6. Couplant

References: 7

The penetrant must meet the high vacuum requirements of the HNB components.

7. Environnent

Radiation background of 1 Gy/hour

I have found no information about the impact of the background radiation on the LPT.

6.3. Conclusion of the NDT comparative study: overall applicability and main ways of R&D

6.3.1. Radiographic Testing (RT)

At this stage it is **not feasible to inspect the HNB lip welded seals** with RT. The two main limitations are:

- The background radiation of 1 Gy/h affects the radiographic image quality and make challenging the detection of defects.
- The X ray source dimensions are incompatible with the HNB lip welded seals.

The main reasons are:

- The radiographic films are sensitive to the radioactivity (see the paragraph **Radiographic Film in Part3 I.4** for more explanations), a dose rate of 1Gy/h will damage the film before the X ray exposure.
- It could be feasible to make an X ray source whose dimensions enable to place it between the weld and the wall (see the **Figure 40** below), but the distance between the radiation source and the film must be optimized to get an exploitable radiographic image. This distance cannot be null and in our case according to **Paul Howarth** close to 300 mm.

RT has other limitation such as the weld penetration because of the impossibility to place the radiographic film below the weld (see the **Figure 38**).

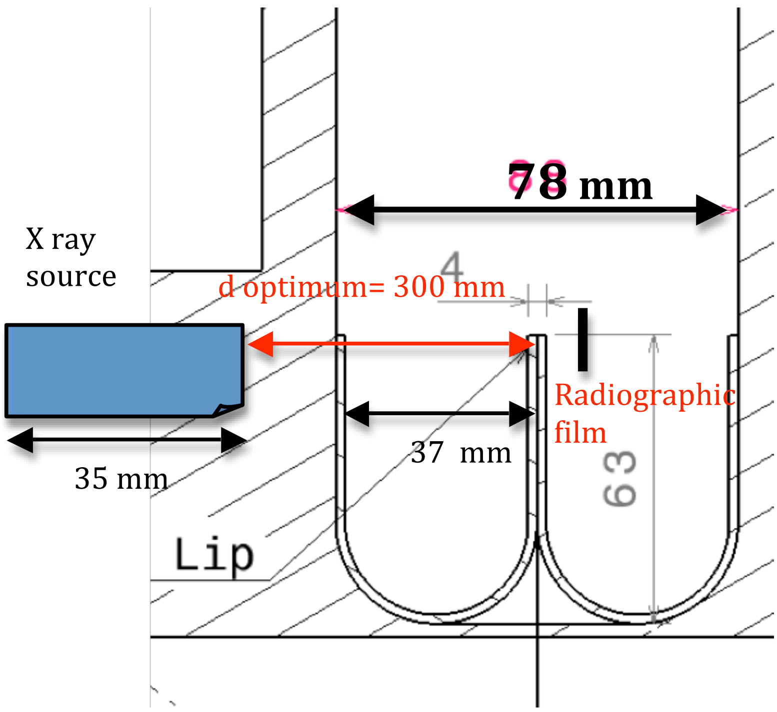


Figure 41 – *X ray source optimum distance*

As for the **HNB lip welded seals the background radiation of 1 Gy/h make the HNB welded pipe inspection impossible** for the reason explained above.

Ways of investigation to overcome the RT performing limitations:

- Developing a radiation protection system as the ***"γ-Prox"*** that reduces the ionizing radiation (see **Mr Chauveau opinion**). This system would protect the radiographic films against the radioactive background.
- As it is fundamentally impossible to reach the optimum distance of 300 mm due to the HNB lip seal dimensions, the only way of improvement concerns the spatial resolution with a distance between the X ray source and the weld almost null.

If we make the assumption that these two limitations are overcome, which is not likely to be the case within a few years, RT is a reliable volumetric NDT that enable detecting many kinds of defects such as cracks, flaws, inclusion, weld penetration… The maximal spatial resolution would be about 0.2 mm.

6.3.2. Ultrasonic Testing (UT)

At this stage it is **not feasible to inspect the HNB lip welded seals and welded pipes** with UT. The main limitations are not due to the UT probe dimensions that are compatible with the HNB lip seals dimensions but due to:

- The HNB lip welded seal complex geometry and small dimensions (4 mm width and 3 mm height) and the maximum HNB pipes thickness of 3 mm make the interpretation UT results challenging.

The main investigation way to overcome this limitation would be to enhance the UT spatial probe resolution to make easier the interpretation of the results. As the UT techniques require a couplant such as water (except for the EMAT), another investigations way would be to improve the after-cleaning to meet the HNB components high vacuum requirements.

If we me make the assumption that these two limitations are overcome (a lot of Research and Development must be done), UT techniques are reliable volumetric NDT that enable to detect and localise many kinds of defects. Moreover, the radioactive background of 1 Gy/h does not affect significantly the UT inspection results as is has been proved in the study of **Article of Fusion Engineering and Design 55**: *Manufacturing and maintenance technologies developed for a thick-wall structure of the ITER vacuum vessel* and **JAERI-Tech 99-048**: *Development of pipe welding, cutting and inspection tools for the ITER*.

6.3.3. Visual Testing (VT)

VT is the cheapest and easiest NDT, it can inspect both HNB lip welded seals and welded pipes. However, the main limitation is inherent to VT:

- VT is only an NDT surface inspection

The camera can be shielded against the radioactive background of 1 Gy/h provided to pay the price.
As the main limitation is inherent to VT it is difficult to improve its performances. The only improvement way is to enhance the camera technology to provide a better resistance against the radioactive background and the pixel resolution at a lower price.

6.3.4. Liquid Penetrant Testing (LPT)

At this stage it is not feasible to perform LPT for the HNB lip welded seals and welded pipes inspection mainly due to the penetrant. Indeed now it does not meet the HNB components high vacuum requirements.
The second limitation is inherent to this NDT that provides only a surface inspection.

Consequently, the main improving way would be to make a compatible penetrant and enhance the after-cleaning. The study of **Article of Fusion Engineering and Design 82:** *Demonstration tests for manufacturing the ITER vacuum vessel*, has shown encouraging results where a new liquid penetrant has been proved to be suitable for high vacuum area. However, a lot of studies remain to be made before having the possibility to rely on it.

6.3.5. Eddy Current Testing (ECT)

At this stage the ECT is the only NDT capable of detecting defects through the surface that could be applicable to the HNB lip welded seals. The main limitation is due to:

- the EC standard depth penetration

However, in the case of the austenitic stainless steel the EC standard depth penetration at a frequency of 20 kHz is about 3 mm. Moreover, some EC probe sensors enhance the standard depth penetration and can extend it up to 7 mm. Consequently, this limitation is overcome in our case.

The EC probes dimensions are suitable for the HNB lip seals inspection. Indeed, most of them have the same dimensions as a pen. The possibility to design specific eddy

current probe adaptalbe to specific geometry is one of the main advantage of this NDT. According to **Mr Chauveau** and **Mr Decitre** there is no doubt about a multi-elements EC probe conception that fits to the HNB lip welded seals.
Moreover, the magnetic and radioactive backgrounds do not affect the EC probes performances.

However, at this stage the EC probes adapted for HNB lip welded seal inspection does not exist. But the technology to make such a probe is available and **Mr Decitre** has no doubt about its conception. Considering all these advantages the ECT is the first NDT to investigate.

We will have to deal with the surface roughness issue and the spatial resolution at required depth.

7. Summary and Conclusions

NDT	HNB welds overall		Main limitations	Main advantages	Ways of ameliorating
	pipes	lip seals			
RT	No	No	Background radiation of 1Gy/h X ray probe dimensions Radiograph depending on multiples variables	Volumetric NDT Detect multiple kind of defects Very good spatial resolution Reliable	Shielding the films against the radioactive radiation Reducing the probe dimensions
UT	Challenging	No	Interpretation of the results challenging for complex and thin geometry Results depending on multiples variables	Volumetric NDT Resistant to radiation Small probe dimensions	Improving the results for complex and thin geometry
VT	Yes	Yes	Surface NDT Expensive shielded cameras to the radiation	Cheap and easy to perform	Improving the cameras technology
LPT	No	No	Surface NDT Penetrant not compatible with the high vacuum requirements	Applicable to complex geometry	Finding a compatible penetrant
ECT	The most applicable for volumetric inspection	The most applicable for volumetric inspection	Standard depth penetration	Volumetric inspection from the surface to the penetration depth Applicable to complex geometry EC probes flexible and adaptable Resistant to radiation Probes dimensions	Improving spatial resolution and depth penetration

Table 36 – Main results of the NDT comparative study summary

The ITER project needs a volumetric inspection NDT, the radiographic and ultrasonic testing were potential candidates but they need further research and development to be applicable to the HNB lip welded seal in a radioactive environment.

The visual and penetrant testing are surface inspection techniques and cannot detect volumetric defects. Concerning the liquid penetrant testing, the liquid must meet the high vacuum requirements. At the moment there is no such liquid.

At this stage, the ECT is the only feasible NDT applicable to the HNB lip welded seals and welded pipes, capable of detecting defects through the surface, that meet the maintenance requirements (resistant to the radioactive and magnetic background and compatible with the HNB lip seals dimensions). The EC inspection has several advantages that give us confidence in its capability to inspect the HNB welds. These advantages are summarized in the **Table 41** in the first chapter of the next ANNEX.

The **NDT Grid in the annex** displays all the results of the comparative study.

8. References

Experts	Contact
5.1 **Roger Davies** TWI	Roger Davies The Welding Institute roger.davies@ccfe.ac.uk +44 123546 44 74
5.2 **Paul Howarth** Caparo Testing Technologies	Paul Howarth Caparo Testing Technologies phowarth@caparotesting.com + 44 1993 778522
5.3 **Daniel Chauveau** Institut de Soudure Industrie	Daniel Chauveau NDT Fellow Product Developt Department d.chauveau@institutdesoudure.com +33 1 49 90 37 32 Institut de Soudure Industrie ZI Paris Nord 2 – 90 rue des vanessses – 93420 Villepinte
Part	**Reference Literature**
3.1 3.2 3.3 3.4 3.5	Introduction to Welding and Non Destructive Testing (WTC17) TWI Techniques de l'ingénieur TI-r1400 www.techniques-ingenieur.fr www.ndt-ed.org
4.1	**Article of JAERI-Tech 99-048** *Development of pipe welding, cutting and inspection tools for the ITER blanket (published in July 1999)*
4.6	**ITER Lip Seal Cutting and Welding R&D Part 2,** Evaluation of cutting and welding processes for Lip Seal maintenance work Research Report VTT VTT's contact address VTT, PO Box 1000, FI 02044 VTT, Finland
4.4	**Article of Fusion Engineering and Design 82 (published in 2007)** *Demonstration tests for manufacturing the ITER vacuum vessel*
4.5	**Article of Fusion Engineering and Design 55:** *Manufacturing and maintenance technologies developed for a thick-wall structure of the ITER vacuum vessel (published in 2001)*
4.7	**FEED BACK OF EXPERIENCE ON CLOSE-RANGE GAMMAGRAPHY TECHNIQUE APPLICATIONS** A. Blettner (Institut de Soudure Industrie – 90 rue des Vanesses – 93420 Villepinte – e-mail : a.blettner@institutdesoudure.com)

ANNEX D
Eddy Current Inspection Tools

Contents

1. Introduction

The ECT has been selected to inspect the HNB lip welded seals and welded pipes. Indeed, the EC probe design is very flexible and can be adaptable to the weld geometry. The multiplicity of different kind of EC probes enables to select the appropriate EC technology to detect subsurface defects in the weld.

The EC technology based on the multi-elements EC probes etched on kapton and the Giant Magneto-Resistance (GMR) sensors for HNB lip welded seals inspection have been investigated. Then the selection of the appropriate EC probe(s) leads to consider the EC inspection tools design. Then the design of the EC inspection tools which includes the EC probe and the carrying tools have been investigated.

This will lead to a feasible EC inspection process but we have to bear in mind that **the EC probe needs further research and development**. Indeed, at this stage of the study, the EC probes capable of inspecting the HNB lip welded seals and meet all the technical requirements, such as detect defects at a depth of 3 mm with accuracy, do not exist. But as this investigation is based on several NDT experts opinions and research studies it led to the conclusion of a feasible EC probe concept.

2. Purpose and Scope

The objective is to come up with a feasible concept design of the EC inspection tools. To achieve this objective I have divided the work into two steps:

- Investigations about EC probes
- Concept Design of the EC inspection tools

The investigation of the EC probes will lead us to the selection of the appropriate EC probe for the HNB lip welded seal inspection. Concerning the HNB welded pipes inspection the same EC probes could be used. Indeed the HNB pipes thicknesses are similar to the HNB lip weld penetration: ≈ 3 mm.

Then given the information gathered about the EC probes we will make a concept design of the inspection tools.

3. Investigation of eddy current probes suitable for the inspection of the lip welded seals of the HNB

The EC has been selected as the most promising NDT for the HNB lip welded seals inspection. Indeed, at this stage the EC meets most of the environmental conditions during the maintenance and the inspection requirements of the lip welded seals.

The **Table 41** below sums up the main EC characteristics to take into account for the HNB welds inspection of the welds.

Parameters	Eddy current characteristics
Automated	Easily feasible
Dimensions of the equipment	The probes have the dimensions required for the weld inspection
Flexibility of the equipment	Total flexibility of the probes. The probes dimensions can be adaptable to the geometry and dimensions of the weld to inspect. Possibility to make specific probes for specific application
Probes	Probes do not need to contact the weld. Inspect shapes and sizes of weld. Several different kinds of probes and possibility to mix them to detect different kinds of defects.
Possibility of battery	Possibility to perform the inspection with battery.
Volumetric inspection	Possibility to detect defects through the surface but has some limitations. Detect cracks.
Surface inspection	Very sensitive to surface defects.
Depth of penetration	Up to 7 mm for austenitic stainless steel.
Accuracy	Depends on the technology of the probe but up to 0.1 mm at the surface.
Sensibility	Sensible to small cracks and other defects with accuracy up to 0.1mm at the surface.
Radiation resistance	Resistant to a background radiation of 1Gy/h
Magnetic field perturbation	Resistant to a magnetic background of 0.1mT
Temperature resistant	Resistant to 100 °C

Table 37 – Main characteristics of the eddy current for the inspection of HNB's welds

However encouraging these characteristics may be, the inspection eddy current tools for the HNB weld do not exist. That is why, further investigations have to be done to prove the feasibility of specific eddy current tools suitable for the HNB weld inspection.

The **Table 42** below sums up the main missing information about the ECT we need to find out.

Missing Information
Spatial Resolution at the required depth
Impact of the surface roughness on the spatial resolution

Table 38 – ECT missing information

3.1. Eddy Current Experts

3.1.1. Daniel Chauveau

Chauveau Daniel: NDT Specialist of the Institut de Soudure Industrie (the French Welding Institute).

Mr Chauveau opinion concerning the HNB lip welded seals inspection is that it is feasible to develop a specific EC probe suitable for this application. Indeed, it is easy to develop custom EC probes. However, given the peculiar geometry of the weld many precautions have to be taken to avoid the edge effects.

He advises to investigate the development of multi-elements sensors eddy current probes based on micro-coils etched on a flexible kapton film, specially designed for the HNB lip welded seal.

The **Figure 42** shows a 32 elements eddy current probe. It has a 350 μm spatial resolution. The detection of the defect is fast and accurate.

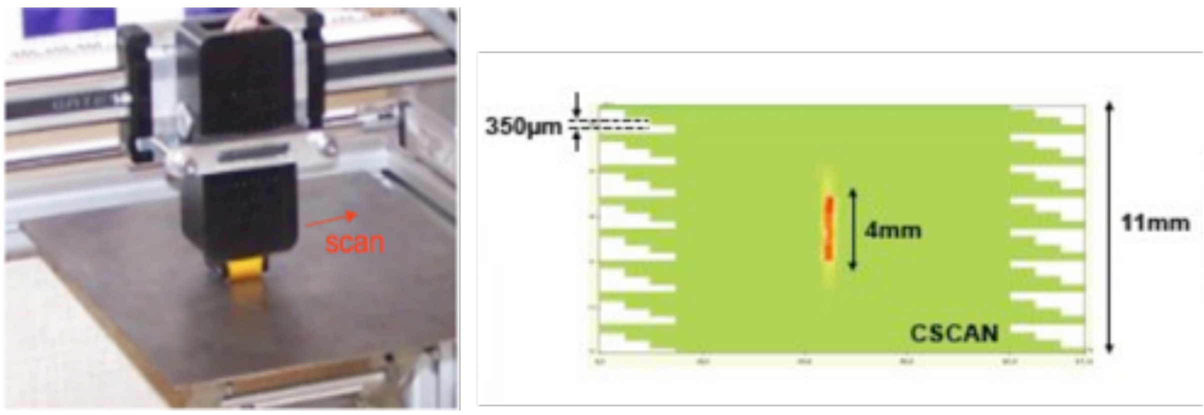


Figure 42 – 32 elements eddy current probe

3.1.2. Jean Marc Decitre

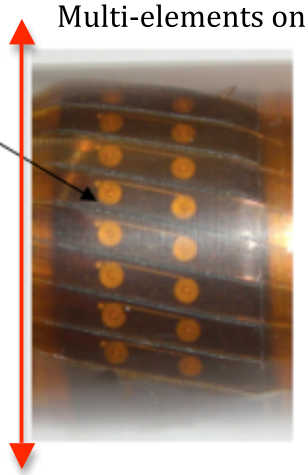
<u>Jean Marc Decitre</u>: NDT specialist of the instrumental and probes laboratory at the CEA-LIST.

<u>Jean-Marc Decitre</u> works in the instrumental and probes laboratory for NDT at the CEA in France. He and his team are very specialised in the field of NDT and are experimenting new kind of probes.

Mr Decitre gave his opinions about the feasibility to design a EC probe that fit to the geometry of the HNB lip welded seals. He thinks that it would be possible to design a multi-elements EC flexible probes etched on kapton that they are developing at the CEA. Indeed, they have already developed these kinds of multi-elements EC flexible probes and Giant Magneto-Resistance (GMR) sensors. They can be adaptable to specific geometry and very complex shapes. The geometry of the lip seals and its dimensions are not an obstacle. That is why we can be confident in the feasibility of a multi-elements EC flexible probe with GMR sensors that fits to the weld geometry.

As an example, **Mr Decitre** and his team have designed a multi-elements EC probe for inspecting pipes from the inside. This probe is capable of detecting defects with a spatial resolution of 100 μm at the surface. This probe is capable of inspecting very complex surfaces up to a curvature radius of 2.5 mm.

<u>Figure 43</u> – Multi-elements eddy current probe for pipe inspection



At this stage we know it is feasible to make a EC probe with a 0.1 mm spatial surface resolution capable of inspecting the HNB lip welded seals. However, we do not know the spatial resolution at 3 mm penetration depth and the impact of the surface roughness.
Concerning these two parameters **Mr Decitre** gave his opinion:

- due to the weld geometry and its dimensions, the spatial resolution at 3 mm depth will be at least 1 mm. However with R & D it it can be improved easily but as we do not know all the weld parameters (roughness…) **Mr Decitre** could not give a precise answer.

- the surface roughness has an impact about the defects detection. Small defects on the weld surface will have an impact on the spatial resolution. But at this stage of the project we do not know the weld quality.

3.2. Literature review

Based on the opinion of **Mr Chauveau** and **Mr Decitre**, multi-elements sensors eddy current probes have been investigated. Several research studies about it conducted by the CEA and the IRSN (Institute for Radiological Protection and Nuclear Safety) have been found.

EDDY CURRENT ARRAY PROBE DEVELOPMENT FOR COMPLEX GEOMETRIES

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(2) IRSN, DSR, SAMS, 92262 Fontenay-aux-Roses, FRANCE

This document can be found on the website: http://www- civa.cea.fr
This research has been done in the framework of a joined Research and Development program between the CEA and the French Institute for Radiological Protection and Nuclear Safety (IRSN).

We notice that **Jean Marc Decitre** is one of the authors of this article, he has also published an article: **RECENT DEVELOPMENTS OF MULTIELEMENT MAGNETIC SENSORS**.

Extract of the abstract.

“Technologies based on Eddy Current (EC) flexible array probe and magnetic sensors with high sensitivity such as giant magneto-resistance (GMR) are a good solution to improve the detection performances.

The first development addresses the inspection of nuclear components with complex shapes. **A flexible array probe based on micro-coils etched on Kapton** has been developed, and its performances have been assessed for the inspection of nuclear components such as reactor residual heat removal (RHR) pipes. The flexibility of the sensor reduces greatly the lift-off noise, optimizes the coupling and thus **enhances the detection of flaws**.

The second development deals with **the detection of deeply embedded flaws**. An EC probe based on GMR sensor has been developed and evaluated for the inspection of the outer face of the RHR mock-up. Cracks induced by thermal fatigue have been successfully detected under a ligament of 7mm. “

Results for the development of an eddy current flexible probe.

A flexible eddy current probe consists to maintain the probe in close contact with the piece's shape during the inspection. In the case of the inspection of a complex shaped piece like the lip welded seal of the HNB, it provides some advantages. Indeed, the flexible technology ensures a good coupling between the probe and the piece, and a low sensitivity to the lift-off variation which could drastically reduce the efficiency of the eddy current detection.

The advantage of this technology is that the probe is adapted on a silicon roll to comply with the test specimen geometry, which could change according to the chosen application. Consequently, we can assume **it is feasible to develop a specific probe for the specific geometry of the lip welded seals**.

An example of flexible eddy current probe is given in the **Figure 19** below.

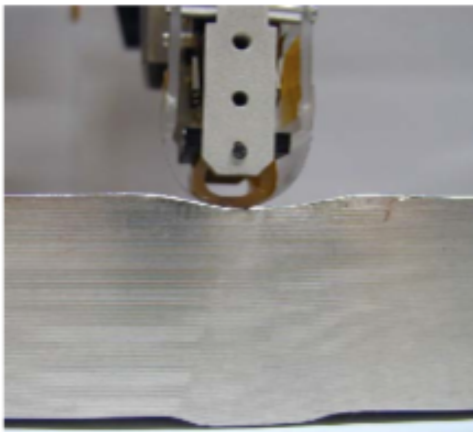

Figure 44 – Prototype of an EC flexible array probe adapted to the inspection of complex shaped surfaces.

The flexible eddy current probe technology has the **major advantage to greatly reduce the lift-off noise, optimize the coupling and then to enhance the detection of laws**. The performances of the flexible probe have been assessed for planar and curved surfaces. The probes have shown good detection capabilities for detection of small surface breaking flaws (length 0.2mm, width 0.1mm, depth 0.2mm).

Figure 45 – EC flexible array probe adapted to the inspection of curve shaped surface.

Results for the development of an eddy current probe based on a GMR sensor.

A probe with a GMR sensor has been developed and evaluated for the inspection of the outer face of 316L pipe with a thickness of 14 mm. The GMR technology looks promising because of the high sensitivity in a large frequency range and low noise which provides the capability of detecting deeply embedded flaws as well as breaking flaws.

The experimental results have validated the use of GMR technology to detect deeply buried flaw up to 7 mm. The lip welded seals has a depth of 3 mm, this means that the GMR technology will be capable of detecting cracks and flaws up to 3 mm.

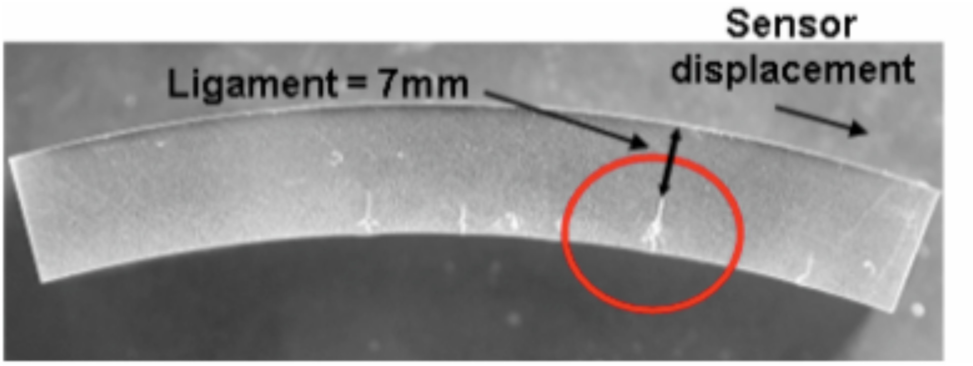

Figure 46 – Transverse section of 316L pipe affected by cracking and crazing induced by thermal fatigue.

3.3. Conclusion

Main results of the EC probe investigation
Micro-coil technology etched on thin Kapton film
Flexible array probe which fits to the geometry to inspect.
Excellent detection for narrow cracks on deformed surfaces.
Capable of detecting defects with a spatial resolution up to ~ 0.1 mm at the surface <1 mm at 3 mm depth with R&D
GMR magnetic sensor
High sensitivity at low frequency
Detect embedded flaw up to a depth of 7 mm

Table 39 – EC investigation main results

The combination of a multi-element EC probe etched on kapton and GMR sensors would be adapted to detect defects in the lip welded seal. Indeed, the flexible probe would fit to the geometry of the weld, the multi-element provide a great sensitivity and the GMR sensors enable to detect deep defects.

4. Design of the Eddy Current Inspection Tools

The opinions of the different specialists and particularly **Mr Chauveau** and **Mr Decitre** led to the conclusion that it is feasible to design a multi-elements eddy current flexible probe etched on kapton that fits to the geometry of the HNB lip weld. We can have confidence in the feasibility of such probe mainly because the technology exists and such probes have already been developed for specific applications and very complex geometry. This is due to the probes etched on kapton, that enables to design flexible eddy current probe, thus the geometry of the lip seal is not anymore an obstacle.

It is possible to detect defects inside the weld easily up to 3 mm with a spatial resolution of at least 1 mm (and better with R&D). However, it is impossible to know exactly the dimension of this kind of probe.

Indeed, the dimensions of the probe are determined with a optimization software as they have at the CEA. The software has to take into account the frequency needed to detect defect up to 3 mm and the spatial resolution we want to that is unknown until now. Consequently, the dimensions of the probe I propose are not definitive and are only an illustration. Further research and development has to be done to know the exact dimensions and the distance between the weld and the probe.

4.1. Concept design of the eddy current probe's head

As it is feasible to design a multi-element eddy current flexible probe etched on kapton that fits to the geometry and the dimensions of the lip seal, we come up with a concept design.

The eddy current probe head is a semicircle that fits to the weld, the **Figure 35** shows the design of the eddy current head and the **Figure 36** shows the dimensions of the weld to inspect.

The probe head dimensions are similar to the weld in order to fit to the geometry except that there is a minimum distance of 1 mm between the probe and the weld. This distance is called the lift-off and has an impact on the defects detection. The lift-off has to be chosen carefully and it is possible that we need to adjust it during the inspection.

However, as at this stage of the project we do not know the technical characteristics of such a probe we cannot know the lift-off and if it has to be constant or adjustable. That is why we have chosen a constant lift-off of 1 mm.

This decision is not a constraint because the design can be easily change, we have enough room to include changes in the dimensions of the probe.

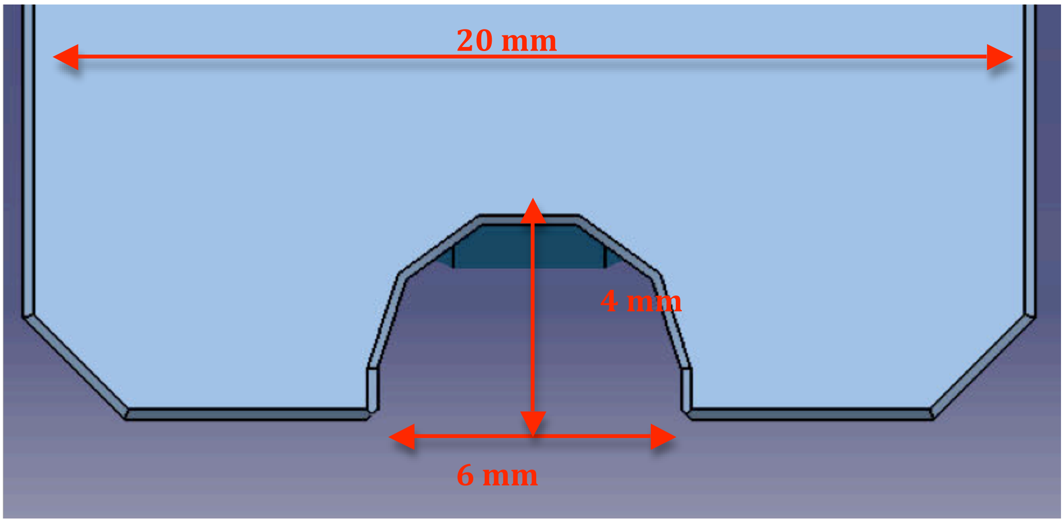

Figure 46 – Eddy current inspection head

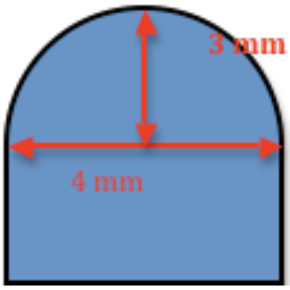

Figure 36 – Lip welded seal

Concerning the eddy current probe, the dimensions have been set up by default. At this stage we do not know how much space we need for the micro coils and the electronic. However, we know that all the components do not require a lot of space. Indeed, we have seen during the EC probe investigation that several different multi-element eddy current flexible probes etched on kapton have been developed for specific application with very small dimensions. The part with multi-elements etched on kapton as shown in the **Figure 43** has the dimensions of a 20 mm square. And the probe has roughly the dimensions of a pen. Moreover, for the height we have a space envelope of at least 100 mm. Consequently, even if the dimensions adopted in the design are not the one that will be for the probe prototype, there will be enough space to modify the design.

4.2. Concept design of the eddy inspection tool

We have come up with the concept design of the eddy current probe. We need to design the tools that will carry the probe. As the carrying tools applicable to the lip seal have already been designed and are capable of carrying the welding and cutting tools, it is convenient to make a compatible design of the inspection tools with these carrying tools. Consequently, the eddy current probe has to be attached to the carrying tools.

Another issue is to come up with a mechanical concept to keep the lift-off constant to 1 mm and find a way to constrain the probe's head to follow the top of the lip welded seal without moving away from the top of the weld. In addition, the simplest the mechanism of these guidance systems is the more we can have confidence and rely on.

Indeed, in a radioactive environment it is always better to reduce the amount of microchips and electric cables to prevent from the components deterioration due to the radiation. Moreover, it is always easier to maintain a tool with basics mechanical systems than with a lot of electronics.

We could have used sensors to measure the lift-off and adjust it with a retroactive loop but there is an easier way to do it with basic wheels and springs.

A small wheel in contact with the top of the weld and attached to the probe enables to keep a constant lift-off. In order to fit to the small variations of the weld geometry, the inspection tools composed of the EC probe and the wheel is spring-loaded to the carrying tool. In order to not move away from the weld top, two clamp wheels are added, one on each side of the lip seal. They clamp the lip seal and prevent from deviating of the path.

Eddy current inspection tool design requirements
- The EC probe has only one degree of freedom: along the vertical axis
- The top wheel moves only on the weld top following it
- The probe head has a constant lift-off of 1 mm
- The EC inspection tool is spring loaded to the carrying tool
- The EC head fits to the weld geometry
- The clamp wheels prevent the inspection tools from moving away from the weld
- The EC inspection tool has: a width inferior to 78 mm, a height that enable it to be connected to the carrying tool, no length restriction

Table 40 – Design requirements

The **Figure 37** below shows a front view of the weld EC inspection tool for the lip seal.

We notice three wheels, the one attached to the eddy current probe will move on the weld's top, the side wheel will move along each side of the lip seal.

The **Figure 38** below shows three different views of the EC inspection tool.

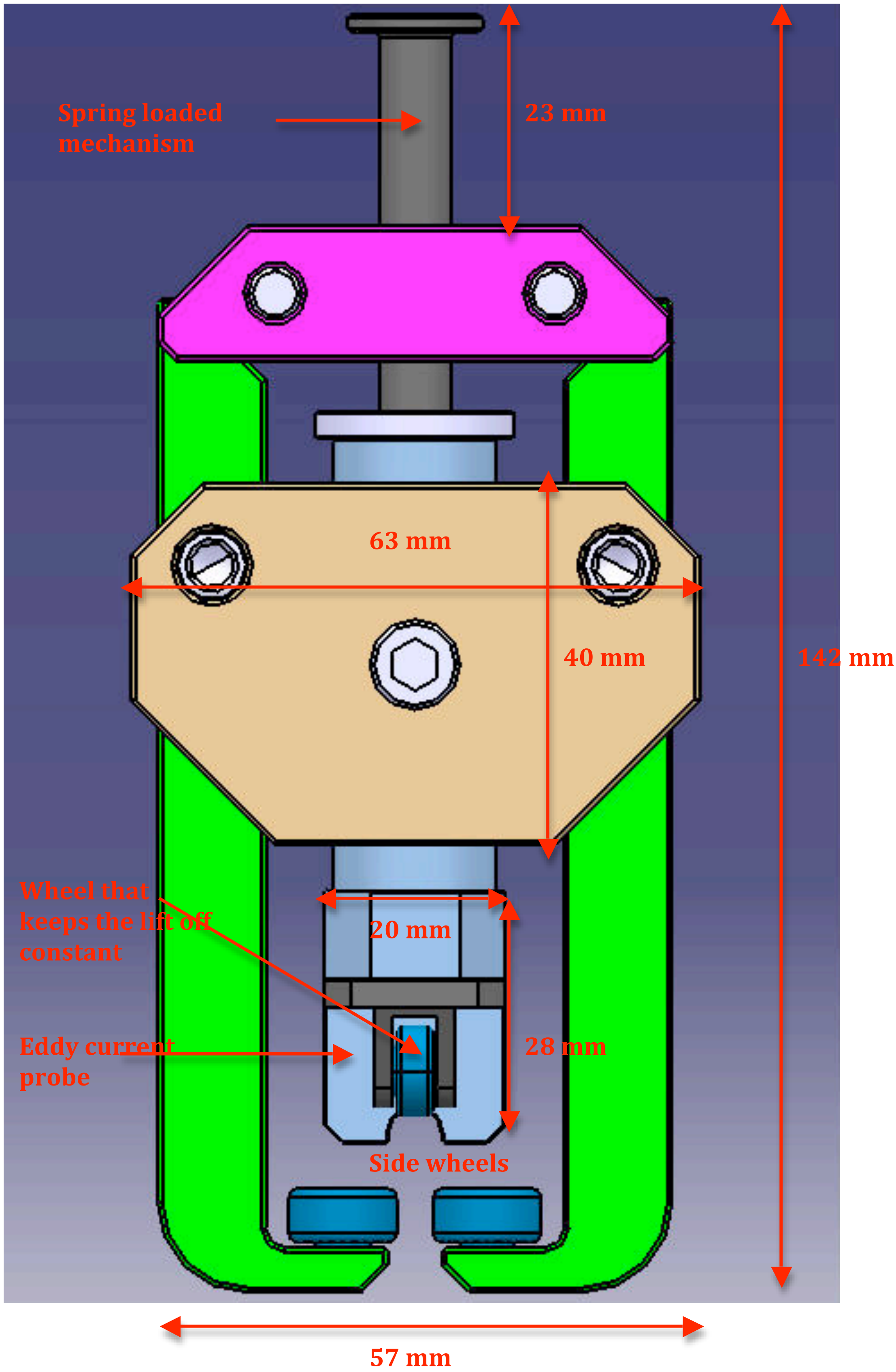

Figure 37 – Weld eddy current inspection tool

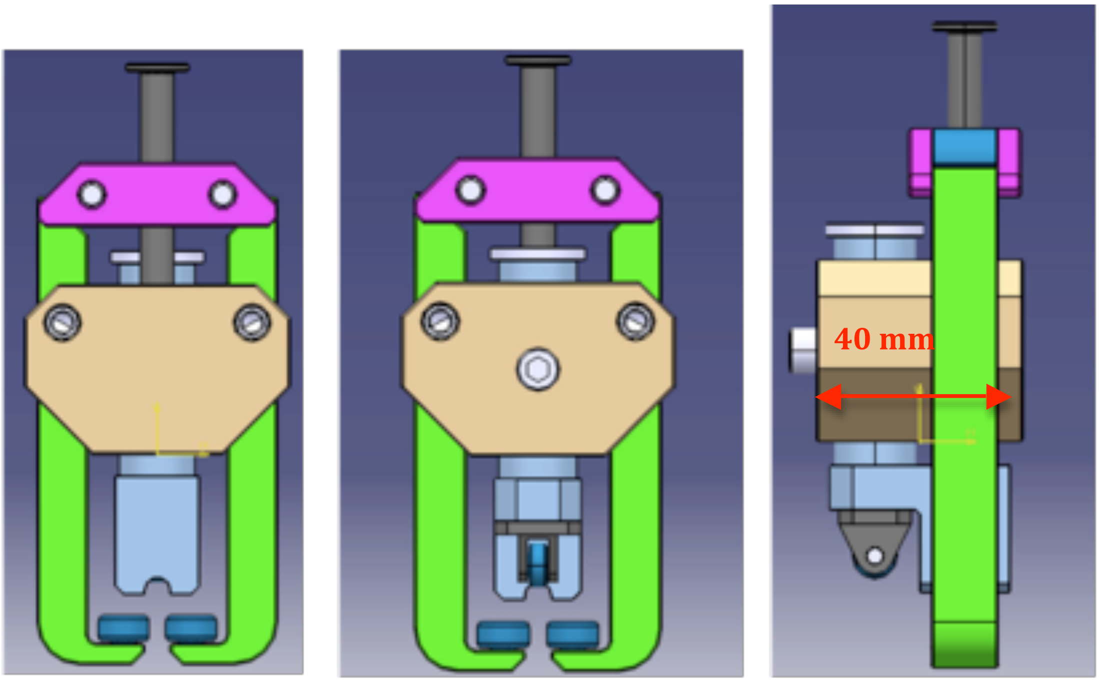

Figure 38 – Back view, front view and side view of the eddy current inspection tool

The **Figure 39** shows the EC inspection and carrying tools during the weld inspection.

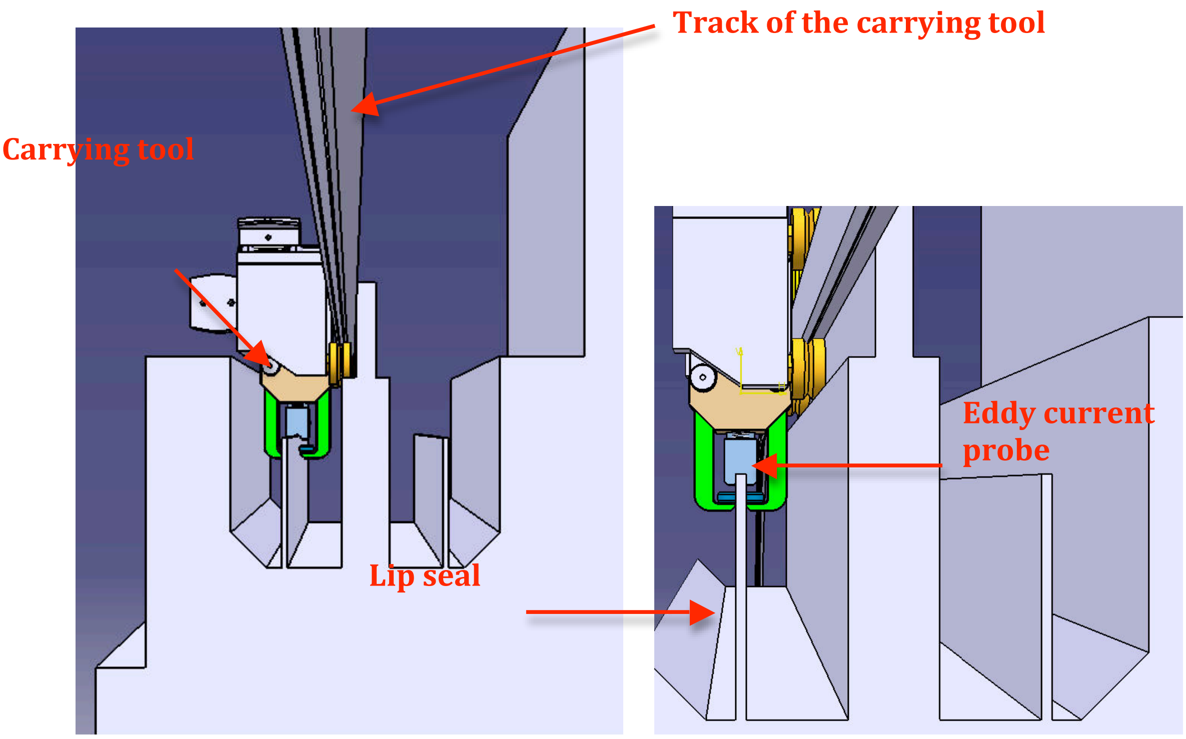

Figure 39 – Back views of the EC inspection and carrying tools during the inspection

Back view Front view

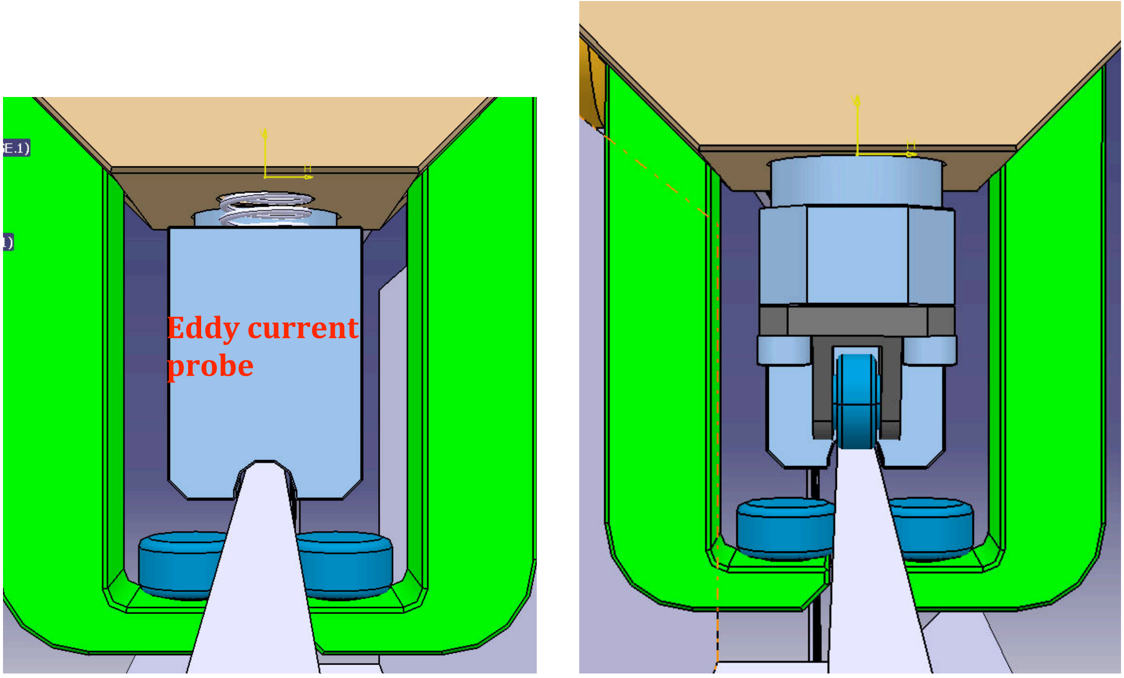

Figure 40 – Back view and front view of the eddy current inspection tool

The **Figure 40** above shows the EC probe during the weld inspection. On the front view we notice the top wheel and the two clamp wheels.

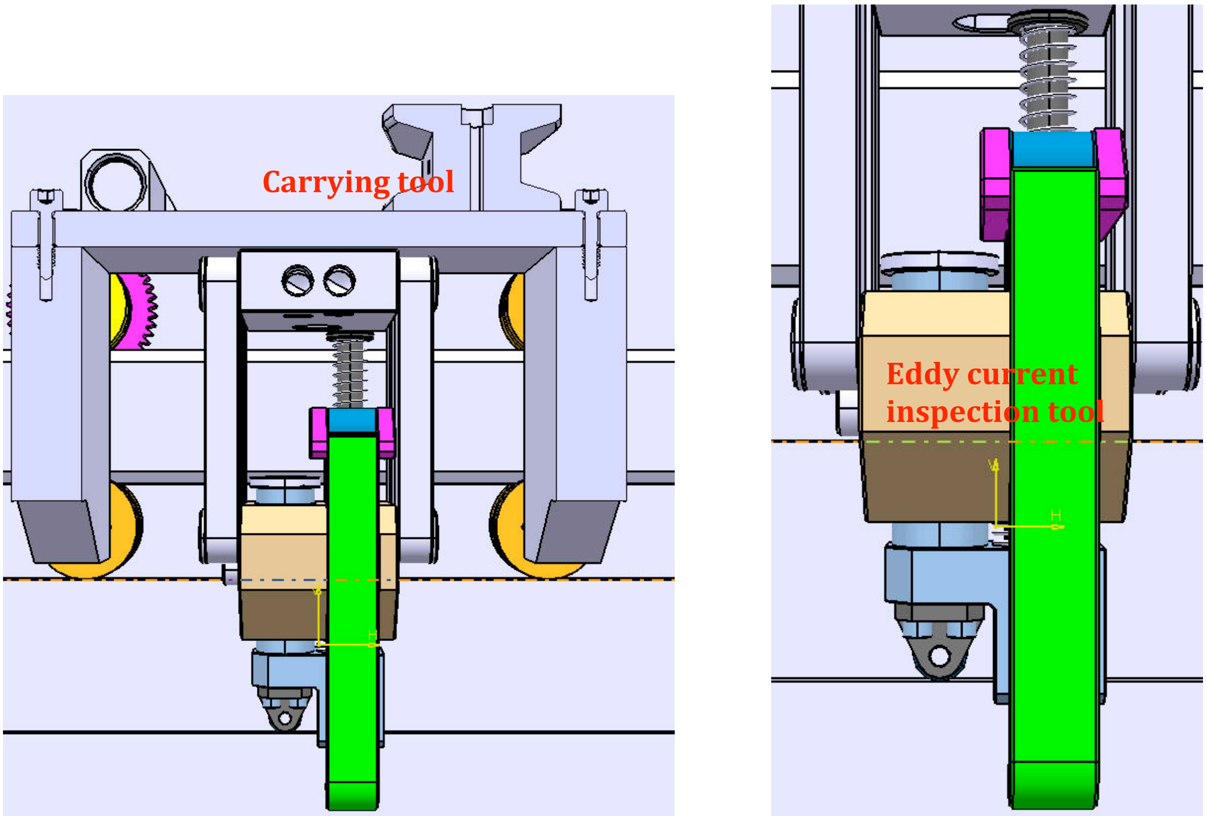

Figure 41 – Side view of the eddy current inspection and carrying tools

5. Summary and Conclusions

We have come up with a feasible concept design of the EC inspection tools. At this stage given the information I have gathered I cannot bring more details about it. The next step would be to consider this concept design and make a R&D project to prove its feasibility.

Research and development have to be made to confirm the concept design of the eddy current probe. The parameters that have to be clarified are in the **Table 45** below.

Eddy current probe technical requirements
- Technology based on multi-elements eddy current flexible probe etched on kapton with GMR sensors has to be tested to confirm the applicability to the lip seal
- Must detect defects up to 3 mm with a spatial resolution as accurate as possible
- Must be very sensitive
- The geometry and the dimensions must be clarified
- The materials have to be resistant to: a radiation background of 1 Gy/h a magnetic background of 1 mT temperature up to 50 °C
- The optimum lift-off has to be determined
- The frequency range used to detect the defects and reach the spatial resolution

Table 41 – Eddy current probe technical requirements

Research and development have to be made to confirm the concept design of the eddy current inspection tool. The parameters that have to be clarified are in the **Table 46** below.

Eddy current inspection tool technical requirements
- Must meet the ITER requirements (electrical, ELM, resistant to radiation, decontamination…)
- The design of the inspection tool must not interfere with the magnetic field produced by the eddy current probe
- The material of the inspection tool must not interfere with the magnetic field produced by the eddy current probe
- The spring loaded mechanism must bear the weight of the eddy current inspection tool in the worst configuration
- In case of an incident the inspection tool must be removed without any difficulties
- The dimensions must be clarified

Table 42 – Eddy current inspection tool requirements

6. References

Reference	Contact
3.1.1 **Daniel Chauveau** Institut de Soudure	Daniel Chauveau NDT Fellow Product Develop Department d.chauveau@institutdesoudure.com +33 1 49 90 37 32 Institut de Soudure Industrie ZI Paris Nord 2 – 90 rue des vanessses – 93420 Villepinte
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Part	**Reference Literature**
3.2	**EDDY CURRENT ARRAY PROBE DEVELOPMENT FOR COMPLEX GEOMETRIES** C. GILLES-PASCAUD[1], F. VACHER[1], J.M. DECITRE[1], G. CATTIAUX[2] *(1) CEA LIST, Saclay, 91191 Gif-sur-Yvette, FRANCE (2) IRSN, DSR, SAMS, 92262 Fontenay-aux-Roses, FRANCE* http://www- civa.cea.fr