Review of in-service inspection and repair technique developments (ISI&R) for French Liquid Metal Fast Reactors (LMFR)

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ABSTRACT

In-service monitoring of nuclear plants is indispensable for both the Operator and the Regulator: the notion of in-service monitoring ranges from the continuous monitoring of the reactor in operation to the thorough in-service reactor inspection during programmed shutdowns.

However, the highly specific environment found in French Liquid Metal Fast Reactor plants – Phénix and Superphénix – makes monitoring and inspection complicated due to the use of a sodium coolant that is hot, opaque and difficult to drain.

The CEA – in collaboration with its traditional French partners, EDF Utilities and FRAMATOME/ Novatome Engineering – decided to conduct a 6-year R&D programme (1994 – 2000) to explore this problem vis-à-vis Superphénix, as well as the possibilities of intervening within the reactor block or on components in a sodium environment.

Furthermore, the safety re-evaluation of Phénix, conducted between 1994 and 2003, represented an excellent “test bench” during which the limits of inspection processes – applied to an integrated reactor concept – were surpassed using techniques such as: fuel subassembly head scanning, ultrasonic examination of the core support and visual inspection of the cover-gas plenum following a partial sodium draining.

Repair techniques were investigated for cleaning of sodium wet structure surfaces, cutting of damaged parts and welding in sodium aerosol atmosphere : both conventional and laser processes were tested.

1. Introduction : reminder of the objectives

The ISI&R in LMFRs meets a need identified since this type of reactor began to operate, particularly as a condition for their development. This activity has therefore become more important as new projects were started (Phénix in the 1970's, then Superphénix1 and 2, finally European Fast Reactor – EFR - in the 1990's). Within the framework of the EFR project, ISI&R was defined as early on as its design and has been studied within a large R&D program.

The objectives of the isi&r program were summarized as follows :

- initiate or intensify all studies, R&D on the methods and materials aimed at ensuring surveillance and the possibility of repairing the essential structures of an LMFR (main vessel and internal structures, components ...).
- for present or future reactor projects, maintain a close collaboration with the teams in charge of engineering work so that measures be taken in the design to make these operations possible.
- help the operator of LMFR plants (Superphénix until 1997 and Phénix since) to meet the surveillance and inspection demands, in compliance with the Safety Authorities.

The materials and techniques studied through R&D were the following :

- the instrumentation which allows a permanent surveillance of the structures and components (vessel, internal structures, steam generators,...).
- the materials aims at carrying out a regular inspection which should be as systematic as possible on these structures and components.
- those which could be used for diagnosing anomalies.
- finally, the tools which could be used to repair in situ the primary circuit components which cannot be moved.

This article gives a large view on ISI&R studies which were performed in France for LMFR need, during the last decades.

1) In-service monitoring requirements

2) Inspecting structures using non-destructive tests

3) Using ultrasounds to inspect sodium environments

4) Inspecting the cover-gas plenum

5) Intervening in the cover-gas plenum

6) R&D perspectives for LMFR in-service inspection and repair

7) Conclusion

2. In-service monitoring requirements

In-service monitoring of fast reactors is used to permanently control the good working order of the reactor. In-service monitoring involves two complementary activities:

- In-service monitoring enabling operators to follow the reactor state uninterrupted (this subject will not be discussed in this paper). The vibration behaviour monitoring process is however worth a brief mention: steel bars are plunged into liquid sodium and vibrations are recorded, which is used to analyse the evolution of sodium flows and neighbouring structures. This method enabled the researchers to quickly detect the presence of gas in the Superphénix primary sodium circuit in 1994.
- In-service inspection is composed of a series of main reactor structure examinations concerning the reactor block, secondary sodium circuits and the steam generators for the most part. Conducted during shutdowns, the inspection includes a series of global controls (telemetric measurements) and local inspections (non-destructive examinations of welds). Repairs to structures are included in the same category as inspection, thus the acronym ISI&R - the symbol of the CEA’s efforts in R&D in this field.

In-service inspection – a fundamental aspect of fast reactor technology [1] due to the presence of sodium which is hot (180℃ during shutdowns), opaque and difficult to drain – began in France with the examination of main vessel welds in the Superphénix plant (using the MIR device, which is mentioned further on). In-service inspection was extended to other structures located in the reactor block (see figure below) as well as other plant components, such as the steam generators.

The measures applied in Superphénix were updated to meet new inspection needs by the engineering department that compiled a list of possible failures for each component (cracking, rupture, progressive deformation, etc.). Two thresholds were defined for specific deformations (the alarm threshold or “recordable conditions” taking into account non-critical failures and the maximum threshold or “maximum acceptable conditions” related to level A of the RCC-MR regulations (design and construction regulations for fast nuclear reactor mechanical material).

The potential damage calculated for each structure is associated with the severity of the failure risk vis-à-vis its safety function. It is therefore possible to ascertain the vital components of the reactor for which R&D must illustrate the feasibility of applying the recordable and maximum acceptable thresholds.

Therefore, each structure of the Superphénix reactor block has been classified as requiring low, medium or high monitoring:

R&D was carried out within a framework of co-operation that lasted several years – from 1994 to 2000 – between the CEA, EDF and FRAMATOME/Novatome. Specialised fast reactor teams and advanced techniques were combined to help LMFR operators and perform exploratory studies. Processes were developed in laboratories and then were automatically tested in sodium environments. The end of operation of Superphénix in 1998 brought an end to such studies.

The Phénix plant – based on an older concept (criticality reached in 1973) – was not equipped with an inspection machine for the main reactor vessel such as the MIR device in Superphénix. However, during safety re-evaluation studies [2] carried out from 1994 to 2003, the good condition of the structures containing core reactivity was confirmed by means of:

- ultrasonic examination of the conical shell supporting the reactor core (see §3 below),
- visual inspection of the above core structure, holding the control rods (see §5 below),
- ultrasonic examination of the main reactor vessel hangers (cited as a reminder).

Non-destructive tests of Phénix sodium circuits, the fuel storage tank and the steam generators [3] were also performed in Phénix, with faulty components being repaired or replaced (cited as a reminder):

- repairs to the secondary sodium circuits,
- changeover of the primary coolant pumps,
- repairs to steam generator units [4]
- replacing of the intermediate heat exchangers,
- changeover of the control rod mechanisms.

Poles were also installed in the main reactor vessel to reinforce thermal (using thermocouples to measure sodium temperatures) and mechanical (using accelerometers and sight optical systems to measure structural displacement) monitoring.

3. Inspecting structures using non-destructive tests

The two main objectives of the R&D programme centred on structural non-destructive tests were: supporting processes used in the existing reactors and developing techniques to inspect the volume of internal structures submerged in sodium.

The LMFR inspection device, MIR (Module d'Inspection des Rapides) was developed to examine welds in the Superphénix main reactor vessel from the inter-vessel. Feedback from the last inspection in 1998 and technological innovations prompted a programme centred on improving the on-board capacities of the MIR device.

No non-destructive tests of vessel internal structures were conducted in sodium. The development of sodium-submergible ultrasonic sensors was abandoned as it is very difficult to obtain material that is compatible with sodium and able to transmit ultrasounds. However, applying ultrasonic techniques to examine Phénix structures located 3 metres under sodium will be discussed at a later point in the article.

Activities supporting existing reactors :

Superphénix plant:

Inspecting the main reactor vessel: several actions were launched to improve control techniques and analysis methods used to interpret results.

New ultrasonic probe technologies were developed to improve the reliability of inspections. These probes are made from composite material and focusing is guaranteed by the piezoelectric pellet. These probes have greater detection and measuring capacities due to their enhanced sensitivity and damping [5].

A computer-aided tool designed to analyse results was developed [6] as the characterisation and measuring of defects in certain configurations was hindered by profile variations and echoes from geometrical surfaces (ex.: misaligned welds, triple point welding). Modelling is therefore extremely useful when analysing results [7] [8]. The simulation software programme currently being developed must be able to a) predict geometry-based echoes caused by weld profiles, b) evaluate the influence of the local geometry upon the defect ultrasonic response and c) take into account the anisotropic and heterogeneous structure of welds on ultrasonic signals.

Specific studies were dedicated to the development of new inspection techniques using the MIR device. One of these studies dealt with the inspection, from the inter-vessel, of an internal shell in the Superphénix vessel (figure 3). This inspection was conducted to detect defects located at great distances from the triple point weld.

A method combining eddy current techniques and ultrasounds was considered to inspect the first few millimetres of the meridian welds of the triple point weld [9] [10] (figure 3).

The use of phased array probes to inspect vessel welds prompted a long-term probe improvement programme. It is possible to modify beam focusing parameters in relation to the geometry and thickness to be inspected when using phased array probes. The ability to optimise and adapt the probe to different inspection configurations improves defect characterisation and measuring, while reducing geometry disturbances. A probe was designed and developed to inspect vessel edge-to-edge welds (figure 4). By adapting the time delay laws of each element, it is possible to obtain different configurations (angle of incidence of 45° or 70°, variable focusing depth) and rectify beam perturbations due to misaligned welds [11].

Inspection of the Superphénix main reactor vessel was also considered using a nuclear process: however, using γ radiation released by the sodium in the primary circuit – Na_{24} isotope – should not be efficient enough to detect a through-wall crack 15 mm deep, 20 mm long and 0.1 mm wide. Radiation attenuation should not be detected by a collimated γ sensor which would be located outside the vessel against the vessel wall, as the volume of the defect is too small.

Inspecting the steam generators :

The CEA developed an eddy current probe to detect volume defects caused by erosion-corrosion which is triggered by small sodium-water reactions: the detectability limit for the Superphénix thermal exchange tubes – $\varnothing_{ext}$25 mm, 2.6 mm thick, Alloy 800 – is better than 5% of the nominal thickness [12].

An ultrasonic probe developed by FRAMATOME is used to detect cracks: the phased array concept was adopted and successfully applied in Superphénix in 1998. This probe is original in its small size (< ∅ 25 mm) and rapid rotating scanning system using the electronic excitation of moving elements [13].

Phénix plant:

Inspection of the conical shell supporting the core was carried out using ultrasounds [2]: the ultrasounds spread through the shell, from outside the vessel to the extremities located in the primary sodium circuit, with more than 3 metres separating the two points (figure 5). The use of Lamb waves was validated on full-scale models before being tested on site, which involved drilling 5 openings in the safety vessel and installing two remote-control handling systems providing contact between the sensors and the main reactor vessel. No defects were found during weld inspection activities.

It is worth noting that a preparatory ultrasonic examination of the fuel subassembly heads was conducted: the fuel assembly handling machine was equipped with a mechanical scanner in order to check if the subassembly heads were still correctly positioned. The precision of these measurements were mediocre but their in-depth analysis was used to confirm the absence of a major disorder with the assembly bundle.

Sodium inspection techniques

R&D work was carried out with the aim of developing resources needed for a volume inspection of the internal sodium structures.

Regarding non-destructive tests on structures, no device currently exists that is able to generate ultrasounds in high-temperature sodium. Two non-destructive test methods were considered. The first method was based on electromagnetism using EMAT (Electro-Magnetic Acoustic Transducers) probes. These probes generate ultrasounds in sodium by means of eddy current signals. The second method uses piezoelectric composite probes. Probes that are acoustically and chemically compatible with sodium must be developed to evaluate the technological feasibility of such probes.

A method using phased array probes has also been considered, with the aim of developing a technique capable of exploring the entire volume of sodium when traditional probes prove to be are inadequate. The small space available for probe movement is compensated by an angular scanning.

4. Using ultrasounds to inspect sodium environments :

Reasons for inspecting sodium using ultrasounds

It is useful to be able to inspect sodium environments for three reasons: to guide and position an inspection apparatus carrier within the reactor; to establish and locate any missing reactor elements; to perform remote-control measurements.

Sodium is an opaque liquid in the light. To be able to "see" through liquid sodium to conduct dimensional inspections from a distance, it is necessary to use a type of wave capable of propagating with little attenuation, such as ultrasounds, at frequencies of several Megahertz. It is therefore possible to obtain an attenuation coefficient of about 0.1 dB/m with ultrasounds. The next step involves applying techniques similar to those found in the active SONAR used by submarines or medical ultrasounds – non destructive tests using ultrasounds.

Principle of an active sonar

In its simplest form, an active SONAR is composed of one unique sensor, still called a probe, which emits an ultrasonic wave, receives this wave after it has been reflected by the surrounding structures and then delivers an electrical signal. The probe uses "directivity", which means that it only transmits and receives within a limited beam range, schematically speaking in the shape of a cone. By rotating the cone to cover all or part of the zone, information concerning the presence, absence and distance of objects in the scanned areas can be collected continuously. The distance (L) between the probe and the located object is calculated using the time of flight information (t) according to the following equation; $L = (c.t)/2$ where c represents the celerity of ultrasounds in the sodium. The cone is rotated by either rotating the probe or by dividing the probe into small electronically piloted elements.

Accessing back-scattered information

The reflection of a metallic structure is in fact composed of three components that all together form the received signal [14]. These components are, in decreasing order of amplitude (figure 6):

- specular echoes, occurring with a delay in time in relation to the transmitted ray that, in the beginning, depends on the distance between the probe and the closest part of the structure. Even if the beam is rotated, the echo takes the same time to be received, which gives the impression that a structure in the shape of a spherical dome is centred on the probe – regardless of the reflecting structure – and whose aperture only depends on the probe's directivity.
- diffraction echoes from structure edges, which, as the name reveals, help locate the edge of structures.
- back-scattered echoes generated by each point of the structure, provided that the local roughness is significant enough for the wavelength.

Optical waves are used all the time in everyday life: backscattered light is most useful to us for locating and visualising objects in three dimensions. Ultrasonic visualisation also uses backscattered acoustic energy.

To separately access backscattered acoustic signals, it is necessary to direct the beam in a direction where it is stronger than the specular and diffracted acoustic signals. The beam must therefore be narrow enough so that only a slight misalignment in relation to the specular direction is enough to eliminate specular echoes. The system must also be sized so that grating-lobe effects (diffraction lobes (dl) of a width related to the size (a) of the emitter and receiver as well as the wavelength λ represented in the equation: $dl = \lambda / a$, and network lobes related to the value of the distance between the elements) remain insignificant. These lobes render specular echoes “visible”, even if the beam is pointed elsewhere.

Sodium visualisation systems, known as "VISUS" [15], already exist in Phénix and Superphénix. These systems are used to detect and locate possible obstacles preventing the rotating plugs from functioning during handling operations. However, these systems are not directional enough and do not enable us to separate the acoustic components from the signal. Therefore, in reality, these systems only deal with specular echoes. The sodium rapid imaging programme, IMARSOD (IMAgerie Rapide en SODium), was carried out (see below) to explore such problematics.

IMARSOD system characteristics

The IMARSOD system is composed of two perpendicular antennas, one transmitting and the other receiving (figure 7) [16] [17]. These antennas are designed so that their focal zones approximately represent a horizontal and vertical line respectively. The focal point that is detected by the system is located at the intersection of the two lines. To move the focal point in a 3-D space, the antennas are divided into elements each equipped with an electronic device enabling electronic focusing by exploiting the time delay laws intervening between elements.

An example of a system measuring technique that designed for Superphénix is provided on the figure 7:

Validating the “active sonar” principle through tests in water

Approximate calculations of the ratio between the backscattered echo and the specular echo for a system dimensioned as illustrated above, with estimated reactor surface roughness of approximately 10µm indicated the fact that separating the echoes is possible but rather complicated. Tests were necessary to confirm these calculations and establish whether the acoustic dispersion “originated” from the electronic noise. An experimental system was installed in the ultrasound container, by “synthetising” the receiver antenna using a single-element moved to the successive positions of the antenna elements. Transmission was carried out using a big single-element antenna, which generated a focalisation line at a normal distance of 2 m.

The “B-scan” image provided by the system when using a flat plate with a width of 700 mm placed 2 m from the antennas revealed that all points of the plate were visible, with glare due to the specular echo coming from the point found closest to the antennas, with excess intensity from the edge of the plate due to edge diffraction echoes.

Conclusion

Sodium inspection using backscattered information may be possible.

Antennas adapted to working in sodium environments need to be developed, as well as creating an electronic receiving and emitting system adapted to orthogonal configurations.

Image processing can also be improved in order to minimise errors due to flicker/ flutter, as well as improving object recognition and measurements.

5. Inspecting the cover-gas plenum

by laser telemetry [18] [19]:

Several processes were used to measure distances in LMFR cover-gas plenums during shutdowns at 180℃ (temperature of sodium). Laser telemetry is generally speaking the most precise and simple technique available. However, it is important to evaluate the uncertainties associated with this technique and elaborate an inspection methodology. Several phenomena can disturb the propagation of light beams: thermal gradients and fluctuations, sodium deposits and aerosols.

The approach that was adopted consists in independently modelling thermal-based factors and the influence of aerosols in order to validate the modules corresponding to the CANDELA computer code dealing with experimental installations. Some experiments focused on studying the influence of sodium deposits on surfaces to be inspected.

Other tests were conducted which helped the validation of computer code modules concerning beam deflections in:

- the thermal boundary layer around a hot cylinder (like the Superphénix heat exchanger skirts during a shutdown):

Beam/ cylinder distance (mm)	2.5	5	6
Measured deflection (mm)	0.78	0.80	0.76
Calculated deflection (mm)	0.87	0.83	0.73

- The turbulent fluctuation zone above a surface with an imposed temperature gradient (tests on the EPISTAR model: figure 8), (like the argon layer just above the free surface of the sodium):

Distance covered (m)	1 + 1	2 + 2
Measured dispersion (mm)	0.29	0.61
Calculated dispersion (mm)	0.26	0.67

- The thermal-layered zone between the turbulent zone and the cold wall (imposed vertical gradient) with tests conducted on the EPISTAR model (figure 8).

Modelling activities were extended to include sodium aerosols, with tests being conducted in the FRUCTIDOR sodium facility. It was possible to observe the effect of sodium aerosols upon the propagation of the light beam:

- "haze" effect when the liquid sodium is hot enough – 300℃ – to generate large quantities of sodium aerosols: the light beam is stopped by the reflection of light upon the suspended particles.
- widening of the light beam when the aerosol content is low (liquid sodium at 180℃).

A more precise study would have required the use of calibrated metallic particles and the possibility of controlling their concentration in order to establish an extinction threshold and validate the CANDELA computer code module.

Tests also helped precise the conditions under which telemetric measurements are possible on sodium-wetted surfaces (directly aimed at steel plates, at droplets suspended under a slab and at a liquid sodium surface):

- out of sodium, it was noticed that high roughness helped obtain better measurements:
    - upon a smooth surface, the maximum angle of incidence is 40° and the telemeter suffers from glare at a normal angle of incidence.
    - upon a rough surface, the maximum angle of incidence reaches 80°.
- In sodium, roughness no longer comes into question:
    - For pure sodium, the maximum angle of incidence is 23°, with glare at a normal angle of incidence,
    - For oxidised sodium, the maximum angle of incidence is 80°,
    - For sodium droplets or a sodium surface, glare also occurs at a normal angle of incidence in the case of pure sodium but measurements are possible with oxidised sodium,
    - In all cases, measurements are extremely disturbed by the presence of edges: the laser must be aimed at a level surface that is bigger than the light beam.

A review of these results could be useful to engineers and operators when establishing telemetry material specifications and defining operation methodologies.

by video inspection:

The overall condition of Phénix and its above core structure welds were inspected using remote video systems [2], figure 9 : optical poles – 19 m long periscopes – were introduced inside the reactor block already drained of half its primary sodium. The temperature and irradiation within inhibits the use of electronic equipment (cameras).

The excellent resolution of the system enabled scientists to inspect welds and other zones above sodium, as well as the fact that the highly reflecting liquid sodium free surface was used as mirror to inspect certain darker zones [20].

6. Intervening in the cover-gas plenum

On-site repairs in the Superphénix reactor block in 1995 greatly justified R&D efforts in this field: thanks to the preliminary results available at the time (sodium-wetted object cleaning tests in glove boxes), the inspection followed by the plugging of a leak found in a argon-filled tube leading to a intermediate heat exchanger cap was successfully performed.

Three types of operations must be viable during cover-gas plenum interventions: cleaning, cutting and welding. These classic mechanical processes are compatible with laser techniques.

Intervention processes have been first subjected to feasibility tests in glove boxes: small sodium-filled containers are used to wet samples before subjecting them to cleaning, cutting and/ or welding activities. During this stage, operations were conducted in a nitrogen atmosphere with an oxygen content of about 200 ppm.

These processes were then qualified using the MIRSA (Mock-up for Intervention and Repair Under Argon) facility which reproduced the conditions present in a cover-gas plenum (argon at 130℃, low oxygen content of several ppm).

Mechanical cleaning processes

These processes prepare structural surfaces for inspection and repairs by removing any residual sodium films or traces (residue thickness after drip-drying is approximately 35 µm).

Preliminary tests were conducted in glove boxes. Among five possible processes, two proved to be effective in reducing the residual sodium film (0.1 to 0.2 µm): blowing hot argon (200℃ at 7 bars) and rotating brushing (brush ∅ 100 mm, 2,000 to 4,000 revolutions/ minute) which can be combined depending on the sodium temperature and purity.

These tools adapted to LMFR reactor conditions were then qualified in the MIRSA facility: argon blowing was able to correctly clean surfaces at 182 dm^2/ hour while brushing obtained 1 to 4 dm^2/ hour.

Chemical cleaning processes

Repairs made to 47 Phénix steam generator units [3] are not discussed in this article: these units were however washed down before being repaired.

This cleaning helped eliminate the residual sodium film stuck to the internal walls of the units following draining: the adopted process involved transforming the sodium into sodium hydroxide by injecting nitrogen containing small quantities of steam. The reaction is controlled by continuously measuring the quantity of hydrogen produced. The sodium hydroxide that is produced is eliminated with a final rinsing.

Mechanical cutting of the structures

This topic was not studied in the French ISI&R R&D programme. However, this type of operation was performed during Superphénix dismantling activities: mechanical and thermal processes were tested and chosen as to avoid or limit the ignition of sodium residues.

Adapting these processes within the ISI&R context must be carried out to make sure all heat treatment scale (gas and fumes) and chips produced during operations are recuperated.

Gas Tungsten Arc Welding (GTAW)

Repairing cover-gas plenum structures using GTA welding and welding material is a reference process as far as reactor block interventions are concerned. This process is relatively easy to use, boasts high tolerance levels and obtains quality results.

GTA welding was used to repair defects in the portion of the 316L grade stainless steel sheet, 20 to 25mm thick. In the case of a through-wall or very deep defect, the repair process must be able to remove a section of the sheet encircling the defect and weld a new section in its place. In the case of other defects, easier repairs can be performed such as an excavation cavity in the sheet containing the defect which is then refilled.

A GTAW tool using welding material compatible with cover-gas plenum conditions (argon at 130°C and containing sodium aerosols) was therefore studied and a prototype was built. Figure 11 illustrates the welding head of this tool: this rather original and adaptable concept produces excellent weld seams. It is important to remember that all traces of sodium must be removed before using this process.

Laser processes

Laser processes have the advantage of using the same tool to clean, cut and weld. Furthermore, the fact that optical fibre is used to transport the beam, cutting is done very easily (no mechanical loads for the laser tool) and the system is rather compact makes this intervention technique very attractive.

Laser cleaning operations

The laser fires a plasma beam that provokes a shock wave on the interface between the substrate and the sodium deposit, which vaporises all or part of the deposit.

A 10 MW high peak power pulsed YAG laser with wave lengths of 1.06 µm was used. The beam was transported by optical fibre with a core diameter of 1.5 mm. Tests performed in glove boxes demonstrated:

- the feasibility of the process using samples at 20 and 200°C (with power of 320 and 80 MW/cm^2 respectively)
- cleaning times, estimated at 6 hours and 1 hour respectively,
- residual sodium thickness, estimated at 0.035 µm,
- the substrate remains unaffected.

A second series of tests performed in the MIRSA facility using a more powerful system (30 MW per pulse) proved that the sodium film completely disappears.

Laser cutting operations [21]

Problematic

The problem of cutting 316L grade steel sheets of a thickness varying between 10 and 60 mm had to be solved. Recuperating scale caused by the intervention also has to be assured.

A solution involving several blind laser cuts assisted by argon followed by a final open cut was suggested.

In order to fully understand argon-assisted laser cutting techniques, the first tests involved single pass cuts only.

Single-pass laser cutting

Argon-assisted, single-pass laser cutting tests were performed at an average power of 1.2 kW per YAG pulse (without transporting the beam via optical fibre). Under such conditions, a maximum thickness of 25 mm can be cut at a speed of 10 mm per minute.

This type of cut is of excellent quality but has the inconvenience of producing heat treatment scale that is cast from the back of the metal sheet and is difficult to recuperate (extremely limited accessibility in the reactor).

In an attempt to solve this problem, new tests were conducted to evaluate a multi-pass laser cutting technique.

Multi-pass laser cutting

Successive passes cut 2mm with each pass. It is possible to recuperate heat treatment scale from the front of the sheet.

Cutting operations involve two stages:

- First stage: multi-pass cuts until a joint root of 1 to 2 mm is obtained on the back side of the steel sheet, while recuperating heat treatment scale.
- Second stage: cut by melting the remaining layer of the sheet (scale remains stuck to the edges of the steel sheet).

Tests helped establish the process parameters for the first stage. These tests were conducted on vertical steel sheets, using an optical fibre laser beam 1 mm in diameter and 50 m long.

The following points were observed:

- argon is necessary to evacuate the heat treatment scale from the cut,
- the cut blowing must be a minimum of 4 mm to evacuate heat treatment scale,
- circular focusing geometry is not as effective as rectangular focusing,
- under the effect of the argon, scale is evacuated locally (reproducible process).

The main difficulty behind multi-pass laser cutting was reproducing consistent cuts of 2 mm each time. The depth of the cut generally decreases with the forth pass. This phenomenon is due to the geometry of the cut which changes from a convex profile (first pass) to a V-shape profile rendering scale recuperation difficult.

General parameters of the multi-pass laser cutting technique need to be optimised to retain a convex profile with each cut.

7. R&D perspectives for LMFR in-service inspection and repairs

While assuring prospective studies, the French ISI&R R&D programme was mainly regulated by in inspection interventions organised for each of the LMFR plants:

- On the one hand, the Superphénix Operator, after having ordered the MIR device for main reactor vessel inspections and the remote eddy current steam generator inspection system, backed the series of above-mentioned studies from 1994 to 2000.
- On the other hand, the Phénix safety re-evaluation programme (1994 – 2003) helped complete and improve reactor block inspections thanks to innovative on-site operations: ultrasonic inspections of a long structure submerged in primary circuit sodium, video inspection of the reactor block structures following the partial sodium dewatering.

Studies concerning devices (mast, remote-controlled arm, etc.) in contact with sodium were relevant to all reactor block inspection and intervention processes. Reliability, precision and reproducibility of the positioning system are all essential qualities required for this tool to successfully carry out operations. Accessibility analysis and in-sodium tests should finalise its qualification.

R&D activities concerning in-service monitoring remain to be completed: analysing acoustic signals recorded above the core could help 1) detect lost parts and the presence of gas in sodium, 2) verify the integrity of the above core structure and the leaktightness of components under the pressure of sodium (discharge from the primary coolant pumps to the core): understanding the recorded signals remains without a doubt a complex challenge.

8. Conclusion

The complexity inherent to inspecting French LMFR plants such as Phénix and Superphénix – due to the presence of the hot, opaque sodium coolant drained with difficulty – represented a real challenge which was met with great success by the studies conducted over the past decades.

The CEA R&D efforts in France regarding ISI&R processes from 1994 to 2000 helped provide engineers with the means to implement LMFR inspection processes while respecting Operator specifications set by the Regulator. Companies such as FRAMATOME are also behind such success, particularly concerning the Superphénix steam generator inspections.

Results collected over the years have consolidated processes available for:

- inspecting reactor block structures (Non Destructive Techniques using ultrasounds),
- inspecting the steam generator tube bundle (Non Destructive Techniques using ultrasounds or eddy current signals),
- checking the position of sodium-submerged structures (telemetry and sodium visualisation),
- checking the position of structures located above sodium (laser telemetry and video inspection),
- cleaning sodium-wetted surfaces (blowing, brushing, laser treatment),
- cutting and re-welding structures in sodium environments.

Inspections carried out in Phénix from 1998 to 2001 mobilised many industrialists who went beyond the known limits in inspection techniques for integrated reactor systems (primary circuit integrated into a large vessel filled with sodium):

- ultrasonic inspection of a long structure submerged in the primary circuit sodium,

- video inspection of the reactor block structures following the partial dewatering of the sodium.

The review of knowledge collected during the sodium-cooled fast reactor ISI&R R&D programme has been integrated into the French database MADONA [22] (30 carefully selected summary documents).

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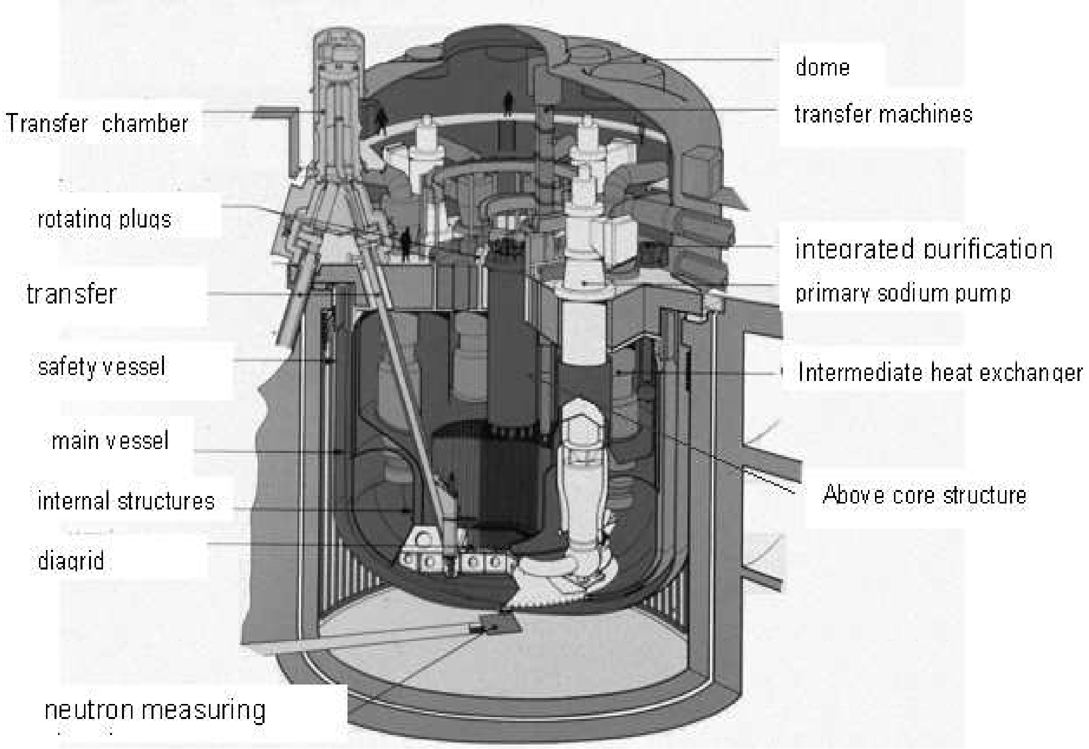


Figure 1: Structures to be periodically inspected in the Superphénix reactor block

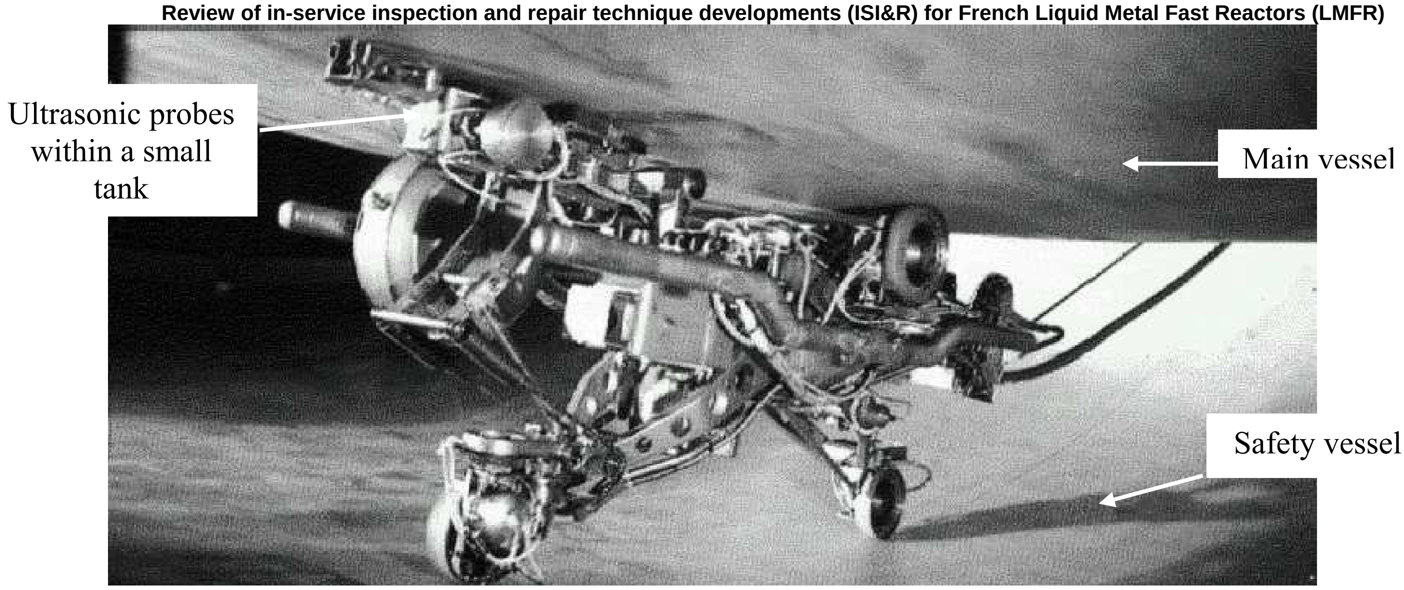


Figure 2: MIR device designed to inspect welding in the Superphénix main vessel

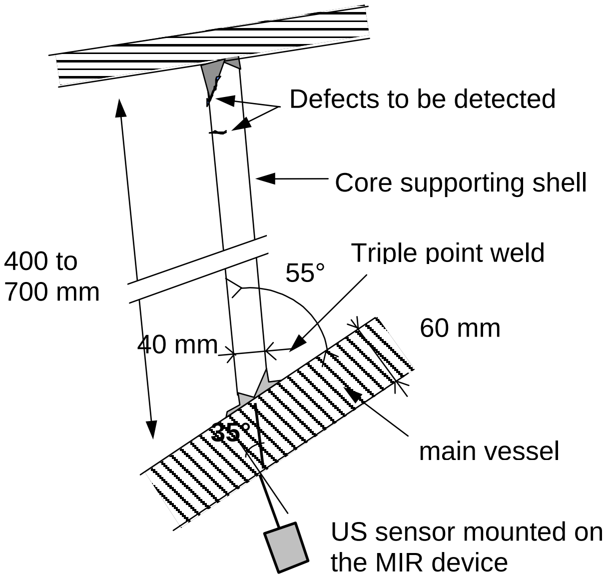


Figure 3. Ultrasonic control of the SUPERPHÉNIX core supporting shell

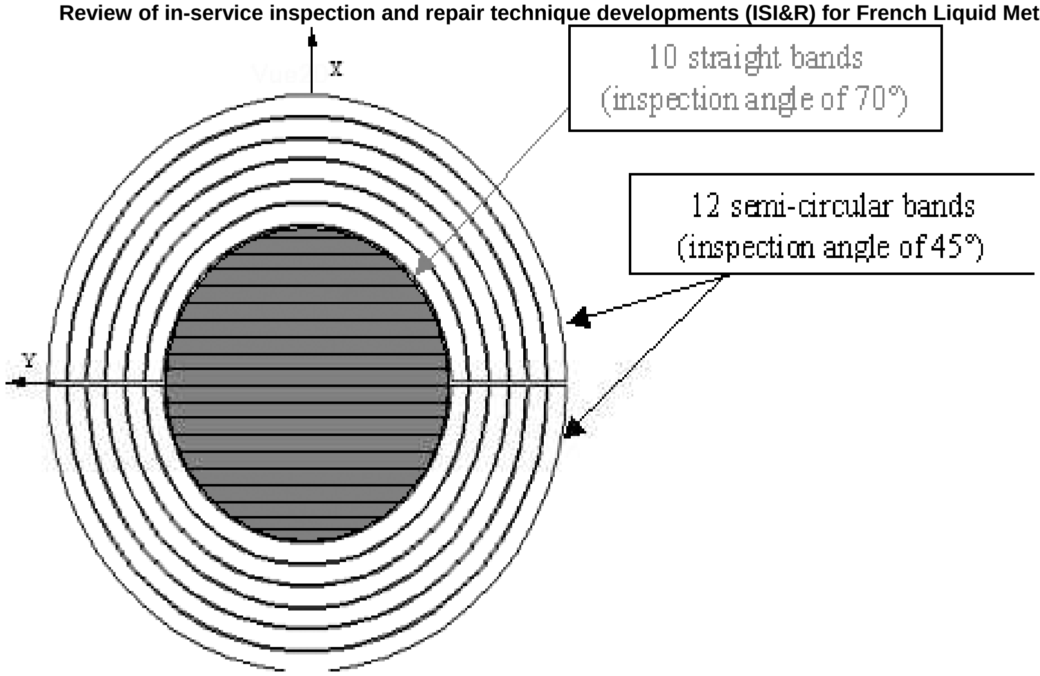


Figure 4. Phased array probe used to inspect edge-to-edge welds in the main reactor vessel

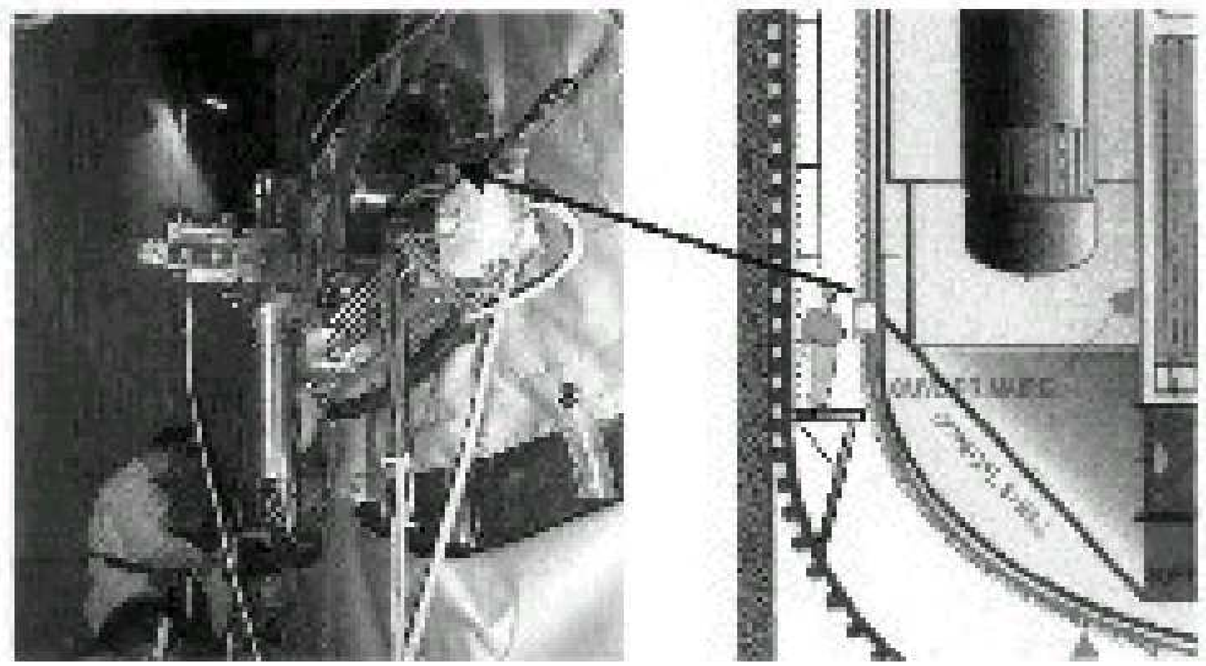


Figure 5. Ultrasonic control of the conical shell in Phénix

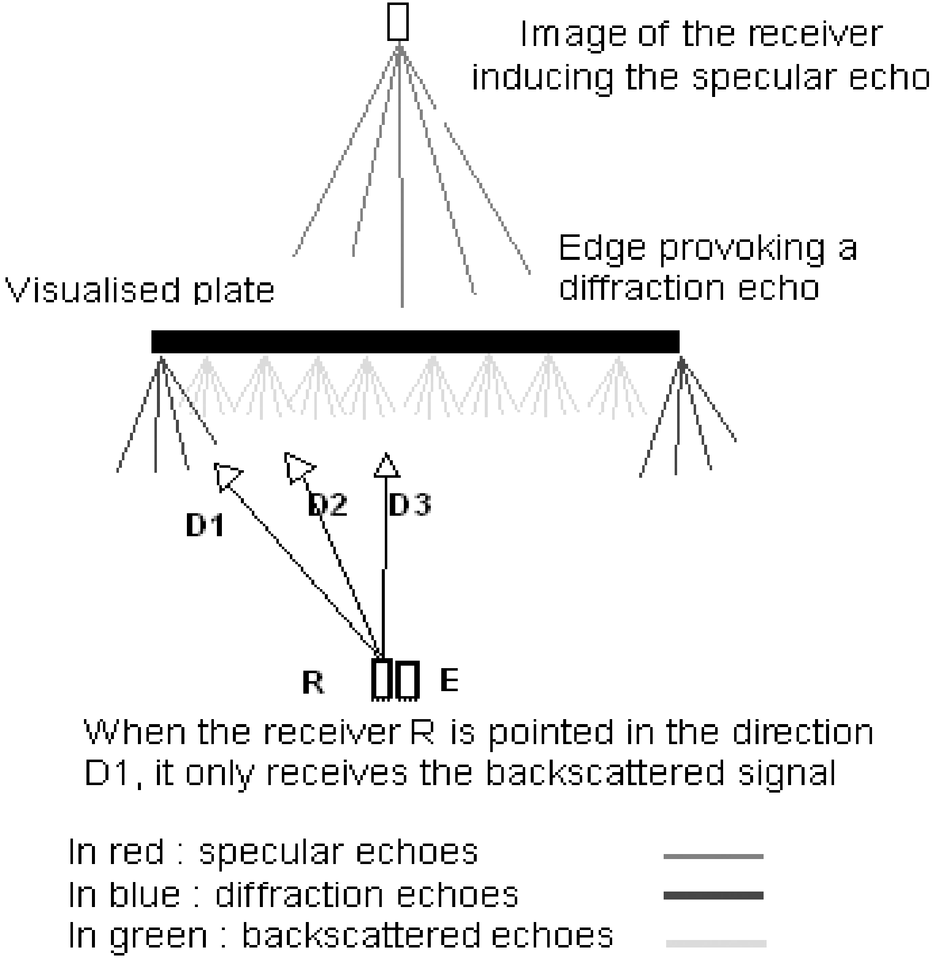
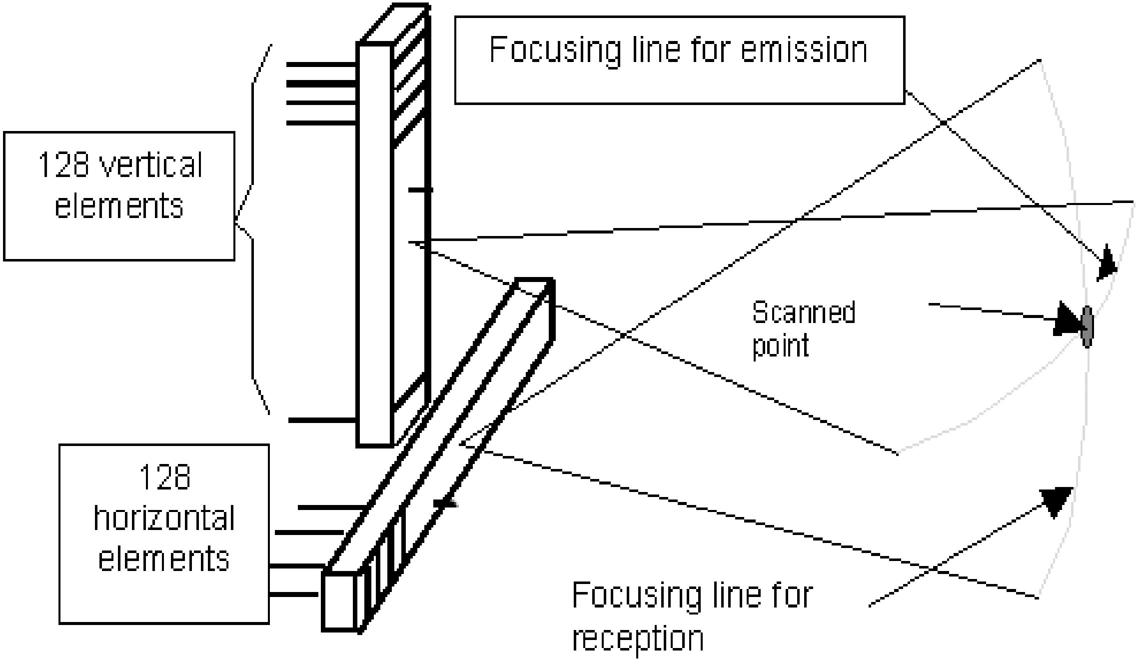


Figure 6. Ultrasonic echoes



Antenna size (horizontal et vertical)	L = 500 mm
Number of elements per antenna	N = 128
Aperture of image	30°
(equivalent to a range of 1020 mm to 2 m in distance)	
Frequency	1,6 MHz (λ = 1.5 mm)
Axial resolution	4 mm
Spatial resolution	0.33°
(equivalent to a range of 11 mm to 2 m in distance)	
Image acquisition time (anolog solution)	
- sectorial (= one segment)	dt = 65 ms
- total (= 64 sectorial images)	64 dt = 4 s

Figure 7. Orthogonal ultrasonic imaging

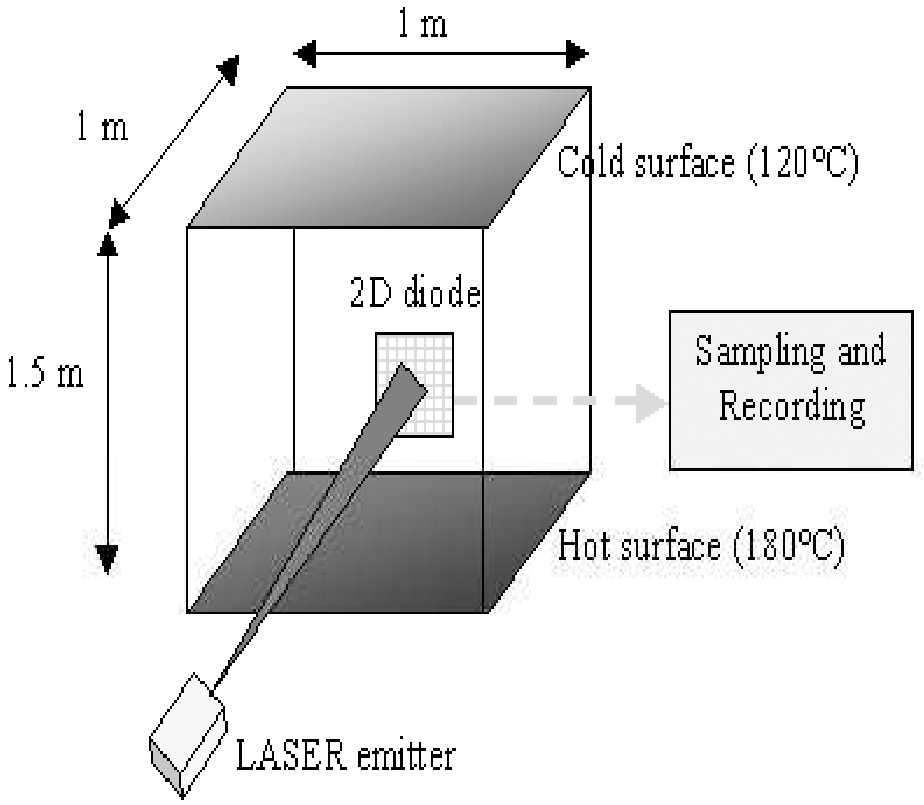


Figure 8. Laser telemetry : EPISTAR model tested in air

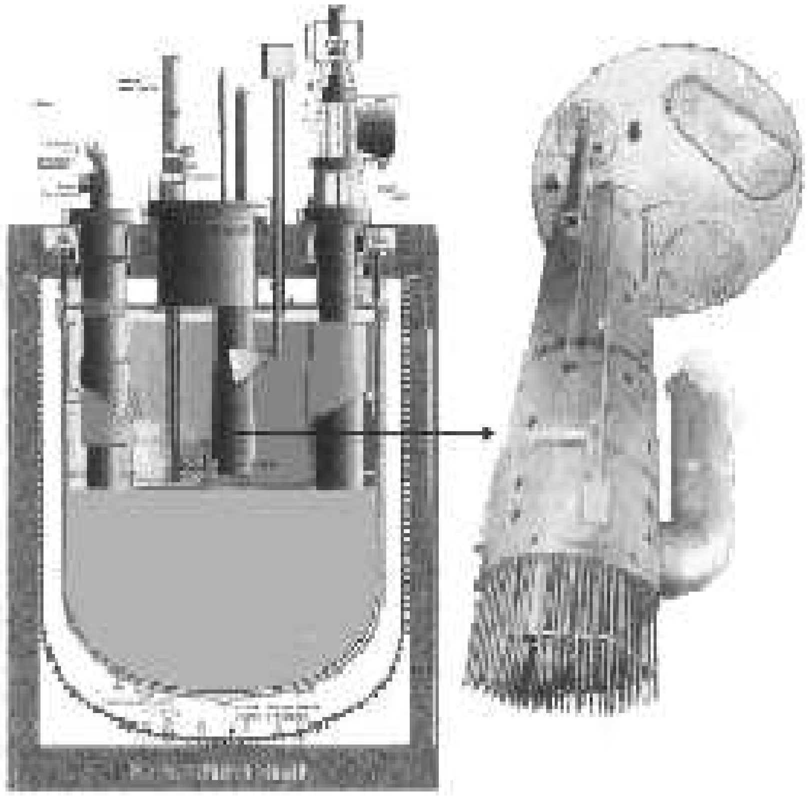


Figure 9. Video inspection of the Phénix above core structure

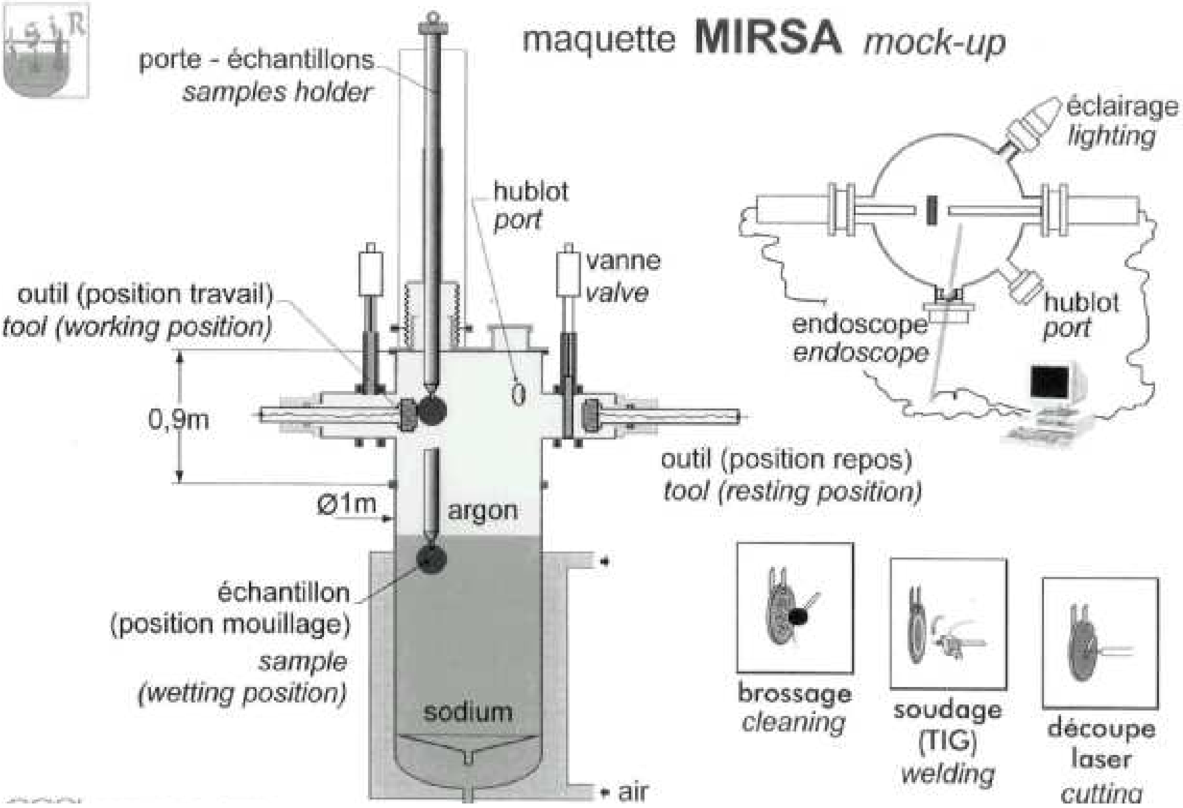


Figure 10. MIRSA sodium facility

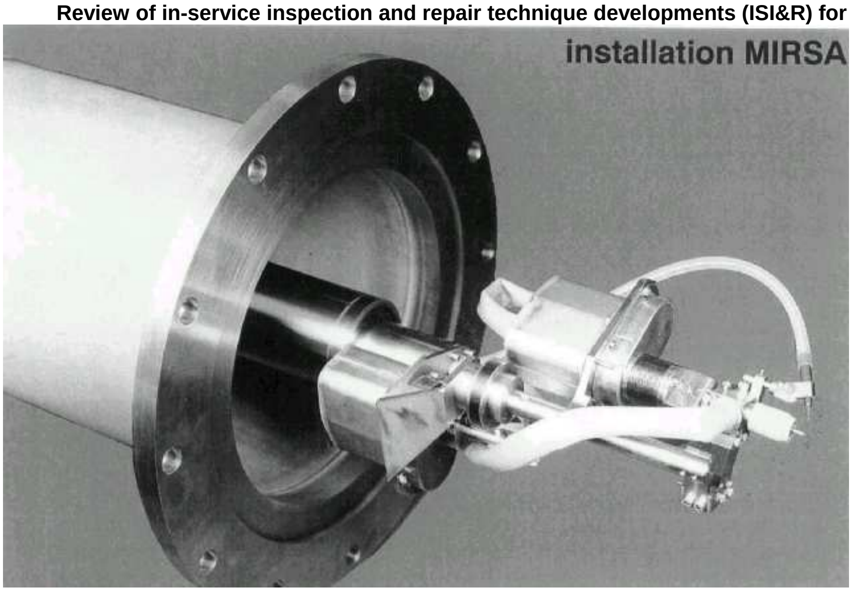


Figure 11. Orbital GTAW welding head