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R&D on Early Detection of the Total Instantaneous Blockage for 4th Generation Reactors – Inventory of non-Nuclear Methods Investigated by the CEA

K. Paumel, J.P. Jeannot, T. Jeanne, G. Laffont, M. Vanderhaegen, N. Massacret

***Abstract*— In the safety analysis for the core of the 4th Generation Reactors, the Total Instantaneous Blockage (TIB) is a hypothetic accident scenario involving the melting of the blocked subassembly with a risk of propagation to the neighbouring subassemblies. To avoid this latter consequence a detection system has to scram the reactor. For Superphénix or EFR project a Delayed Neutron Detection Integrated (DND I) was considered as efficient to limit the melting to the first neighbouring subassemblies. Nonetheless for the CFV core the objective of improving the safety leads to limit the melting to the blocked subassembly. For this purpose, the CEA has launched a program development to find a new detection method. This paper provides a brief review of the feedback of R&D, progress and program on the various early non-nuclear detection methods investigated by the CEA:**

- **Temperature measurement at the subassemblies outlet by thermocouples. The advantage of this method is that it will require no additional instrumentation to that already present for continuous monitoring.**
- **Temperature measurement at the subassemblies outlet by Optical Fibers Bragg Grating (OFBG). This technology has the electromagnetic immunity, compactness and short response time.**
- **Temperature measurement at the subassemblies outlet by ultrasound. The measuring point is located closer to the head subassembly and the response time could be shorter.**
- **Acoustic detection of sodium boiling. Boiling occurs early in the accident progress and the area to be monitored may be covered by few sensors.**
- **Subassemblies loss of flow detection by eddy-current flowmeters. This method seems logically the easiest and the most immediate method to detect a blockage.**

To date, none of these methods has been fully demonstrated to be feasible. It should be noted that temperature measurement methods will probably consist of the detection of a low increase rate using specific signal processing. These methods have been compared according to their performance that may be expected and their maturity level. The shorter time to qualifying is for eddy-current flowmeters and thermocouples.

K. Paumel, J.P. Jeannot, M. Vanderhaegen and N. Massacret are with the CEA, DEN, Nuclear Technology Department, F-13108 Saint-Paul-lez-Durance, France (e-mail: kevin.paumel@cea.fr).

T. Jeanne is with the CEA, DEN, Reactor Studies Department, F-13108 Saint-Paul-lez-Durance, France (e-mail: thierry.jeanne@cea.fr).

G. Laffont is with the CEA, DRT, LIST, F-91191 Gif-sur-Yvette, France (e-mail: guillaume.laffont@cea.fr).

***Index Terms*— Sodium Fast Reactors, Total Instantaneous Blockage, Detection Methods, Thermocouple, Optical Fiber Sensors, Ultrasonic Thermometry, Passive Acoustic Detection, Eddy-current Flow-meter.**

I. Introduction

In the safety approach for the core of the 4th Generation French Sodium Fast Reactor, the Total Instantaneous Blockage (TIB) is a hypothetic accident scenario belonging to Prevention Situation category (probability inferior to 10^{-6} per year). This event involves the melting of the blocked subassembly with a risk of propagation to the neighbouring subassemblies in around ten seconds. This scenario is very unlikely as it assumes a complete and simultaneous blockage of all the subassembly inlet ports while the reactor is at full power. However, the study is justified because it is considered as a limiting accident.

The Delayed Neutron Detection Integrated (DNDI) is currently the only means of monitoring for the TIB detection. However, in the case of the CFV (low sodium void effect core), it seems that the time available for detection is reduced compared to Superphénix or EFR, and the effectiveness of the DNDI could be questioned. And anyway, it is likely that the DNDI could not avoid the fusion of the six neighboring subassemblies, especially if the ejection of delayed neutrons emitters in the hot plenum requires the rupture of the adjacent hexcans. Highlighting new detection methods, and in particular methods limiting the fusion only to the blocked subassembly, is therefore a major issue.

Ideally, these new methods of detection would prevent, by their quickness, the rupture of the blocked subassembly, either for reasons of safety margin, constraints on investment protection, plant availability, but also to facilitate the safety demonstration. For the latter, it is clear that the more the accident spreads in time, the more difficult is to understand complex phenomena by simulations or experimentation.

The purpose of this analysis is to establish a short feedback, a status of R&D already begun, and a program of R&D that remains to carry out on the various methods of non-nuclear detection and "fast" that are considered by the CEA. In this

paper, is described as "fast" any method to detect the TIB and stop the accident before the rupture of the hexcan of the blocked subassembly.

After a review of the last available information on TIB and associated physical phenomena, the objectives and specifications of the detection methods are indicated. Then the five methods currently being studied by the CEA, namely: core outlet temperature measurement by thermocouples, by optical fibers, by ultrasound, passive acoustic detection of boiling, flow or speed measurement by eddy-current flowmeters are described. Finally, the methods are compared based on performances that can be expected and with regard to their maturity.

II. Phenomenology of the TIB

The TIB is a hypothetical accident leading to a full and instantaneous cancellation of the sodium cooling flow in a subassembly while the reactor is at nominal power [1]. The fusion of the subassembly which could then spread, could lead to the fusion of the whole core.

A. Accident Kinetics

Table I shows the time between the TIB at t = 0 and various events of the accident according to the first SIMMER calculations conducted at the CEA, and the control rods drop time estimated for CFV core. These SIMMER results are preliminary; note that SIMMER developments are undergoing.

The reference calculation, the most conservative, provides a period of 9 s to completely stop the accident before the rupture of the blocked subassembly. Taking into account of a little less than a second for the control rods drop time, the accident must be detected, the information submitted and the trip triggered in about 8 s.

If the "no flow" information of the blocked subassembly comes from t = 0 and, for simplicity, lasts throughout the course of the accident, it is not the same for the "boiling" information. The reference calculation predicts a beginning at t = 1.33 s and an end (not shown in the table) concerning the upper fissile zone at t = 1.51 s (follows the drying). This immediately gives an idea of the immense challenge reserved for acoustic detection of boiling. The boiling of the lower fissile zone occuring from t = 1.52 s to t = 1.80 s, is probably not "accessible" to the acoustic detection because of the "screen" formed by the vapor phase of the upper fissile zone that prevents the acoustic transmission through the sodium to the sensors. This calculation also shows that damage (ie irreversible) of the blocked subassembly begins after only less than 4 s.

B. Physical phenomena that could be detected

The physical effect of the blockage that is the most obvious is the cancellation of the outlet sodium flow rate of the blocked subassemby. However, other physical effects appear before the fusion of the subassembly:

- abnormally high fuel temperature,
- abnormally high cladding temperature,
- abnormally high sodium temperature in the subassemby, or sodium temperature exiting the subassembly,
- abnormally high sodium temperature in the inter-subassembly zone and in the neghbouring subassemblies,
- sodium boiling (vaporization of a fraction of the liquid sodium in the subassembly, recondensation phenomena in subcooled regions),
- cladding dryout.

TABLE I
MOMENTS OF VARIOUS EVENTS OCCURING AFTER A TIB AT T = 0 AND TIME OF CONTROL RODS DROPTIME.

Event	Time (s)		
	Reference calculation	Calculation without activation of candling and pressure loss models	"Porous plug" calculation
Beginning of sodium boiling	1.33	1.41	1.33
Beginning of cladding fusion	3.63	4.64	3.63
Blocked subassembly rupture	9.01	13.06	-
Neighbouring subassemblies rupture	14.09	-	-
Control rods drop	0.7 – 0.8		

It is clear that the available precursory signals for detection are those covered by the methods presented in this paper, namely the increase of the sodium temperature and the sodium boiling. However, it misses the wetting defect (or contact) of the fuel cladding by sodium, representative of the dryout, which is difficult to detect without contact of a sensor with the subassembly.

III. General Information on Detection Methods

The TIB accident is classified as a prevention situation. For this category, the safety constraints require a defense line. If there is no other defense than the detection, it must be a “strong” one that could lead to the automatic shutdown of the reactor. The protection strategy should allow one hand to limit the fusion to a single subassembly and secondly to provide a second means to limit the fusion to seven subassemblies (thanks to the DNDI for example).

This latter method is based on the detection of delayed neutrons emitters by fission products that are released following the rupture of an adjacent subassembly, after the fusion of the blocked subassembly and the rupture of its hexcan. For one of the SIMMER models (cf. §II.A) the beginning of the rupture of a neighbouring hexcan occurs at $t_{P1C} \approx 14$ s. The available time in seconds for the triggering of the scram on the DNDI threshold and for the control rods drop is (without taking into account safety margin):

$$t_{DNDI} \approx t_{P2R} - t_{HT} - 14 \quad (1)$$

where t_{P2R} represents the time corresponding to the rupture of a subassembly of the second row (this is the limit not to reach to ensure that the accident do not spread to all the core despite the control rods drop) and t_{HT} the hydraulic transfer time of the delayed neutrons emitters from the blocked subassembly to the detection area of the DNDI sensors. This method therefore responds to a detection criterion accepting the fusion of seven subassemblies. Note that t_{P2R} has not been calculated so far.

For the "fast" methods, detection must occur before rupture of the hexcans of the neighbouring subassemblies. In this case, the detection criterion tolerates only the fusion of the blocked subassembly, i.e. a detection time of less than 9 s (8 s if one takes into account the control rods drop, cf. §II.A).

The protection requirement implies that a device should not only be capable of delivering order(s) of scram with excellent reliability with respect to the detection of the event to avoid, but also to be affected by a very low rate of spurious detection. The "strong" defense lines have a failure rate expected of 10^{-3} to 10^{-4} per demand.

The detection of TIB is currently an unsolved problem. Ideally all the possible methods should be regarded. Currently, the CEA R&D work is limited to the methods that will be discussed below, excluding nuclear methods, namely:

- temperature measurement by thermocouples,
- temperature measurement by optical fibers,
- temperature measurement by ultrasound,
- passive acoustic detection,
- sodium flow (or speed) measurement by eddy current flowmeters.

All these methods perform a measurement between the bottom of the upper core structure (UCS) and the subassemblies outlet.

Each method presented later in the paper is assigned a level value (see Fig. 1) coming from the application of the maturity estimation approach for a concept or a technology: Technological Readiness Level (TRL) [2].

IV. Temperature Measurement by Thermocouple

A. Principle

The continuous monitoring of the fuel and fertile subassemblies outlet temperature aims at detecting any abnormal change in temperature [3]. These temperature changes can have very different origins and dynamics that detection strategies must take into account.

The core outlet sodium temperature is monitored by thermocouples located inside a thimble above each subassembly. These thimbles are maintained in the UCS. In the French concepts (Phénix and Superphénix) thermocouples were enclosed in thimbles.

The quality of information gathering is essential. This is to reduce as much as possible the influence of neighbouring subassemblies by taking the temperature of a single subassembly. This requirement impacts the position of the sensors relative to the head subassemblies. Obviously, the location of thermocouples close to or within the assembly would improve the representativeness of the measurement with respect to the thermal condition of the subassembly. However, this would imply strong operating constraints during handling operation.

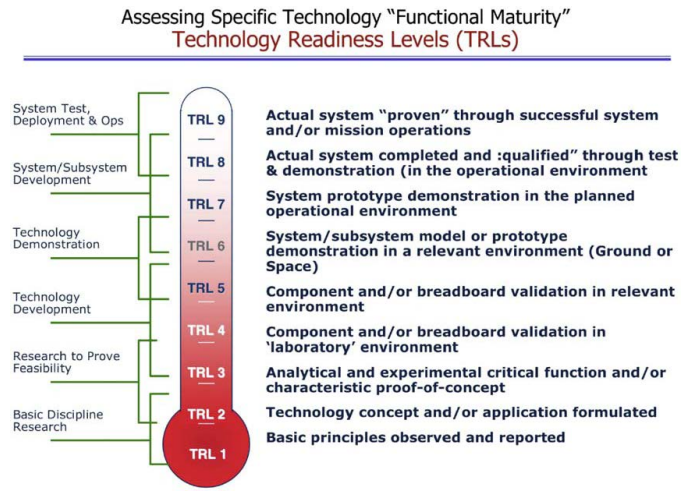

Fig. 1. Overview of the technology readiness level scale (from [2]).

B. Phénix and Superphénix Core Outlet Thermocouples

For Phénix and Superphénix (French sodium-cooled fast reactors), at nominal power and flow, thimbles were located 10 cm above the subassembly heads. At Phénix, all the subassemblies were each monitored by two chromel-alumel thermocouples (type K) with an average time response of 4.2 ± 2 s. At Superphénix the principles used are the same as Phénix. The thimbles have two type K thermocouples with an average time response of 1.1 ± 0.5 s and an accuracy of 4°C for a core outlet temperature of 545°C. The difference in response time between the thimbles of Phénix and Superphénix comes from the mounting configuration of the thermocouples inside the thimble. For Superphénix, the mounting is an "immersed type" one where the seal is deported in the upper part. This allows a better thermal contact between the thermocouple and the sheath of the thimble.

The Phénix and Superphénix operational systems used the raw value of core outlet temperatures, that is to say without performing digital processing. The purpose of this individual monitoring of the subassemblies was to ensure protection against sudden temperature changes and monitoring against slow drifts. Temperature measurements were processed by two computers called TRTC. The thermocouples response time, the scan rate (at Phénix each thermocouple was scanned every 3 s) and some other parameters have made the TRTC insensitive to detect events such as the TIB.

C. Detecting from the Blocked Subassembly Measurement

It is generally accepted that in the absence of flow in the blocked subassembly, the dedicated thermocouple becomes "blind". Indeed, in the past, it was assumed that, following the blockage, sodium no longer circulating, the dedicated temperature measurement provided a signal that was only representative of the jets mixture coming from the

neighbouring subassemblies. However, the demonstration has not been clearly made. It could be shown that the thermalhydraulic anomaly generated by the TIB leads to a specific thermocouple signal that could be used for detection.

For example it will determine whether the sodium boiling in the fissile zone, resulting in a rapid vaporization of a certain mass of sodium and thus in a large increase of its volume, leads to a significant ejection of the liquid sodium column (downstream) towards the thermocouple. It will then determine the temperature rise induced by this small flow (sodium having a very high thermal conductivity) on the overall sodium reaching the thermocouple.

To illustrate this idea, flow measurement downstream of the test section in the GR19BP campaign [4] exhibited oscillations due to the onset of boiling. These oscillations, albeit small (the amplitude of the oscillations was less than 10% of the nominal flow) may be likely to lead to a "specific" and detectable variation of the temperature signal. These oscillations are also found for a CFV subassembly (see Fig. 2) in the SIMMER simulation of the CEA. Furthermore, the temperature value supplied by SIMMER on the axis of the subassembly at its top end (see Fig. 3) indicates an increase of 25°C at t = 5 s. This deviation from the nominal value (corresponding to the unblocked case) tends to decrease from t = 5 s to t = 10 s but remains higher than 15°C.

Despite these hopes, we must keep in mind the very "thinner" skill of the neighbouring subassemblies flows. In addition, the first interpretations of the CEA from SIMMER calculation results suggest that the low amplitude oscillations flow and the short period of these oscillations can not propagate a significant signal to the thermocouple. Concerning the temperature signals of GR19BP they were not looked but anyway, this test was performed with a single bundle simulating a single subassembly.

D. Detecting from the Neighbouring Assemblies

The principle of this method is to detect an abnormal temperature rise with the thermocouples that monitor the neighbouring subassemblies. This temperature rise is a consequence of the heating of adjacent subassemblies by conduction through the hexcans. It has been estimated that this heating resulted in an increase of the neighbouring jets temperature of a few tenths of °C per second for 10 s (until the hexcans rupture).

1) Experimental Monitoring Device: ALPES

An experimental monitoring device called ALPES [3], based on a process of digital processing of the subassemblies outlet temperatures, was developed by the CEA and tested at Superphénix at the end of operation (years 1994-1996). This system had basically two complementary objectives:

- monitoring and protection improvement with respect to subassembly fusion accidents such as TIB;
- improvement of the support to the operator by the provision of a tool for online viewing, thus contributing to a better understanding of phenomena and thus providing decision support.

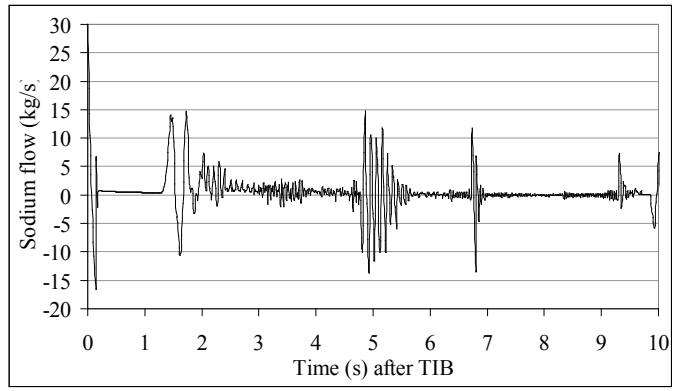

Fig. 2. SIMMER simulation of a CFV subassembly undergoing a TIB at t = 0: subassembly flow calculated at its upper end (head).

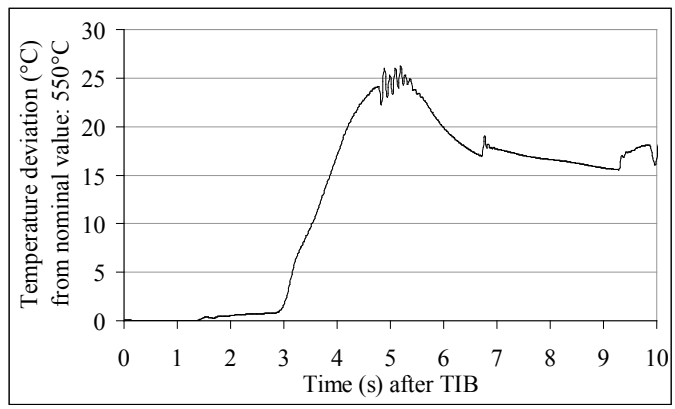

Fig. 3. SIMMER simulation of a CFV subassembly undergoing a TIB at t = 0: sodium temperature increase at its upper end (head).

Several methods have been developed and tested. Those based on the raw signals (either by simply exceeding a threshold or by comparison to a standard signal) only leads to insufficient performance in relation to the objective. However, the method of detecting concomitant by exceeding of filtered signals thresholds (filtering eliminates unwanted signal components, thereby improving the signal/noise ratio) is promising. In the central region of the core, the latter provides a reliable detection of a temperature rise in the neighbouring subassemblies of about 0.3°C/s for 10 s or less, provided that the temperature rise affects the entire row.

2) Using the SIMMER Calculation Results

As indicated in the results of the SIMMER calculation concerning the neighbouring subassemblies (see Fig. 4), detection by exceeding a threshold appears too late. Indeed, at t = 10 s the temperature rise is only 5°C and the hexcan rupture has already occurred. Over time, the accident phenomenology becomes increasingly difficult to predict and the risk of the neighbours' blockage is not excluded after the rupture of the neighbours' hexcans at about 14 s.

Therefore, as for ALPES, a detection of temperature change is rather considered. Especially since the SIMMER calculation results show a temperature rise ramp of about 0.3°C/s for the first 10 s. In addition, it will check if the "peak" of 2°C in the first second can be exploited by an appropriate algorithm.

Note that these temperature values provided by SIMMER are those located on the axis of the subassembly at its top end.

However, the first CFD calculations of the CEA indicate that the temperature remains constant over the entire height of the space between the subassemblies heads and the UCS for both cases: nominal and TIB.

Thus, the ALPES method appears very promising for the TIB detection. It will be necessary to recalculate the non-detection and false alarms rate by introducing the temperature rise ramp obtained at the thermocouple by coupling the SIMMER results and a CFD calculation.

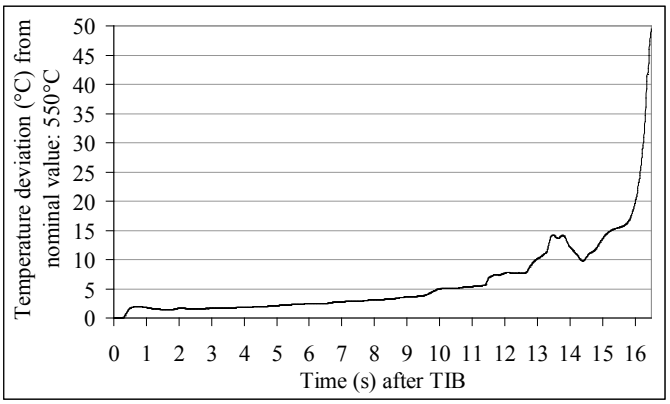

Fig. 4. SIMMER simulation of a CFV subassembly undergoing a TIB at t = 0: sodium temperature increase of neighbouring subassemblies at their upper end (head).

E. Current Option

The reference option is to individually monitor all fissile subassemblies and the first row of subassemblies reflectors through thimbles implemented along the UCS and ending in thimble. The end of the thimbles is currently located 100 mm above the head of each subassembly. This value is a compromise between the desire to have the thimble closer to the subassemblies outlet and the need to have sufficient space for the ultrasonic beam of the VISUS (ultrasonic system for checking the absence of connection between the core and the UCS before any handling). This value may be adjusted later.

The reliability and robustness of the concept of thermocouple make it as the reference sensor in terms of potential acceptance by the safety authority. The stainless steel sheathed K-type thermocouple still seems the best solution nowadays. It is a simple and robust sensor that has a large feedback in reactor operation.

For a 2/3 redundancy, three K-type thermocouples are necessary in the thimble for a strong protection line. In addition, a Bragg grating optical fiber is also planned but only as an experimental sensor. In addition, N-type and sodium-steel thermocouples could be implemented for an experimental purpose, but elsewhere to avoid cluttering the thimble, and for experimental applications.

On the thimble, whose influence on the response time is preponderant (because of the delay of heat conduction through its thickness), its geometry and in particular the geometry of thermocouples housings have to be studied in detail.

F. R&D Steps to Carry out

In the TRL scale, the thermocouple itself could be classified at level 9. However for TIB application, the feasibility of this method depends much on the TIB specific signals compared to normal temperature fluctuations. Thus, it is proposed to classify this method at the level 5 of the TRL scale.

In the very short term, it will be using the results of CFD calculations to assess the previously proposed methods. Then, a refinement of the calculations taking into account these objectives may be proposed. The TIB detection being highly dependent on flow conditions under the UCS, this numerical approach will support the design of the thimble containing the thermocouples.

Moreover, it would be interesting to launch an analysis on the detection capabilities of flow reduction (less than 100%) by thermocouples depending on the position of the subassembly, such as the study carried out by IGCAR [5]. IGCAR has been estimated that the thermocouples (positioned 100 mm above subassemblies heads) were able to detect, by an exceeding of 10°C above the nominal temperature, flow reductions greater than 7% for fissile subassemblies and greater than 12% for fertile. The other advantage of this study is that it reveals brutal stalls of the thermocouple measurements compared with the temperature at the subassembly head, beyond a certain threshold rate reduction (60% for example) for certain subassmblies positions. Indeed, for some subassemblies, there may be a fairly abrupt transition from a situation where the thermocouple still measures the temperature of the monitored subassembly jet to the situation where neighbouring jets take over.

Finally, the study of thermocouples with a shorter response time (<0.5 s) can be considered given the rapid evolution of the temperature signal associated with a TIB. For example, "open" sodium-steel type thermocouples are faster, but they are more sensitive to parasites. Anyway, it certainly does not expect to be a decisive improvement in comparison of the signal processing core outlet temperatures.

V. Temperature Measurement by Optical Fiber [6]

The monitoring objectives that could fill the optical fiber thermometry are identical to those filled by existing thermocouples: continuous monitoring of operating parameters, anomaly detection, but also safety and reliability improvement.

Since 2008, the CEA focused its studies on Bragg gratings Optical Fiber Sensors (OFS) and their associated electronics. On the application of detecting the TIB, the advantages of these sensors compared to thermocouples are:

- their slightly smaller size (outer diameter ~ 125 µm),
- their electromagnetic immunity would reduce the measurement noise,
- the ability to measure the temperature at various points in series along the sensor, which would thus draw temperature gradients.

However, the disadvantage of the OFS is their sensitivity to radiation. This drawback has to be eliminated in order to

ensure the same function as a thermocouple.

The detection methods described above in the context of temperature measurement by thermocouple remain applicable to OFS provided they are not linked to the intrinsic technology of the thermocouples.

A. Principle

A Bragg grating is a periodic structure formed by modulating the refractive index of an optical fiber core, single mode usually. This component acts as a diffraction grating with the characteristic of reflecting a very fine spectral band around a resonant wavelength called Bragg wavelength.

The Bragg length is directly sensitive to three physical parameters: temperature, strain (relative elongation) and pressure (hydrostatic or not). Any change in the temperature of a Bragg grating leads to a shift of the Bragg wavelength. This shift with temperature is linear over a range of about 300°C. To work up to much higher temperatures, e.g. 600°C, it is necessary to use a calibration curve obtained by polynomial regression. The principle of the OFS is based on the measurement of the spectral shift of the wavelength of the reflected signal (Bragg wavelength) under the action of a measured physical parameter (temperature, strain, pressure, for example). Their use as a transducer requires implementing appropriate techniques to measure fine variations of the Bragg wavelength.

Unfortunately, Bragg grating naturally undergoes a slight drift over time of its optical characteristics (the Bragg wavelength, reflectivity, full width at half maximum). Higher the temperature, faster is the drift. Temperatures above 300-400°C can lead to a deletion within a few days of a Bragg grating inscribed on a standard telecom fiber.

In addition, exposing optical fibers to radiation involves:

- an increase in optical attenuation, which reduces the signal/noise ratio and limit the measurement reach;
- a densification of the silica, which causes a drift in the measurement;
- a mechanical weakening, which will limit the ability of Bragg gratings to resist deformation and/or significant extensions;
- the occurrence of a radio-luminescence signal, which has no influence on the metrological performances.

B. Progress of R&D

The work carried out by the CEA helped develop Bragg gratings with stable optical properties over a temperature range from 400 to 600°C and beyond. Thus, the barrier of the temperature resistance is crossed. These Bragg gratings called "regenerated" (or "chemical") were manufactured using new annealing processes. Indeed thermally accelerated aging tests have shown the stabilization of the reflectivity of the regenerated gratings, and for over 2000 hours at temperatures up to 890°C. Aging tests are continuing, but life span at 600°C much higher than a few years are already anticipated.

The high temperature resistance of the regenerated Bragg gratings encouraged further studies, especially with sodium tests. The fiber is inserted into a capillary made of Inconel 600 ($ø_{outer}$ = 1 mm, $ø_{inner}$ = 0.3 mm). Firstly, the functioning of the sensors has been validated in liquid sodium at 500°C. A response time less than 150 ms was then obtained from 300°C. Finally, temperature gradients less than a few tenths of a degree Celsius per millimeter were characterized through spectral multiplexing of Bragg gratings. It is clear that, by an appropriate choice of the spectral gap between two consecutive Bragg gratings in manufacturing, it is possible to adjust the performance of the measurement to gradients to measure. It is thus possible to measure gradients of up to 40°C/mm.

C. Current Option

Firstly, the objective for the regenerated Bragg grating OFS is to qualify this type of innovative temperature sensor in operating conditions. At the moment, it is expected as an experimental rather than an operational device. Therefore, if the sensor meets the requirements of robustness identical to those of a thermocouple, it is planned to incorporate just one OFS in each thimble.

D. R&D Steps to Carry out

In the TRL scale, the OFS itself could be classified at level 4. For TIB application, it is proposed to classify this method at level 4 of the TRL scale.

Aging tests and metrological characterization of OFS will continue. In addition, following the literature on the behaviour of OFS under irradiation, tests in research reactor are being planned.

VI. Temperature Measurement by Ultrasound

The purpose of this method of ultrasonic thermometry is to detect overheating at the subassembly outlet directly at the subassembly heads.

It is often reproached core outlet thermocouples for:

- their long response time (especially relative to the kinetics of accident to detect),
- the remote nature of their measuring point (10 cm above the subassembly outlet) that makes them "vulnerable" to the jets of adjacent subassemblies (measuring a temperature of the mixture) especially at the periphery where the jets tend to bend outwards from the core, but also for reduced flow of the monitored subassembly.

This ultrasonic method would avoid the disadvantages of thermocouples due to the gain in terms of response time, number of sensors and the local nature of the measurement.

A. Principle [7]

This thermometry method is mainly based on the British patent (UKAEA) in 1985 [8] on an ultrasonic method of measuring liquid sodium temperature. This method relies on the dependence of the velocity of ultrasound with regards the sodium temperature, which is given by the formula [9]:

$$c_{US} = 2577{,}25 - 0{,}524 \times T \qquad (2)$$

where c_{US} is the speed of sound (m/s) and T (°C) the sodium temperature. This law is supposed valid from 100 to 1400°C.

By emitting a monochromatic wave train at grazing incidence towards the subassembly outlet (see Fig. 5), the

ultrasonic transducer receives two distinct echoes by reflection on both sides of the subassembly. Knowing the distance between these two edges, the speed of ultrasound is deduced from the measurement of the time difference between receipt of the two echoes, and the average sodium temperature between these two edges is then calculated.

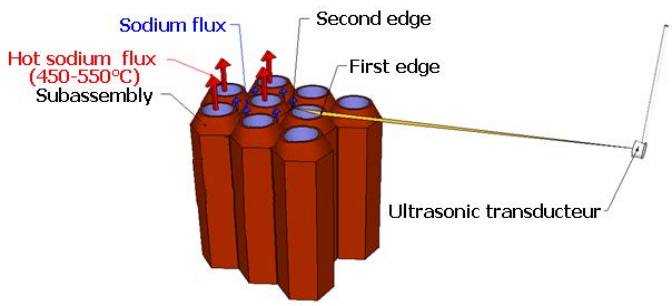

Fig. 5. Principle of sodium temperature measurement of subassemlies outlet by ultrasound.

To apply this method, it is necessary that the path of ultrasound between the transducer and both edges of the subassembly are almost identical. Thus, it can be assumed that the time difference of flight between the two echoes is due only to the medium between the two sides of the subassembly. For this assumption to be valid, the transducer is located so that the ultrasonic beam reaches the subassembly head at grazing incidence.

This method has advantages:

- Repetition rate of ultrasound shots may be of the order of a few kilohertz, which allows a very fine temporal sampling of the temperature signal to be measured. The main limiting factor here is rather time signal processing.
- In addition, the measured temperature is only that of the sodium exiting the subassembly because the measurement zone is closest to the core outlet; therefore neighbouring sodium flows do not disturb the measurement. Referring to the SIMMER calculation results shown in Figure 3, the interest of this method compared to thermocouples is clear as it could possibly detect the peak at 25°C or the following plateau at 15°C.
- Finally, the instrumentation encumbrance is not increased above the core because the pole wearing the ultrasonic transducer can be deported at the periphery of the core; and because the same ultrasonic transducer can measure the sodium temperature of several aligned subassemblies with a single wave train (see Fig. 5). In the experiments reported in [10] it was shown that it was possible to perform the measurement of 6 assemblies simultaneously.

But this method also has drawbacks that must be addressed in order to make it more reliable:

- The main disadvantage is the ultrasound sensitivity to this environment with very disturbed velocity and temperature fields. Because of these inhomogeneities, ultrasound will undergo deviations (due to the speed change in the medium), diffraction (spatial distribution of the acoustic energy) and scattering if these inhomogeneities have a characteristic size close to the ultrasonic wavelength. These deviations of ultrasonic beams can cause noise and lead to short interruptions of the temperature measurement (some experiments, such as [10], indicate that despite these interruptions, the measurement frequency is such that the response time of this method is very good), or a mistaken identity of the subassembly that is targeted (this case is much more problematic because it is difficult to detect).
- Another factor to consider is the deformation of the subassemblies geometry. During temperature transient, dilatation phenomena occur that alter the distances and distort the measurement. In this case, it is possible to correct the measurement by introducing dilatation models. However, the neutron flux can also cause subassemblies deformations whose it is more difficult to consider.
- Gas bubbles presence in sodium can also be problematic. Indeed, in normal operation, the sodium conveys argon microbubbles throughout the reactor primary loop that damp the acoustic signal.

Thus, the development of this method requires precise knowledge of the influence of environmental parameters on the propagation of the acoustic wave.

B. Foreseen System at the Time for EFR

The UKAEA planned to use a system based on this principle for EFR [11]. It was baptized USTM for UltraSonic Temperature Measurement. The targeted subassemblies were the fertile ones in periphery for which the problems of jets mixtures were the most important. A configuration with immerged ultrasonic sensors, such as TUSHT [12] (sensors developed by the CEA) for example was proposed. It consisted of six slab penetrations, each comprising five guide tubes with 40 mm diameter sensors. The aim was to cover all fertile subassemblies of the second row.

According UKAEA, in water and in sodium tests would have demonstrated accuracy of ± 2°C for an outlet temperature of 550°C. In addition, temperature fluctuations would be measured by the USTM system up to 400 Hz. The UKAEA then concluded sensitivity for EFR better than ± 0.5°C and therefore the ability to easily detect partial blockages.

C. Progress of R&D [7]

From 2009 to 2012, experiments in water were conducted to check the industrial feasibility of this method. The results show that there are many echoes from neighbouring tubes representing neighboring subassemblies in a core. It is therefore difficult to distinguish the targeted one. The medium of the measurement zone has to be known and the mechanisms of wave deflection understood and mastered to validate this method.

Thus numerical simulation works are carried out in order to understand the importance of disturbances caused by the medium on the ultrasound propagation. A ray theory code was developed with Matlab© to predict acoustic paths in this complex environment. Analysis of the results allows us to understand the influence of environmental heterogeneity on ultrasonic thermometry measurement.

D. Current Option

To date, the sensors envisaged for in sodium acoustic instrumentation are the TUSHT [11] that have multiple resonant frequencies (the lowest frequency being of the order of 700 kHz). In sodium tests showed their temperature resistance up to 600°C.

This method is considered for the moment only experimentally, given the unknowns remaining, especially on the ultrasound sensitivity to the environment under the UCS with very disturbed velocity and temperature field.

E. R&D Steps to Carry out

In the TRL scale, the acoustic sensor (TUSHT) itself could be classified at level 8. For TIB application, it is proposed to classify this method at level 3 of the TRL scale.

Two experiments are planned to validate simulations of ultrasonic wave propagation. The first, in a viscous and temperature inhomogeneous liquid, will observe the temperature dependence of the ultrasonic deflection (using a strioscopy bench). The second, in water, will implement Kelvin-Helmholtz instabilities in order to measure the wave propagation dependence on turbulent flow.

VII. Passive Acoustic Detection of the Boiling

The boiling detection is also a so-called "fast" detection method as the boiling occurs during the first phase of the accident (after less than 1.5 s after the TIB, cf. §II.A). In addition, compared to other methods such as temperature measurement by thermocouple, acoustic detection has the advantage that the whole area to be monitored can be covered with a few sensors. Finally, even with a limited number of sensors, the source localization of the anomaly signal is theoretically possible.

A. Principle

Passive acoustic detection by sensors in the hot plenum under the UCS is based on the continuous comparison of the current situation and a "normal" reference situation referred to as "acoustic background noise." The occurence of a noise change, characteristic of an anomaly, in this case: the specific sodium boiling associated with TIB, triggers an alarm or a scram.

The development of this method therefore requires:

- knowledge of the source (the acoustic signal of the TIB specific boiling),
- knowledge of the background noise,
- knowledge of the transmission between the source and the sensor,
- to develop an acoustic sensor capable of measuring the boiling noise and withstanding the hot plenum conditions,
- to develop specific tools for signal processing to discriminate a possible source in the background.

B. Foreseen System at the Time for EFR

The passive acoustic detection feedback is significant. Without going into detail, it should be noted that such a system, called ABND for Acoustic Noise Boiling Detection, was foreseen for EFR [11]. Unlike Superphénix whose UCS included waveguides (six in number), it was planned to implement in EFR immerged TUSHT sensors (30 poles each with three sensors for a 2/3 vote).

C. Progress of R&D

1) Characterization of the acoustic signal of the source

The TIB incident is a rapid thermalhydraulic transient and as such the typically boiling regimes, deduced from quasi-stationary transients, are not representative. Hence the conclusions on the acoustic detectability of these quasi-stationary regimes can't be extrapolated. As such, the CEA launched in the period 2011-2012 a study to predict the specific acoustic boiling noise proper to a TIB incident. Without such knowledge, the feasibility of the acoustic detection method to the TIB incident cannot be confirmed.

The acoustic boiling noise was characterized for a subassembly blockage accident, with a particular emphasis on the total inlet blockage. This modeling step is based on a profound analysis of the general boiling phenomena in a typical SFR subassembly [13]. Additionally a bubble dynamics study [14] confirmed that the condensation, i.e. the implosion, generates most of the noise during sodium boiling. The acoustic pressure pulse generated during condensation depends on the liquid subcooling (temperature below the saturation point). However, the exact pressure during condensation is difficult to determine and the problem becomes even more complex when non-spherical perturbations are taken into account.

The fact that the condensation is the main contributor to the acoustic noise is interesting, as the propagation of the sodium vapor is mainly determined by structural heating. The latter means that there is always a subcooled region in the subassembly where condensation takes place, even during a TIB accident. However, during a TIB there is no flow and it is thus possible that a stable vapor zone is created. This vapor zone can have a more or less stable liquid/vapor interface, thus resulting in no or a weak acoustic pulse.

The microscopic stability of the vapor/liquid interface can't be simulated with system codes like CATHARE-Na or SIMMER; SIMMER for example will only show a time-averaged stable vapor zone. Unfortunately the problem is still too complicated to be tackled with current-day CFD codes. As a last resort, two-phase flow charts can be consulted. However, prudence is necessary for reactive flows and they can certainly not be used for the very rapid reactive flow transient that occur during the TIB transient. The only available option to deduce the microscopic behaviour of the vapor is experimental data.

There is plenty of valuable data that can be deduced from past sodium boiling experiments, but experiments were not focused on the microscopic behavior at that time. Sodium boiling experiments are very difficult: high saturation temperature, small margins to dry-out, sodium risks… It is thus not surprising that an experimental sodium boiling campaign like GR19 on the CFNa-loop at CEA Grenoble [4] demanded a high investment. This especially applies to the electrical heating pins for the pin bundles. And it is just this heating technology that has to be redeveloped. And one should count on a period of at least 5 years before reliable heating pins might be available. To have some results on the short

term, a simulant fluid has been studied. As a result, an equivalent water boiling loop is being designed at the moment [15]. Nonetheless, it should be noted that the equivalency between sodium and water is incomplete from the thermal-hydraulic and acoustic point of view. This is due to the high thermal diffusivity of sodium, the temperature dependence of gas solubility, etc. Hence the results will be qualitative in nature.

It can thus be concluded that it is very difficult to verify the feasibility of the acoustic boiling detection method in the case of a TIB incident: It is difficult to rebuild the sodium boiling experimental facilities, there are only incomplete equivalencies between sodium and water, and the condensation phenomenon is very complex to model.

2) Characterization of the Reactor Background Noise

Intrinsically, this measurement method is sensitive to other "parasitic" noise sources in the primary vessel, such as pumps, turbulent sodium flows, etc. [16]. The overall noise combining all these parasitic sources is called acoustic background noise. This sensitivity to parasitic sources is relative since the background noise is essentially a low frequency noise (<10 kHz), while the acoustic signature of violent condensation of bubbles is rather broadband (up to approximately a few MHz).

This vision is unfortunately simplistic for two reasons. First, very impulsive events (and broadband) appear in the background and could be troublesome. And secondly, it is not excluded that the signal associated with the TIB boiling does not reach high frequencies. This could especially be the case if the boiling is characterized by relatively stable vapor slugs, that is to say not imploding violently. Therefore, it became essential in the opinion of the CEA to launch a study to characterize the background noise, in particular to determine the predominant noise sources and parameters to reduce them.

Within this framework, three studies have been launched:

- analysis of acoustic detection signals recorded in the Phénix reactor in 2009,
- analysis of the acoustic similarity of the turbulence between sodium and water,
- numerical simulation of the acoustic propagation in the primary vessel.

The first two were completed in 2012 and the last is not yet but is expected to be completed in 2013.

D. Current Option

It is to develop an acoustic sensor capable of measuring the boiling noise and withstanding the hot plenum conditions. The TUSHT with a diameter of 15 mm are relevant for the passive acoustic application. Reappropriation of the manufacture of this sensor is in progress but for now, the effort is focused on TUSHT with a diameter of 40 mm.

This method is considered for the moment only experimentally, given the unknowns remaining, especially on the acoustic signal of the source to detect.

E. R&D Steps to Carry out

In the TRL scale, the acoustic sensor (TUSHT) itself could be classified at level 8. For TIB application, it is proposed to classify this method at level 3 of the TRL scale.

Before unwinding the R&D program established in 2010 by the CEA, a decision to prosecute will be taken in 2013 on the basis of which was previously discussed above and of the R&D progress on other methods.

VIII. Eddy-Current Flowmeter

The solution proposed here is the implementation of the sodium flow (or speed) measurement at the subassemblies outlet. The Eddy-Current Flowmeter (ECF) seems to be the best suited for use at the core outlet.

A. Principle

The ECF was patented in the United States in 1948 [17]. It works on the principle of the deflection of a magnetic field due to eddy currents induced by the sodium flow (see Fig. 6). It consists of three coaxial windings or coils, arranged in series (some designs have 5 coils). The central primary winding, the magnetic field generator, is flanked on either side by two identical secondary windings. The sodium flow distorts the magnetic field so that electromotive forces generated in the two secondary coils differ in proportion to the sodium speed.

There are two types of ECF: External flow (three coils are embedded in a thimble and sodium circulates around) and internal flow (three coils are located around the pipe in which the sodium flows). This paper will focus on the external flow ECF.

The advantages of ECF are its small size and its ability to withstand temperatures up to 600ºC (value to check) and radiation above the core.

The conductivity of materials comprising the ECF and the sodium electrical resistivity are temperature dependent. When the temperature increases, the latter increases (which reduces eddy currents). Anyway, the measurement can be made temperature independent by appropriate adjustment of the current frequency [18]. However, this setting may be at the expense of the depth of penetration of the magnetic field in sodium, which also depends on the frequency.

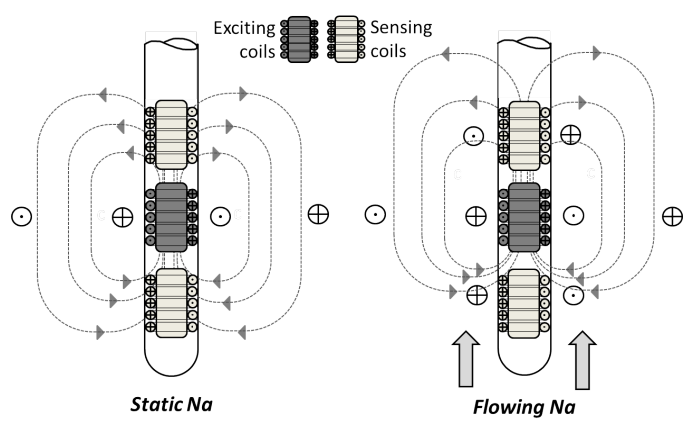

Fig. 6. Diagram of an external flow ECF (the three coils are in a thimble). Left: sodium is stagnant and the magnetic field emitted by the central coil is not deflected. Right: the sodium flows upwardly and the magnetic field is deflected upward.

B. Feedback from Phénix Reactor on the IGCAR's ECFM

A brief bibliography on the ECF is proposed in [18]. Here the information will be limited to the recent conclusions from

the Phénix reactor. An ECFM (for Eddy-Current FlowMeter) developed by IGCAR has indeed been implemented and used in Phénix in 2009 as part of the end of life tests of the plant. Its functioning proved simple and its behaviour was consistent with that expected in its design. The measurements were very good, both in terms of the sensitivity and stability with regards to the conditions of reactor operation. The ECFM measured speeds ranging from 0 to 9.6 m/s over a temperature range of 250-380°C. The largest Reynolds number (for a speed of 9.6 m/s, a sodium temperature of 380°C) obtained in the flow around the sensor was calculated to be about 230,000. Despite this high value, no signal "artifact" was observed.

C. Current Option

The option that is currently being studied and thus constitutes the reference option is to individually monitor all fissile subassemblies and the first outer row (such as that provided for thermocouple measurement). At first, the only regarded measurement position is under the UCS in the same thimble as thermocouples and SFO.

At this place, due to the presence inside of the thermocouples and the OFS, and outside of the cladding rupture detection systems, acoustic sensors, control rods sleeves, structures allowing the mechanical strength of the UCS and the sodium flow, encumbrance is a major constraint for the design of the ECF.

The ECF measurement range and resolution in m/s depend directly on its design (including the length of the coils and the number of turns in its windings). These features must be carefully chosen to detect the TIB (but also other types of flow reduction) reliably.

The manufacture of the ECF was mastered by the CEA in the 90's and it seems that the technology does not require a major reinvestment to get the know-how again.

D. &D Steps to Carry out

In the TRL scale, the ECF itself could be classified at level 6 (perhaps 7 or 8 for IGCAR and JAEA). However for TIB application, the feasibility of this method depends heavily on the flow. Thus, it is proposed to classify this method at level 4 of the TRL scale.

The R&D work to be done to qualify this method can decouple a numerical simulation part (COMSOL and CFD) and an experimental part (mainly in sodium).

1) Numerical Simulation

The CFD calculation mentioned above for temperature measurement will be also used to extract velocity fields seen by the ECF. The thimbles and protruding structures under the UCS will be taken into account. Moreover, currently a COMSOL simulation of the ECF is developing based on the model developed by IGCAR [19].

The combination of these two calculations aims to:

- define a design of the ECF and a measurement position optimized for the TIB detection, but also for other accidents leading to a flow reduction, while respecting the constraints of encumbrance;
- assess the sensitivity and response time of the entire method for the widest field of possible thermohydraulic scenarios (definition of a criterion of detectable reduction flows).

The calculations results depend on the position of the targeted subassembly (subassembly flow and power) as well as protruding structures below the UCS located on the passage of the blocked subassembly jet and those of its neighbours. It will then ask if a CFD calculation for each individual assembly is required to assess the corresponding speed change given the major influence of obstacles on the flow. If the core has symmetry planes, the number of different subassemblies to simulate will be significantly reduced.

The COMSOL study was begun in 2013. This simulation work is divided into several steps:

- validation of a first simplified model (2D-axisymmetric, permanent flow, laminar, with and without boundary layer) from [18,19] and the results of end of life tests of Phénix;
- implementation of the first model to the TIB configuration and design optimization of the ECF (design parameters) excepting the thimble;
- refinement of the model especially with regards to the flow (taking into account the turbulence and boundary layers) and design optimization of the thimble;
- study of miniaturization to meet the encumbrance constraint (following the results of the CFD modeling).

The studied design parameters are:

- the length and the inner and outer diameters of the coils (and so the dimensions of the core)
- he number of turns of the coils (and so the diameter of the coils wire),
- the materials of the coils wire and the core.

These parameters are studied for two adjustable parameters of the flowmeter: the intensity and frequency of the supply current of the primary coil. These parameters are also studied as a function of several variables of the sodium flow, such as:

- its temperature,
- its average speed,
- its characteristics of turbulence,
- the boundary layer around the thimble.

2) Experimental Validation

The CEA has an ECF of the 90's. It is being implemented on a sodium loop for tests planned for 2013. The ECF is located in a thimble positioned in the axis of a portion of pipe. The primary objective of these tests is to validate the COMSOL model for different sodium speeds and temperatures and to observe the behaviour of the ECF in both directions of sodium flow. Moreover, according to the possibilities of operation of the loop, the behavior of the ECF will be looked after flow rate cancellation.

These first in sodium tests will study only the feasibility of the method. However, it will be necessary to qualify this TIB detection method by performing tests in the most representative conditions, including on the topology of the flow (open and not guided in a pipe). It can be dynamic tests with seven subassembly outlets, a pole measurement including among others an ECF, and a modular structure above the measuring point simulating the lower part of the UCS. Ideally, the seven subassembly outlets would eject independently from each other with adjustable temperature and flow rate. The

program of these tests is foreseen for 2014. The choice of the loop and the design of the testing apparatus will be made in early 2014.

Finally, in water hydraulic tests are considered to qualify the thimble design selected through simulation.

IX. Conclusion: Comparison of the Methods

In conclusion on the TIB detection methods studied by the CEA, a comparison of their performance is proposed. The different methods are named in Table II and Figure 7 as follows:

- TC : Thermocouple
- OFS : Optical Fiber Sensor
- UST : UltraSonic Thermometry
- PAD : Passive Acoustic Detection
- ECF : Eddy-Current Flowmeter

This comparison is based on seven criteria, weighted according to their importance relative to the need. Note that the sensitivity criterion of the method does not appear because it depends mainly on the thermalhydraulic environment still unclear between UCS and core outlet. Thus, it is assumed that all methods are equivalently sensitive to the TIB. In addition, TC and SFO methods are supposed detecting the TIB by detecting the heating of adjacent subassemblies, while the UST method is expected to detect sodium overheating of the blocked subassembly.

For criterion No. 1, TC and OFS methods have had only one because their detection is based on a ramp. Indeed, the ramp time required to reach the detection threshold is unknown but the ALPES device required 10 s. However, one can hope that the new methods of signal processing are able to reduce this time. UST method gets an honorable score since a temperature rise of 25°C appears at the subassembly head after about 5 seconds.

Regarding criterion No. 2, these methods (TC and OFS) have had only two because of the previous remark and the fact that the thimble induces a relatively high response time. The PAD receives the lowest rating because the boiling in the CFV fissile part runs from t = 1.3 s to t = 1.5 s approximately (cf. § II.A).

For criterion No. 3, the OFS is superior to other techniques through its electromagnetic immunity. The UST method gets only two due to possible deviations of the ultrasonic beam that can generate measurement interruptions, errors in targeted subassembly or noise. The PAD still gets the lowest rating because of its sensitivity to noise such as cavitation (which can be likened to the boil) or damping due to an abnormal presence of gas bubbles in sodium.

Regarding criterion No. 4, the TC and OFS methods do not unduly encumber the thimble but one has to manage a large number of channels. For the UST method, it is possible to manage a greatly reduced number of channels due to the ability of a sensor to monitor multiple subsassemblies at the same time. However, an ultrasonic sensor is bigger than a thermocouple. As for the PAD, the ultrasonic sensors are a priori smaller (ø15 mm instead of ø40 mm) with a small number of sensors (90 planned for EFR).

For Criterion No. 5, the temperature measurement should not suffer from the difficulties encountered with a complete cancellation of flow, at least for the limited flow reductions (less than 50% for example). The PAD could also works because in this case the type of boiling is more "classic" and noisy especially if steam bubbles are ejected and if they collapse at the subassembly outlet. But for this, it is obviously necessary to reach the boiling point in the subassembly. The ECF may be entirely appropriate, provided that the resolution of the measurement is sufficient.

Regarding criterion No. 6, the overall flow in the subassembly is supposed to be not affected by this type of anomaly, so the ECF is blind unless the fault causes flow fluctuations. However, the methods of temperature measurement could be sensitive provided the local heat generated is sufficient to raise the temperature of the overall flow in the subassembly. It explains the mark 3. Regarding the PAD, it could detect such anomalies if collapses of small bubbles occur and if the acoustic pressure generated is sufficient.

Finally, for the criterion No. 7, the UST method has the advantage over the other two methods of temperature measurement to be sensitive to the passage of gas, which is also the case for the ECF and the PAD.

Figure 7 illustrates the results of Table II showing the TRL value of each method and an estimate of the qualification date of the method and the project risk associated.

The performances of the ECF are better than those of other methods mainly because of the simple and straightforward nature of the measurement with regards to the signal "reduced or cancelled flow rate".

Logically, it seems that the most mature methods are TC, OFS and ECF. TC is the only one whose qualification could be ensured before 2017. For the OFS and ECF methods, the qualification date is extended to 2022 because of the technology that requires particular irradiation tests, and for which the safety authority has no feedback.

TABLE II
COMPARISON OF THE PERFORMANCES OF ALL TIB DETECTION METHODS.

N°	Weight	Performance criteria	TC	OFS	UST	PAD	ECF
1	4	Delay between TIB and appearance of the useful signal	1	1	3	4	5
2	4	Duration of available useful signal / response time of the method	2	2	4	1	5
3	4	Reliability (low levels of non-detection and false alarms)	3	3	2	1	3
4	3	Encumbrance et management of the measurement channels (number and size of sensors)	3	3	3	4	1
5	2	Adaptability to detect partial or progressive inlet blockages or loss of flow	5	5	5	3	5
6	2	Adaptability to the detection of anomalies inside the pins bundle (blockages or abnormal heating)	3	3	3	3	1
7	1	Adaptability to the detection of other core anomalies (RIB, abnormal gas presence, etc..) or to continuous monitoring.	3	3	4	3	2
		Total Performances	52	52	65	51	69
		TRL Level	5	4	3	3	4

PAD and UST methods are not mature at all. Moreover, the risk of never being usable as safety devices is high. Not to mention the fact that the instrumentation and control of these acoustic systems has to be studied, especially their reliability.

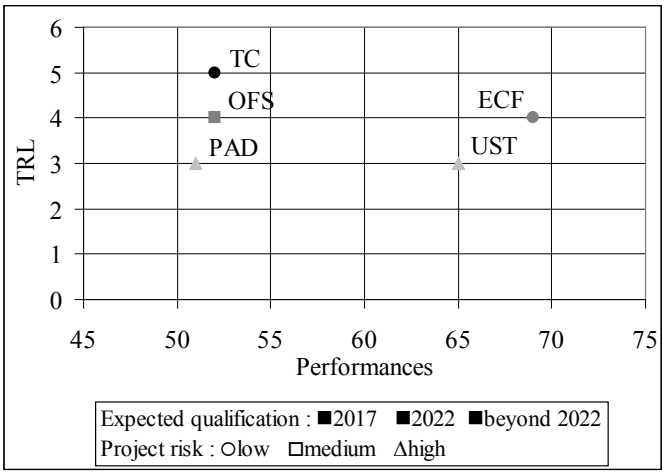

Fig. 7. Multi-criteria comparison of all TIB detection methods.

The CEA will therefore continue its efforts primarily on the ECF whose applicability to TIB should be quickly established. Simulations and associated thermalhydraulic tests will also be used for methods of temperature measurement in the thimble. Concerning the two acoustic methods, the more fundamental R&D work should continue.

Finally, R&D will be conducted with a priority related to TIB but the approach should not set aside the assessment of detecting more realistic accidents or anomalies such as partial or progressive inlet blockages or inside the pins bundle.

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