GREENPEACE

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Madrid, 29 de septiembre de 2016

Asunto: Solicitud de Información sobre las cuestiones sin resolver relativas a los componentes defectuosos en Asco y Almaraz

Estimados miembros del Consejo de Seguridad Nuclear,

Greenpeace se dirige a ustedes nuevamente sobre un asunto significativo sobre la seguridad nuclear de las centrales nucleares de Almaraz y Ascó actualmente operativas.

El pasado 9 de mayo les formulaba algunas preguntas que siguen sin contestar, y con la información publicada por el CSN en su comunicación pública del 15 de septiembre de 2016, quedan sin resolver algunas cuestiones urgentes, que les formulo a continuación:

1 - El CSN no informa sobre el contenido de carbono de los generadores de vapor en Almaraz y Ascó suministrados por AREVA. Greenpeace solicita, apelando al derecho a la información y el pricipio de transparencia, la publicación inmediata de todos los resultados de los datos de las pruebas de las partes correspondientes, incluyendo el contenido de carbono.

2- El CSN se refiere a las pruebas, incluyendo pruebas destructivas, pero no dice que materiales fueron testados, si se refiere al acero de su fabricación original o a otro nuevo material testado; y en este segundo caso debe explicar quien produjo ese material, y proporcionar de inmediato los detalles de todo el material ensayado.

3 - El CSN se basa en los estudios realizados por Equipos Nucleares SA (ENSA) y Areva para ofrecer garantías de la calidad y seguridad de los generadores de vapor suministrado y esto no ofrece credibilidad, ya que tienen grandes intereses en defender esta defectuosa tecnología. El CSN debe explicar qué evaluación independiente se ha realizado de los datos de la prueba y porqué agencia de seguridad los ha confirmado, y si no es así, explicar porque no lo ha hecho.

4 - Las pruebas en curso en Francia se basan en las llamadas 'spark tests' que proporcionan análisis del contenido en superficie del acero, incluyendo el contenido de carbono. Sin embargo, como AREVA ha confirmado a partir de ensayos no destructivos limitados, ha encontrado que la macrosegregación de carbono que tiene aumenta a través de la profundidad del acero de Le Creusot. Por lo tanto, si la confianza del CSN es sobre pruebas de superficie en el acero, esto no proporciona ninguna seguridad de que el contenido de

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carbono sea conocido y por lo tanto la seguridad nuclear no se puede afirmar. El CSN debe proporcionar todos los datos pertinentes sobre el régimen de las pruebas realizadas.

5 - El informe de Large & Associates, para Greenpeace, que adjuntamos con esta carta, muestra que la producción de acero de Le Creusot a partir de 2008 no cumple con la Directiva Europea de Equipos a Presión - ni los componentes forjados han obtenido un certificado de conformidad del regulador francés, ASN. El CSN debe confirmar que los componentes del generador de vapor suministrados e instalados en Almaraz y Asco cumplen con la Directiva Europea y han obtenido un Certificado de Conformidad, ya sea en Francia o en virtud de la normativa española, y en este último caso, el CSN tiene que explicar los medios por los cuales se certificaron los generadores de vapor.

6 - El IRSN confirma que el contenido de carbono en exceso en los generadores de vapor aumenta el riesgo de fallo del generador de vapor y podría dar lugar a una fusión del núcleo del reactor. Puede el CSN confirmar que están de acuerdo con el IRSN, o en caso contrario explicar el fundamento de la posición de CSN, y qué estudios se han realizado para demostrar su conclusión.

7 - El CSN no ha publicado los datos de la cadena de suministro de los generadores de vapor instalados en Almaraz y Asco, y debería publicar toda la información pertinente, incluyendo la fecha de fabricación en Le Creusot, costes, y qué función de supervisión jugó el CSN para asegurar la calidad de durante la producción.

8 - El CSN debe proporcionar toda la documentación recibida desde el regulador francés, ASN, relativo a las implicaciones para la seguridad nuclear, incluidos los datos de las pruebas.

9 - A la espera de la publicación de lo anterior, y sin demostrar que los generadores de vapor en Almaraz y Asco están ausentes el problema de exceso de carbono, el CSN debe tomar medidas para detener inmediatamente la operación de los cuatro

Quedo a la espera de recibir una respuesta a estas preguntas lo antes posible.

Atentamente, reciban un cordial saludo.

Fdo: Raquel Montón, responsable de la campaña nuclear de Greenpeace España

Large and ASSOCIATES

Review

Irregularities and Anomalies Relating to the Forged Components of Le Creusot Forge

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Irregularities and Anomalies Relating to the Forged Components of LE Creusot Forge

Summary

In late 2014, AREVA notified *Autorité de Sûreté Nucléaire* (ASN) of the results of material tests carried out on a component manufactured at the Creusot Forge. These tests were undertaken by AREVA as part of the much-delayed *Qualification Technique* (QT) of components for the European Pressurised Reactor (EPR) presently under construction at the Flamanville 3 (FA3) nuclear power plant (NPP). The part tested was a supernumerary equivalent of each of the two components, the upper and lower head shells, that had already been incorporated into the FA3 reactor pressure vessel (RPV) now installed within the nuclear island at the NPP site.

To much consternation the test results revealed that the material characteristics, particularly the impact or fracture toughness, did not conform to the design-basis specification and, moreover, it arose from a small but nevertheless significant increase in the carbon content across a large zone of macrosegregation present throughout most of the thickness of the equivalent head shell – this is the so-called *'carbon anomaly'*.

In the macrosegregation zones of excess carbon the toughness or resistance of the steel to tearing and cracking is lowered rendering forged components vulnerable to abrupt and catastrophic failure via rapid crack propagation and fast fracture – the fracture toughness is a particularly important material characteristic of the through-life components of the nuclear primary pressure circuit for which *'break preclusion'* (ie no opportunity for catastrophic failure) is an absolute prerequisite of the design-basis and nuclear safety case. When applied to the already installed FA3 RPV, such was the seriousness and potential implications of these test results that ASN required AREVA to i) undertake a further test and analysis programme evaluating the risk and acceptability of the FA3 RPV for nuclear power service and ii) review quality assurance practices at the FA3 component manufactory, Le Creusot Forge.

i) **AREVA's Further Test and Analysis Programme of the Carbon Anomaly:** The immediate implication of this non-conformity against the design-basis specification of the nuclear safety critical FA3 RPV is certain to stall the analysis and reporting of the test programme of i) until mid-2017, if not later, and quite possibly it will set back the ultimate delivery date for the FA3 NPP – if the non-compliance of the material properties of the FA3 RPV is unacceptable to ensure future, tolerably safe operation then its replacement in the virtually completed nuclear island containment at Flamanville NPP could result in several additional years of delay and involve many millions of Euros to effect remediation.

The present status of the FA3 RPV is that it does not have an ASN issued *Certificate of Conformity*, meaning that it neither complies with European Pressure Equipment Directive 97/23/EC *Équipements Sous Pression Nucléaire* of December 2005 (ESPN); nor satisfy the ASN prerequisite of January 2008 that all new components require a *Certificate of Conformity* before production begins. Moreover, ASN has not made clear whether it has received a request from AREVA for it to evaluate the Creusot manufacturing route(s) in preparation for a retrospective *Certificate of Conformity* and that, if it has, if this evaluation has been set back by ASN's recent (June 2016) deprioritisation of the FA3 carbon anomaly investigation.

It is unclear if other AREVA delivered forged components of the FA3 primary pressure circuit (ie the pressuriser, steam generators, etc) also do not have their respective *Certificates of Conformity*, irrespective of whether these components were sourced from Creusot or an overseas forge such as the Japanese Casting and Forging Company (JCFC) and/or the Japan Steel Works (JSW).

ii) **AREVA's Review of Past Quality Assurance Practices – the Irregularities:** The outcome of AREVA's review of past practises at Creusot, revealed that not only was quality assurance and component conformity unsatisfactory, particularly in that the manufacturing route for the FA3 upper and lower heads had never been subject to QT and thus had not obtained a *Certificate of Conformity*, but also that these uncertainties involved components that had been manufactured as far back as 1965 – ASN refers to these uncertainties as *'irregularities'*.

The consequences of the *irregularities* are now coming to light in dribs and drabs, extending back in time to around 400 flawed components produced at Creusot from 1965, about 50 of which are presently installed in operating NPPs across France and, quite possibly, there are others installed in overseas NPPs.

iii) **Steam Generator Forgings:** Most recently (July 2016), and quite separate from components affected by the *irregularities*, steam generator (SG) forgings installed at 18 NPPs have been identified as suspect with an additional NPP (Fessenheim 2) being held shutdown until further investigation has been completed. Some of these at-risk SGs are believed to have been manufactured in Japan by the JCFC and, possibly, JSW so the suspect component sourcing spreads beyond the single forging plant of Creusot.

The salient characteristics of the three different categories of at-risk components are summarised as follows:

	ASN Defined Category	Indirect Cause	Involves QT	Potential Failure Mode	Manufacturing Forge	Nº of French Operational NPPs Involved	Overseas NPPs
i)	Carbon-Anomaly	macrosegregation	YES	fast fracture	Creusot	1 - Flamanville 3 – in construction	possibly 2 Taishan
ii)	Irregularities	as yet not defined	probably	not defined	Creusot	21 - col 3 Table 6	quite probably
iii)	SG Forgings	macrosegregation	YES	fast fracture	Creusot + JCFC-JSW	18 + Fessenheim 2 - col 4 Table 6	most likely

This Review considers the implications and/or potential consequences of each of these three categories of at-risk components, these being as follows:-

Delivery of Flamanville 3: It is fact that components of the FA3 reactor pressure vessel do not comply with the design-basis requirement that precludes fast fracture, catastrophic failure of the RPV - on this fact alone, the FA3 RPV does not meet the design-basis and thus is not fit for service.

The now acknowledged defect in the FA3 components, manifest as increased carbon content of the positive macrosegregation zone formed during the ingot casting-cooling stages at Creusot, resulted in reduction of material toughness, thereby escalating the vulnerability of the at-risk components to the fast fracture failure mode. No doubt, the intent of AREVA's latest programme of analysis and physical testing of the FA3 supernumerary forged components is to show that, even with account of the non-conformity, particularly the degradation of fracture toughness, the FA3 RPV assemblage as a whole will have a sufficient margin to curb fast fracture and thus operate at an acceptable risk of failure throughout its service life.

Even so, the RPV assemblage remains non-compliant with the material heterogeneity requirement introduced in 2005 as part of a revised QT, which means that the *'break preclusion'* prerequisite of the design-basis will no longer underpin the first level of defence of the FA3 nuclear safety case. Thus, for the FA3 NPP to proceed into licensed operational service, ASN will have to grant a dispensation relaxing the all-important design-basis bulwark of *'break preclusion'* that underpins the FA3 NPP nuclear safety case.

FA3 Defence in Depth: Because RPV failure is not included in the nuclear safety case there is nothing in the *third level of defence* to mitigate the consequences of RPV failure. Thus a licence dispensation allowing for RPV failure in the principle of *Defence-in-Depth* would be a very substantial departure from the design-basis. Such a dispensation would require fundamental revisions of the first two levels of defence-in-depth entailing hardware and systems modifications to now embedded aspects and features of the FA3 NPP.

FA3 by Inference Means: At this time there is no intention to undertake anything other than non-destructive inspection and examination of the installed FA3 components with, instead, the physically disruptive and destructive material sampling and testing being undertaken on supernumerary, replica components that have been through the same Creusot manufacturing route. This approach relies upon the tested components being exact replicas or clones in all respects of the FA3 components.

For the FA3 at-risk components the carbon anomaly has been linked to the size and cooling of the forging ingot stage of the Creusot manufacturing route. However, the presence and extent of a macrosegregation zone can only be fully detected, mapped and examined by destructive means, so any potential defects have to be deduced via inference testing of i) a test ring taken from the surplus edges of the component and/or by destructively examining ii) a supernumerary or equivalent, replica forging that has followed through the same manufacturing route as the FA3 component.

It is now acknowledged that results from the FA3 test ring are unreliable, so a greater reliance has to be placed upon the examination and destructive testing of supernumerary, replica components. However, there must be strong doubts about the reliability of such replication, especially when the formation and spread of the macrosegregation zones within the cooling ingot are subject to so many poorly defined and least understood factors that form part of and/or are introduced during the manufacturing route.

Moreover, serious doubts have been raised about the reliability of the QT record-keeping during the early stages (2005 to 2008) of manufacturing the FA3 and supernumerary upper and lower head components: In effect, AREVA did not prepare a comprehensive QT file to record all of the relevant parameters of the manufacturing route prior to embarking upon making the components and, of course, there must be concern that the FA3 components may also have been subject to much the same *irregularities* of similar components produced earlier at Creusot. The absence of thorough QT manufacturing records means that there may be important variations between the individual manufacturing routes for the FA3 and supernumerary test components - nothing has been produced to show otherwise - thus there can be no guarantee that the supernumerary test components will be sufficiently reliable emulations of the FA3 at-risk components that are now fully and irreversibly integrated into the installed FA3 RPV.

These uncertainties place considerable reservation on the reliability of the proposed inference methodology to determine the suitability for service of the original FA3 components.

FA3 Prognosis: There is no doubt that AREVA will endeavour to demonstrate that the FA3 RPV is fit for purpose and thus suited to enter nuclear operation – there are three possible options for this.

First, restore the operational and materials characteristic margins curtailing fast fracture by derating the NPP and, particularly, by introducing a regime compensatory measures such as pressure-temperature management rules (P-T Limits), along with safeguarding procedures to cover all normal and anticipated modes of abnormal operation. However, this option also necessitates abandoning the *'break preclusion'* of the N1 safety critical components and, even if derating could be practicably implemented, it would result in a NPP of significantly reduced generation efficiency.

The second option would be to replace the at-risk components of the FA3 RPV and restore the *'break preclusion'* prerequisite of the nuclear safety case. If so, it would be impractical to carry out such repairs whilst the FA3 RPV remains in-situ in the reactor pit of the nuclear island containment. Moreover, removal, repair or complete replacement anew of the RPV assembly, together with its eventual reinstatement into the nuclear island containment, would be a very expensive and time-consuming exercise, so disruptive to be likely to jeopardise the financial viability and continuance of the FA3 project. Even so, ASN has suggested to AREVA that studies of this repair and/or replacement option should be undertaken, although to date nothing has been made publicly available on this issue.

The third option is to demonstrate that the RPV, even with its localised reduced toughness, is satisfactory for commissioning and in-power service. For this third option AREVA will have to demonstrate that the presence of positive macrosegregation, its locality about the head component(s), in the depth of the shell, and with its reduced toughness due to increased carbon content, will not render the in-service component unacceptably vulnerable to fast fracture failure at any time, and in any credible service condition, throughout the projected RPV life of some 60 or so years. AREVA's present investigation is likely to concentrate on i) determining by analysis (calculation) the value of toughness required for a revised design-basis; ii) evaluating (by testing) the actual minimum value of toughness of a replicate component(s); and iii) comparing i) with ii) to substantiate the AREVA claim that the revised design-basis is achievable.

For this third option, none of this will be known until AREVA has completed its present round of analysis and testing, following which ASN will have to evaluate and, whichever appropriate, reject or issue a licence dispensation to enable the FA3 NPP to proceed – the AREVA findings and ASN judgment are unlikely to be delivered until mid-2017, if not later because, most recently (30 June 2016), ASN declared that for FA3 *"caractérisation en cours mais non prioritaire"*

Future EPR RPV Components: The same Creusot manufacturing route used for the already installed but yet to be commissioned FA3 RPV upper and lower head shells, may also have been used for and, hence, the same flaws are very likely to be present in Creusot-sourced components for the two Taishan, China EPR NPPs presently nearing commissioning, and could arise in future orders such as Hinkley Point C EPR in the United Kingdom. In fact, to investigate the extent and severity of macrosegregation AREVA chose to destructively test the advance order upper heads manufactured for Hinkley Point C and a now cancelled United States EPR – the available data for these components show that both were below the design-basis specification in material toughness.

For these and future new orders of EPR NPPs a number of issues remain outstanding, the most demanding of which is that the flawed Creusot manufacturing route, being reliant upon cropping and upset forging of a single, large conventional ingot, will have to undergo reappraisal and fresh QT to qualify via a *Certificate of Conformity*. If, on the other hand, this particular manufacturing route is found to be unreliable, which presently and strongly seems to be the case, then for future EPR RPV head forged components a new manufacturing route will have to be developed and technically qualified – it is not immediately obvious that the *Lingot a Solidification Dirigée* (LSD) technique developed for smaller head components can be readily upscaled for the larger EPR head components nor, indeed, that this process is a guarantee against the formation and retention of positive macrosegregation zones within the finished component.

Resumption of construction and commissioning of the nuclear pressure circuit at FA3 is presently frozen whilst an enforced investigatory phase is undertaken. Most likely, the evaluation of the FA3 RPV will not be completed until at least mid-2017, although now that ASN has deprioritised the FA3 investigation and (it is assumed) the qualification evaluation for the *Certificate of Conformity*, reverting to productive work on the NPP could delayed further into 2017 or, perhaps, 2018. Then, before production of other EPR components is permitted to proceed at Creusot, the manufacturing route(s) will have to be reassessed and issued by ASN with a *Certificate of Conformity* for each type of specialised forged component. Moreover, switching the manufacturing to another forge, such as the JSW, is unlikely to shortcut the resumption of production because this manufactory will also have to be subject to conformity appraisal by ASN.

It is difficult to foresee just how the FA3 RPV will ever comply with ASN's ESPN, particularly with the irrecoverable lapses in the AREVA QT file and the acknowledged presence of a positive macrosegregation zone in the lower head shell that now forms an integral part of the RPV. If the FA3 NPP is to proceed to nuclear commissioning, ASN's January 2008 prerequisite will have to be waived and significant dispensations (relaxation) of its design-basis and operating licence will have to be granted. Whatever, it is becoming increasingly doubtful that FA3 will be commissioned by the much delayed final quarter of 2018 date.

Such delays could jeopardise new and/or existing orders for EPR NPPs, such as the UK Hinkley Point C (HPC) since the UK government Credit Guarantee for funding HPC is conditional upon FA3 being completed, fully commissioned and generating to the design intent for a trial period by December 2020. If this Base Condition cannot be met at Flamanville then, with the UK Credit Guarantee locked out, the drawdown of funds will fall entirely upon EdF and its co-investors.

Importantly, in manufacturing the upper and lower head components AREVA chose RCC-M M140 qualification instead of QT, a practice that was halted by ASN from January 2008 when it stipulated that a *Certificate of Conformity* had to be issued prior to manufacturing commencing. It follows that it is also likely that AREVA adopted the same M140 approach exclusively for quality assurance of the manufacture of other N1 primary pressure circuit components up to that date and, so, there may also be shortfalls in the QT for other components manufactured not just at Creusot but also overseas at the JCFC and JSW forges known to have sourced a variety of primary pressure circuit components – these potentially at-risk components could include the larger RPV annular rings that make up the main body of the RPV, steam generator tube sheets and bottom head manifolds, and so on.

Other Creusot-Sourced Components: Equally, if not more galling for the French NPP operator, *Électricité de France* (EdF), is the revelation that the macrosegregation defect could also apply to Creusot-sourced components already installed in operating French nuclear power plants. This startling exposé arose when AREVA reported its review findings to ASN in March-April 2016 that some 400 Creusot forged components manufactured in the period since 1965 are subject to *'irregularities'* and at least 50 of these are installed in NPPs presently operating across France.

Although not confirmed by ASN, it is likely that the *'irregularities'* affecting components of earlier NPPs (eg the 900MWe series commissioned in the late 1970s and 80s), arose from what seems to have been much the same failings, omissions, etc., now known to have corrupted QT files for conditions at Creusot for the FA3 at-risk components.

Cruas 3 and Chinon B3: Both Cruas 3 (~1984) and Chinon B3 (~1987) are fitted with upper closure heads sourced at Creusot under the single, large conventional ingot manufacturing route. If, as it might be reasonably assumed, these components are also subject to the same frailties as the later FA3 components (also forged from conventional ingots) then they, too, are at risk of depletion of fracture toughness in any positive macrosegregation zone remaining in the component shells.

Until the present AREVA programme of evaluation of the FA3 components has been completed, shutdown or derating of these two NPPs might have to be considered, particularly taking into account further degradation of material toughness due to strain-induced and thermal ageing over the respective operational service history of each NPP.

Irregularities in Creusot Components since 1965: There is very little information and data available for a number of now identified French NPPs that ASN acknowledge contain Creusot-sourced components dating from 1965 and which are known to have *'irregularities'* associated with their production files.

ASN defines *'irregularities'* to *"comprise inconsistencies, modifications or omissions in the production files, concerning manufacturing parameters and test results"*. Obviously, such a broad-ranging definition caters for a multitude of variations in the manufacturing route, material defects, poor and/or dubious recordkeeping, mismanagement and so on – components that have such *irregularities* attached must be, until demonstrated otherwise, considered sufficiently *'at-risk'* to jeopardise the nuclear safety case.

Whatever the details of the *'irregularities'* it is clear that the QT requirements in force at the appropriate times of manufacture failed to 'capture' a true, factual record of the components sourced from Creusot.

Like the December 2005 ESPN QT, the earlier QT requirements set out in the February 1974 and October 1999 Orders seem to have each failed to prescribe the basis of a reliable QT system at the respective times.

If, as it seems, the QT system has been inadequate since 1974 or earlier, back to 1965 as implied by AREVA, then this form of quality assurance system failure could have allowed a diverse range of component non-conformities to slip through unchecked, unnoticed and/or in corrupted form. In other words, it is unlikely that the *'irregularities'* are confined solely to the presence of macrosegregation associated with the use of single, conventional forgings in the Creusot manufacturing route. Indeed, the at-risk components might be sourced from a variety of manufacturing routes and other causes of non-compliance so, until details of the *irregularities* are publicly available, the risk and potential severity of failure of the operating NPPs can only be a matter of speculation – the recent addition of the steam generator (SG) bottom heads and, particularly, the suspension of the Fessenheim 2 SG because of the presence of a positive macrosegregation zone in the distinctly different lower shell annular forged component might well be a strong portend of this.

Recently (12 September 2016) ASN acknowledged that *"since the end of 2015, three different cases of Counterfeit, Fraudulent and Substandard items (CFSI) related to the nuclear industry"* have been raised in France. One possible example of fraudulent recordkeeping occurred in March-May 2016 when three, or possibly, four replacement SGs were scrapped (or withdrawn for partial replacement of the lower manifolds) because the Creusot test records (QT) registered incorrect carbon content and omitted the presence of a positive macrosegregation zone,

A further ambiguity is that, to date, other than stating that there are 50 at-risk components installed in operating French NPPs, although EdF has identified the NPPs by name it has not declared which at-risk components are installed. The situation is further confused by recent industry media reports together with a statement from ASN of 23 June 2016 that similar zones of positive macrosegregation have been found in the semi-spherical, bottom heads of SGs in service at a total of 18 NPPs of the 900MWe and 1,450Mwe series – it is believed these at-risk SGs are in addition to the 50 at-risk components previously stated by ASN but do not include a further 3 or 4 replacement SGs that were scrapped in or around May 2016 following discussions with ASN.

The manufacturing routes for the SGs installed in the 18 NPPs were sourced from both Creusot and JCFC, with the latter involvement having the potential to widen the international scope of this problem.

In the past, it seems that AREVA deployed M140 of the RCC-M code, dealing with and prioritising quality control over the design of components, at the neglect of quality assurance of the manufacturing route (ie the QT file approach). In 2005 ASN introduced the *Équipements Sous Pression Nucléaire* (ESPN) measures to improve the quality control and assurance of the manufacturing route, although not entirely successfully with, in 2007, ASN expressing strong disappointment (*'situation préoccupante'*) over AREVA's reluctance to adopt the ESPN based QT – the apparent entrenchment of AREVA may echo its poor practice of previous years during which the at-risk SGs were manufactured at Creusot and elsewhere.

It may be appropriate to retrospectively apply the basis of the *Équipements Sous Pression Nucléaire* (ESPN) introduced in 2005 to each of the operating NPPs believed to have installed at-risk components, even if these at-risk components were manufactured in years past with incomplete and/or corrupt QT files. If so, the shortfalls in the QT record could be filled, wherever practicable, with data amassed via a rigorous inspection regime at each NPP – there is opportunity for the plant operator (EdF) to 'reconstitute' missing parts of the QT.

Whatever, the present situation whereby NPPs are operating with at-risk components of unknown manufacturing track record (ie an incomplete or *'irregular'* QT) is unacceptable in nuclear safety terms. The issue cannot continue to be dealt with on a case-by-case basis with the risk being tackled reactively when and where it arises. The approach needs to be regular, across-the-board and pre-emptive – it would be reprehensible of ASN if it dithered further on this, allowing EdF-AREVA to continue the programme of appraisal of both FA3 and the operational NPPs at-risk components without first having an effective and properly managed QT with its *Certificate(s) of Conformity* in place.

In fact, the general case assessment for a SG manifold failure has been completed by EdF and reviewed by IRSN on behalf of ASN. The IRSN review covers CPO, CPY and N4 NPPs, concluding that EdF requires further material data for its analysis to be applicable; it disagrees with EdF that the nuclear fuel core is safeguarded, with IRSN finding that in certain fault conditions involving the catastrophic failure of a SG manifold, the fuel core could melt; and to bolster the margins mitigating against a fuel core melt situation, it recommends that EdF should immediately implement a series of (unspecified) compensatory measures at each operating NPP with the at-risk SGs installed. In effect, the IRSN review is tacit recognition that an undeclared number of CPO, CPY and N4 NPPs are presently operating an unquantified level of risk of incurring serious radiological event.

Fessenheim 2 Suspension: Example of the case-by-case approach is the recent test certificate suspension of one of the replacement steam generators at Fessenheim 2. This action was taken by ASN upon discovery of a macrosegregation zone in the SG lower shell component, whereas it had been previously certified as fit-for-purpose in February 2012. The suspension of the certificate arose because, it now transpires, at the ingot cropping and discard stage (during which any macrosegregation inclusions should have been removed) the recorded weight of the working ingot remained unchanged, indicating that the discard had not taken place – presently there is an ASN action on AREVA to demonstrate compliance of the SG component and it is doing so, in part at least, by testing a replicate component that has followed the same Creusot manufacturing route.

The Fessenheim 2 SG suspension casts doubts on the claim that centre-pierced forgings (ie annular rings – the lower shell of the Fessenheim 2 SG) do not have present remaining zones of macrosegregation – this claim was deployed by EdF Energy in the UK to substantiate why the Creusot-sourced nozzle and transition rings for the Sizewell RPV did not merit further consideration as possible at-risk components.

UK Sizewell NPP: The EdF-AREVA progress on analysing the safety of the operating NPPs that have at-risk components installed is yet to be made publicly available by ASN. However, the UK safety regulator (Office for Nuclear Regulation – ONR) has received a response (March 2016) from the EdF Energy the operator of the pressurised water reactor (PWR) NPP at Sizewell B, Suffolk. This EdF Energy response may provide insight into the approach to be adopted by its French counterpart for the NPPs operating in France.

Interestingly, EdF Energy considered only 2 of the 6 major components sourced from Creusot to make up the Sizewell B RPV, thereby tacitly assuming that there was no potential for carbon excess in any of the Creusot-sourced annular forgings. The recent Fessenheim 2 SG certificate suspension because of the presence of a zone of positive macrosegregation in an annular forged shell may cast doubt on this, although at this time it is not possible to identify the manufacturing routes, particularly similarities, of the Sizewell and Fessenheim forgings.

In considering the Sizewell B RPV head shells, EdF Energy admitted that results from the test ring (a disposable part taken from the outer rim of the of the forging) were insufficient to demonstrate material compliance throughout the component, stating *"demonstration of consistency throughout the forging is not possible with these {test ring} results alone"*.

Instead, the EdF Energy response to ONR almost entirely relied upon a 1985 conference paper describing the development of the *Lingot a Solidification Dirigée* (LSD) manufacturing route, but which did not specifically refer to or contain data expressly relating to the Sizewell B head shells. Surprisingly, on this basis, that is referring to a 1985 paper that was *"carried out at around the time of SZB {Sizewell B} dome forging manufacture"* and also trusting that because the manufacturing route was different to the large, conventional ingot used for the FA3 head shells, the at-risk potential of the Sizewell B Creusot forgings was dismissed without much further ado and concern.

The Sizewell B response illustrates how not to approach technical qualification of an existing at-risk component. This is because it has not, particularly with the recent ASN acknowledgement that SG components are also at risk of positive macrosegregation, been irrefutably demonstrated to derive from a single, identifiable manufacturing route (for example, for the FA3 at-risk components the large, conventional ingot instead of the LSD ingot).

Unreliable Test Ring Results: The existence of the FA3, RPV and other N1 components in operating NPPs and, possibly, SG at-risk components, together with lack of confidence shown in the recent Sizewell B re-evaluation, strongly suggest that dependence upon the forging sacrificial test ring for material analysis and testing is unreliable – indeed, for the FA3 at-risk components the test ring material was drawn from the peripheral parts of the upset-forged plate that was furthest from the centre-plate zone of positive macrosegregation.

Accordingly, it would be prudent to review all forged components from Creusot (and because of the SG flaws similar JCFC and, possibly, JSW components) that have been overly reliant upon the test ring for material characterisation analysis and physical testing – it may be that the QTs dating back to 1965 for all of these at-risk components are fundamentally flawed. Also, it is worthwhile noting that the 1985 conference paper claimed to demonstrate the LSD manufacturing route to be free of macrosegregation for the UK Sizewell B substantiation, itself relied upon results taken from test rings trepanned from much the same locations as those now considered to be unreliable.

Obviously, each of the at-risk components has to be assessed and technically qualified afresh on a case-by-case basis. Since the presence of excess carbon in the positive macrosegregation zones places greater emphasis on the need to safeguard against fast fracture failure, the evaluation of the individual operating NPPs presents a demand of increased complexity (and incalculable uncertainty) needing to take into account both brittle and ductile response regimes of each at-risk component as these have developed over the unique service life of each particular NPP.

Quality Assurance and Technical Qualification (QT): For the FA3 components it is quite clear, from ASN's strong admonishment of AREVA in April 2007, that proceeding with the manufacture before the QT regime was established and approved was unacceptable. That said, for reasons best known to itself, ASN chose not to halt the manufacture even when an adequate QT was not in place and that it, itself, had not issued a *Certificate of Conformity* – ASN has now acknowledged (16 August 2016) that a *Certificate of Conformity* has not been issued for the FA3 RPV. Indeed ASN permitted, although it may not have been armed with legal means to do otherwise, AREVA to weld assemble the bottom head to complete the FA3 RPV and install it in the reactor pit of the nuclear island at Flamanville in January 2014 – all of this virtually irreversible engineering activity taking place before, it is claimed, AREVA had inspected the RPV for heterogeneity and conformity with the ESPN QT requirements first introduced in 2005 and mandatorily imposed by ASN in February 2008.

The situation regarding the at-risk components being installed at operating NPPs whilst subject to *'irregularities'* is even more uncertain. This is because ASN's foreboding over the FA3 components *"il se pourrait que la garantie de qualité des 8ucléa fabriquées auparavant ne puisse pas être apportée, ce qui conduirait au rebut de ces 8ucléa"* must, surely, equally apply to any previously manufactured components where the QT record is believed to be inadequate, that is prone to *'irregularities'* together with the caution, according to ASN, *"l'ASN n'aurait malgré tout pas pu mener sur la fabrication de ces 8ucléa les contrôles visant à évaluer la conformité de leur fabrication de manière pertinente puisque les paramètres essentiels de cette dernière ne seraient pas connus au moment de sa realisation".*

In other words, ASN's judgment for the FA3 components equally applies retrospectively to any component that has an *'irregular'* QT. As admitted by AREVA, 400 or so components of doubtful QT provenance have been sourced from Creusot since 1965, with 50 of these presently installed in operating French NPPs. Added to these at-risk components, it is now acknowledged that, also, there are at-risk steam generators installed in the primary circuits of 18 operational NPPs and that certain of these may have been manufactured by the Japanese companies JCFC and JSW, thereby introducing an international dimension to this very serious setback to the confidence in the safe operation of the French nuclear power industry.

Summary of At-Risk NPPs Operating in France: TABLE 6 of this Review lists the French operating NPPs that have at-risk components installed – this is drawn from both the *'irregularities'* and at-risk steam generators installed in operational French NPPs.

TABLE 6 AT-RISK OPERATING FRENCH NPPS

NPP SERIES	NPP	ASN DEFINED IRREGULARITY	AT-RISK STEAM GENERATOR	UNIT MWE	FIRST COMMERCIAL OPERATION
900 MWe	Blayais 1-4	Unit 1, 3	Unit 1	910	81, 83, 83, 83
	Bugey 2-3	Unit 2, 3		910	79, 79
	Bugey 4-5	Unit 4	Unit 4	880	79, 80
	Chinon B1-4	Unit B1, B3	Unit B1, B2	905	84, 84, 87, 88
	Cruas 1-4			915	84, 85, 84, 85
	Dampierre 1-4	Unit 1, 3, 4	Unit 2, 3, 4	890	80, 81, 81, 81
	Fessenheim 1-2	Unit 1, 2	Unit 1, 2	880	77, 78
	Gravelines B1-4		Unit 2, 4	910	80, 80, 81, 81
	Gravelines C5-6	Unit 3		910	85, 85
	Saint-Laurent B1-2	Unit B1, B2	Unit B1, B2	915	83, 83
	Tricastin 1-4	Unit 2, 3	Unit 1, 2, 3, 4	915	80, 80, 81, 81
1300 MWe	Belleville 1 & 2			1310	88, 89
	Cattenom 1-4	Unit 1		1300	87, 88, 91, 92
	Flamanville 1-2			1330	86, 87
	Golfech 1-2	Unit 2		1310	91, 94
	Nogent s/Seine 1-2			1310	88, 89
	Paluel 1-4	Unit 1		1330	85, 85, 86, 86
	Penly 1-2			1330	90, 92
	Saint-Alban 1-2			1335	86, 87
N4 – 1450 MWe	Chooz B1-2			1500	96, 99
	Civaux 1-2	Unit 2	Unit 1, 2	1495	99, 00

The challenging breadth of this issue is illustrated by the fact that of the total French nuclear generating capacity around 44% involves at-risk NPPs. Similarly, of the various NPP types the 900MWe series has about 68% of its generating capacity is at-risk; the 1300MWe series is around 15% at-risk, and the N4 NPP series has 50% of its generating capacity is at-risk.

AT-RISK ALL NUCLEAR

AT-RISK 900MWe SERIES

AT-RISK 1300MWe SERIES

AT-RISK 1450MWe SERIES

The resource demands of the inspection and possible remedial programme required for the greater number of French operating NPPs is likely to be very challenging. Until ASN provide further details, the timing, cost and potential loss of generating capacity arising from this countrywide remedial programme is open to speculation. However, it might be reasonably assumed that EdF's human and equipment resource limitations will necessitate the inspection and assessment programmes being staggered over the existing pre-scheduled refuelling and/or maintenance outages for the individual NPPs. Judging from the number of NPPs involved such a staggered approach might be expected to take several years to complete.

If the individual NPPs continue at power until their allotted inspection date, etc, then the public will have to live with and tolerate an unspecified measure of increased risk of accident arising from failure of the installed at-risk components. On 26 April 2016, ASN charged EdF and AREVA jointly that *'as soon as possible'* they were to provide *'assessment of the consequences for the safety of the facilities'* although, to date, some 5 months later, nothing in this respect has been forthcoming and made publicly available.

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ABBREVIATIONS AND ACRONYMS

AREVA	French state owned company specialising in nuclear equipment and plant
A-SEGREGATES	Narrow, pencil-like macrosegregation patterns found in the outer columnar zone of steel ingots with small equi-axed grains, enriched by various solute elements such as carbon, sulphur, and phosphorus
ASME	American Society of Mechanical Engineers
ASN	*Autorité de Sûreté Nucléaire* – Nuclear Safety Authority
AUSTENITIZING	Forming Austenite which is a high-temperature, face-centered cubic form of iron
CHARPY TEST	Charpy is a swinging, weighted pendulum test that breaks a notched steel specimen to determine the toughness characteristic via the energy dissipated in the breakage.
CP0, CP1, CP2	Variants of the 900MWe series of French PWR NPPs
DEP	*French Directorate for Nuclear Pressure Vessels*
EDF	Électricité de France S.A – French stated owned power company
EDF ENERGY	The UK subsidiary of the French state own EdF
EPR	European Pressurised Reactor
ESPN	*Équipements Sous Pression Nucléaire* – ESPN Order of 12th December 2005 for Nuclear Pressurised Equipment (ESPN) FR (24FF4V)
GDA	*Generic Safety Assessment* (GDA
HCTISN	*Le Haut Comité pour la transparence et l'information sur la sécurité 10ucléaire* – High Committee for Transparency and Information on Nuclear Security
J	Joule – a derived unit of energy – 1 newton meter (N-m) = 1J
JCFC	Japanese Casting and Forging Corporation
JSW	Japan Steel Works
LSD	*Lingot a Solidification Dirigée* – a casting technique for ingots
MWe	MegaWatt electricity – a unit of electricity power – 1 MWe = 1,000,000 Watts
N1	French nuclear equipment is classified in levels N1, N2 and N3 according to the potential quantity of radioactive release in the event of failure – reactor primary systems classification is N1
N4	Series name of the 1450Mwe French PWR NPPs
NDI	Non-Destructive Inspection (or Examination)
NNB GENCO	NNB Generation Company – a subsidiary created by EDF Energy to build and operate two new nuclear power stations in the UK at Hinkley Point C and Sizewell C
NRC	Nuclear Regulatory Commission – the United States nuclear safety regulator
ONR	Office for Nuclear Regulation – the UK nuclear safety authority
PCSR	PreConstruction Safety Report – a stage of the nuclear licensing process in the UK
PED	European Pressure Equipment Directive 97/23/EC
PELLINI	A mechanical test that indicates the resistance of a steel to cracking
PWR	Pressurised Water Reactor
QAM	*Quality Assurance Manual*
QA	Quality Assurance Manager under QAM
QC	Methods/Control Manager under QAM
QT	*Qualification Technique* – Technical Qualification
RCC-M	The French 'equivalent' of the ASME pressure vessel code – this defines the limits of the design-basis being primarily aimed at establishing the mechanical design of the pressure equipment – although the RCC-M code includes quality assurance requirements, for example M140, the means of and controls over the manufacturing route are subject to a *Certificate of Conformity* issued by ASN (DEP) once that the particular manufacturing route has been scrutinised by DEP.
RPV	Reactor Pressure Vessel
RT_{NDT}	Ductility transition reference temperature
SG	Steam Generator
SZB	Sizewell B NPP located in Suffolk, UK
UPSET FORGING	Passing the billet under parallel plates at high pressure
VF	Validation Factor – the margin over crack propagation

IRREGULARITIES AND ANOMALIES RELATING TO THE FORGED COMPONENTS OF LE CREUSOT FORGE

THE CARBON ANOMALY IN THE FLAMANVILLE RPV

On 7 April 2015, the French regulator, *Autorité de Sûreté Nucléaire* (ASN), announced that a material non-conformity (ie defect) existed in the reactor pressure vessel (RPV) of the European Pressurised Reactor (EPR) under construction at Flamanville.[1, 2]

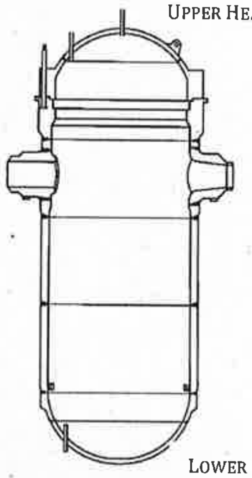

FIGURE 1 - EPR RPV SHELL

Referred to as a *'carbon anomaly'*, the aberration was found by chemical analyses and physical testing of equivalent supernumerary forgings to the two components of the Flamanville 3 (FA3) RPV, these being the separate upper head or lid, and the lower head or dome forged component that closes the RPV. The lower head has, in the process of fabrication, been welded to the centre ring forgings via a transition ring, forming the main body of the RPV. The finished RPV welded assembly, machined and lined with a stainless steel welded surface has now been installed within the dome containment structure of the nuclear island at the FA3 NPP site.[3]

The upper and lower head dome forgings for FA3 were manufactured at the AREVA Chalon/Saint-Marcel Creusot Forge[4] in or about 2006 and 2007 respectively and the larger, annular ring components, beyond the ingot tonnage capacity of Creusot, were forged in Japan by the Japan Steel Works (JSW).

Prior to ASN's April 2015 announcement, in 2014 or earlier,[5] AREVA reported to ASN variations in mechanical properties and carbon content of the RPV upper and lower dome forgings. The ensuing investigation programme carried out by AREVA included tests on a dome component[6] representative of the FA3 heads. For two separate forgings, a series of three test specimens gave below par results for the material toughness,[7] being 52 Joules (J) compared with a minimum individual test compliance value of 60J. Further examination of the representative forging indicated the presence of a high carbon zone

1 ASN Information Notice, Technical Clarifications Concerning the Manufacturing Anomalies on the Flamanville EPR Reactor Pressure Vessel, Montrouge, 8th April 2015.

2 Flamanville 3 (FA3) is currently under construction at Flamanville, Manche on the Cotentin Pensinsula in France. Construction work began in December 2007, the containment dome of the reactor building was put in place in mid-July 2013 and the RPV was installed in the reactor pit in January 2014 and has undergone the in-plant hydraulic test, and has been welded to the primary circuit branches. The reactor was originally scheduled to start commercial operation in 2013, but due to delays is now expected to start up in 2017 or later.

3 The EPR RPV is a bottom closed, carbon steel cylinder of four forgings welded together, comprised three rings, including the upper nozzle ring, and the lower head with the final, machined assembly being approximately 12.7m height and 5.7m diameter, all of overall weight (including the separate upper head) of about 525 tonnes – the domed lower head forging, when finished machined, is approximately 150mm thickness.

4 Creusot Forge became a subsidiary of AREVA in 2006 prior to which it was then owned by CreusotLoire, under contract for Framatome. Creusot Forge and the separate Creusot Mécanique specialise in heavy forged components for the nuclear power plants, including component parts for the RPV, the pressuriser, main valve bodies, and parts of the steam generators.

5 There are a number of media reports suggesting that AREVA knew of the anomaly as early as 2006 – for example, Le Canard alleged in July 2015, although uncorroborated, that a note *from Institut de radioprotection et de sûreté nucléaire* (IRSN) to ASN stated that certain parts of the RPV contained twice the permitted norm of carbon.

6 Referred to as the UA head or dome.

7 Toughness is an indicator of the ability of a material to withstand the propagation of cracks. For a reactor vessel, this property, usually defines as the *Bending Rupture Energy*, is in particular significant regarding thermal shock, for instance following the emergency injection of cold water in the primary circuit of the reactor. Particularly, the performance of the RPV in fast fracture mechanics must be proof of *'robustness'* of the design against relatively large flaws, defined conventionally independently of the mechanisms that could promote their existence – the carbon anomaly is such a mechanism.

spread over a surface area of 1m diameter and, moreover, for one of the three samples tested the zone extended into the shell by a depth exceeding the mid-thickness of the dome wall (ie greater than 75mm).[8]

In its interim reporting of October 2015 AREVA informed ASN that the lower head component of the fabricated (and installed) FA3 RPV included areas of *"lower than expected mechanical toughness values"*. This attracted the ASN response that it

> *"... considered that this relatively superficial review – which only went back as far as 2010 – was insufficient and did not give a complete picture of the organization and practices at Creusot Forge, the quality of the parts produced and the safety culture prevailing within the plant"*

This rebuke reveals ASN's dissatisfaction that the FA3 material and chemical qualities of the components fell short of the regulatory framework,[9] both in compliance with the design-basis under the RCC-M code[26] and, particularly, for conformity with the *Qualification Technique* (QT) as this relates to establishing a proven manufacturing route of the FA3 components.[50] On QT conformity, ASN required AREVA to review the Creusot manufacturing processes and quality assurance programmes back until at least 2004 when preparations for forging the first FA3 components commenced.

Presently AREVA has underway a further series of investigations, tests and evaluations to demonstrate whether i) the mechanical and chemical properties of the installed FA3 RPV components satisfy the RCC-M code and, separately, ii) if the quality and consistency of manufacture of these components comply with the *Certificate of Conformity* (that should have been) agreed prior to manufacturing commencing.

The (i) mechanical and chemical tests, material sampling etc., are to extend to a depth of three-quarters of the shell thickness of each of the two parts – a third but unspecified forged component is also to be similarly analysed and tested by AREVA and the whole series of tests outcomes reported to ASN following completion of the test in late or at the close of 2016. On compliance of the manufacturing route (ii) ASN subsequently directed AREVA-EdF to provide an assessment of the implications for the safety of NPPs operating across France that might contain at-risk components identified to have *'irregularities'* in the production and recordkeeping processes at Creusot.

And so the exchanges between AREVA and ASN, often involving the FA3 licensee EdF as an intermediary, continued and, indeed, continue to date.

The ASN (and probably AREVA) reporting stages for this campaign of work on FA3 components will stretch out into 2017. The modelling and analysis is to include operating situations taking into account both material ageing and certain fault conditions that could, it is argued, result in catastrophic failure of the RPV thereby necessitating re-examination of the nuclear safety case for FA3 and other EPR nuclear plants both awaiting order confirmation[10] and presently under construction.[11] ASN has also raised the

8 *Report to the Advisory Committee of Experts for Nuclear Pressure Equipment CODEP*-DEP-2015-037971 IRSN Report /2015-00010 Public Version, Session of 30 September 2015.

9 It is not intended here to reiterate the regulatory framework applied to the RPV and primary coolant circuit components other than to note that the RPV is a level N1 equipment item in that is most important for nuclear safety and that its failure is not postulated in the nuclear safety case, that being that failure of the RPV is excluded at the design stage.

10 In the UK, the proposed two EPR nuclear plants at Hinkley Point C presently awaiting contract approval from EdF with a final but much delayed decision expected in September 2016. One of the advance order RPV head forgings

alternatives that AREVA consider all scenarios, including replacing the upper and lower heads of the RPV[12] which, for the latter with the RPV welded in situ to the primary coolant loop, would require the RPV being lifted out of the reactor pit and, possibly, removed from the reactor island for the highly specialised replacement operation – if implemented this option would set back the FA3 programme by years and incur many millions of €s overcosts.

The awaited outcome and potential consequences of the carbon segregates 'anomaly', is yet to be determined by this latest and ongoing series of AREVA tests as these apply to FA3 (and possibly the Taishan and Hinkley Point C EPR nuclear plants), will be further discussed in a later section of this Review.

A chronological outline of developing events and actions relating to Flamanville 3 Creusot components is given in APPENDIX I.

QUALITY CONTROL AND ASSURANCE ISSUES AT CREUSOT FORGE – EARLIER FORGED COMPONENTS

It is the startling revelations revealed by AREVA in response to ASN requirement for analysis of the quality assurance controls in place at Creusot Forge back to 2004, that have potentially very serious implications for virtually all of the operational nuclear power plants across France and certain NPPs elsewhere worldwide.

When asked by ASN to give a " . . . *complete picture of the organization and practices at Creusot Forge, the quality of the parts produced and the safety culture prevailing within the plant*", in its 26 April 2016 response AREVA informed ASN that its review had identified *'irregularities'* in the manufacturing checks on about 400 forged component produced at the Creusot facility since 1965, adding that about 50 of these parts are believed to be currently installed at French operational nuclear power plants. In response, ASN served a two-part notice[13] on AREVA requiring that, first:

> "... *These irregularities comprise inconsistencies, modifications or omissions in the production files, concerning manufacturing parameters and test results."*

and in view of these uncertainties, second, that as soon as possible AREVA provides

> "... *its assessment of the consequences for the safety of the facilities, jointly with the licensees concerned".*

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destined for Hinkley Point C has been subject to destructive testing by AREVA and, if the contract goes ahead, will have to be replaced anew.

11 It is believed that the RPVs of the two EPR nuclear plants at Taishan also include Creusot Forge upper and lower head components but the first ordered EPR RPV at Olkiluodon ydinvoimalaitos (Finland) comprises only Japan Steel Works forgings, although it has been reported that the RPV for the second Taishan EPR unit was wholly manufactured in China.

12 ASN to AREVA, 14 December 2015 – Under Application 14 *"L'ASN vous demande de réaliser, en lien avec l'exploitant, une etude technique des scénarios d'extraction du corps de cuve du puits du bâtiment réacteur et de remplacement de la calotte du fond de la cuve. Cette étude devra analyser les avantages et inconvénients pour la qualité de réalisation et la sûreté de l'installation".*

13 By directly requiring AREVA to provide reassurances and data on the operational and licensed nuclear power plants, ASN has somehow circumvented the role of EdF as the licensed operator – the authority for ASN to action this is not at all clear although to facilitate AREVA's reporting a technical committee has been set up in connection with EdF,

There is little further information on the actual components subject to these *'irregularities'* although it is known that Creusot provided forged and finished-machined components throughout the reactor primary coolant circuit, including the complete RPV {1}, steam generators {2}, main pump bodies {3}, and pressuriser {4}. Unlike, the larger FA3 RPV components being limited to the upper and lower heads, for the smaller RPVs of the 900MWe CP0, CP1 and CP2 series (a total of 34 nuclear power plants) all forged components including the centre and nozzle rings are likely to have been sourced from Creusot. Also, it is not absolutely clear that the *'irregularities'* applied to components dating back to 1965 are confined to (or indeed explicitly include) the *'carbon anomaly'* found in the FA3 upper and lower head forged components.

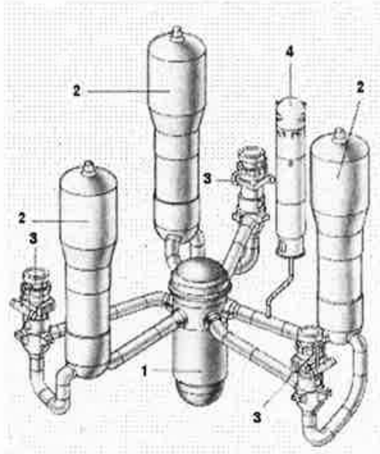

FIGURE 2 REACTOR PRIMARY COOLANT CIRCUIT
TYPICAL OF 3-LOOP 900 MWe SERIES

THE PRESENT SITUATION (AUGUST 2016)

1) FLAMANVILLE 3 RPV HEADS

As previously noted, for the FA3 head component shells the final results of analysis and testing are unlikely to be publicly available until the first half of 2017. These results will have been drawn from the physical, destructive examination of equivalent forged components, possibly three in total.

The most likely next steps in the assurance or fit-for-service process will be for AREVA to demonstrate:-

i) a reliable means of non-destructively assessing the presence and severity of the carbon 'anomaly' in the FA3 installed RPV – which may require hitherto undeveloped inference modelling;

ii) the matching and reliability of material coupons (ie precursory test pieces) to be installed in the operational reactor for periodic removal and testing throughout the irradiation service life;

and depending upon i) and ii) in account of the material characteristics at start of life and, separately, its degradation throughout service life,

iii) any necessary modification to the operational envelope of the FA3 nuclear plant (ie the Ductile-Brittle Transition Regime shift over its projected operating lifetime, Pressurised Thermal Shock, etc., during abnormal trains of events), together with the introduction of *'compensatory'* measures to ensure an acceptable nuclear safety case for both normal and abnormal operational modes.

Completion of these steps will incur further delays in the approval, if at all, for the FA3 to proceed to the commissioning and fuel-core criticality stages.

2) IRREGULARITIES RELATING TO CREUSOT COMPONENTS MANUFACTURED FROM 1965

Much the same steps are required to assure continuing compliance with the nuclear safety case for the earlier but operational French nuclear power plants that have installed, across the board, 50 or so Creusot-sourced at-risk components subject to *'irregularities'*.[14]

If, as it reasonable to assume, the irregularities relate to the potential existence of a *'carbon anomaly'* then monitoring for this adds further degrees of difficulty and uncertainty because

a) the service and irradiated ageing of each component for every different service/irradiation history of the individual NPPs has to be incorporated into the analysis;

b) access to the installed components may be difficult, if not impracticable, because of radiation levels and inaccessibility by the presence of other equipment and plant; and

c) the range and diversity of the components potentially at risk is likely to be greater than the two similar upper and lower head shells in the case of Flamanville 3.

That said, because of the very limited detail available in the public domain, essentially confined to the ASN statement *that the 'irregularities comprise inconsistencies, modifications or omissions in the production files, concerning manufacturing parameters and test results'*, it is not possible to more precisely scope out the task set by ASN for AREVA to report on the *'consequences for the safety of the facilities'*.[15]

THE CARBON ANOMALY

Since the FA3 and other EPR components were each manufactured at Creusot, each would have followed a similar manufacturing route. To date nothing has been revealed in either the AREVA and/or ASN published information to suggest that any significant changes to the Creusot manufacturing route have occurred during the EPR production run.[16]

The preliminary manufacturing stage for a FA3 forged component at Creusot comprised a conventional vacuum poured ingot of low carbon ferritic steel.[17,18,19] Following pouring,

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14 Other than the outline review of the Sizewell B NPP in the United Kingdom, overseas NPPs that might have installed Creusot-sourced at-risk components are not considered here.

15 On 13 June 2016 EdF issued a short statement: *Défaut d'assurance qualité sur des dossiers de fabrication d'Areva pour des équipements du parc nucléaire d'EDF: pas de remise en cause de la sûreté* listing the NPPs affected although no further details of the at-risk components was given – the NPPs affected are Blayais (3), Bugey (2, 3 and 4), Cattenom (1), Chinon (1 and 3), Civaux (2), Dampierre (1, 3 and 4), Fessenheim (1), Golfech (2), Gravelines (3), Paluel (1) St. Lawrence (1 and 2) and Tricastin (2 and 3). For the 12 remaining findings on 9 components installed only on the Blayais (Unit 1) and Fessenheim (2), currently in outage, characterization supplements are needed to reinforce the demonstration.

16 This only applies to the EPR upper and lower head component (and possibly the Cruas 3 and Chinon B3 upper heads but excepting Olkiluoto 3 – see later) since before EPR production began in or around 2004-5 the generally smaller diameter heads were manufactured using a different preliminary forging stage. Specifically relating to the upper and lower RPV heads, the Creusot production run since around 2005-6 would have included components for FA3, UA, Hinkley Point C and, possibly the two Taishan units – the UA and Hinkley Point C upper heads have or are to be used as sacrificial supernumerary replicas for the present round of destructive tests to determine the condition of the FA3 heads.

17 For the FLA3 heads, typically a 16MND5 specification low carbon steel ingot of gross weight of about 160 tonnes in accord with RCC-M specification.

18 ASN Information Notice, *Technical Clarifications Concerning the Manufacturing Anomalies on the Flamanville EPR Reactor Pressure Vessel, Montrouge*, 8th April 2015.

19 Report to the Advisory Committee of Experts for Nuclear Pressure Equipment, Analysis of the procedure proposed by AREVA to prove adequate toughness of the domes of the Flamanville 3 EPR reactor pressure vessel (RPV) lower head and closure head, IRSN Report /2015-00010, 30th September 2015.

the ingot is permitted to slowly cool from a melt temperature of about 1,540°C thereby undergoing solidification of, in this case, the carbon alloy.

During the solidification process the solute is partitioned between the solid and liquid (molten) phases to either deplete or enrich the interdendritic (a branching, tree-like crystal structure) regions. The progress of the 'mushy' solid-liquid phase varies within the body of the ingot and, particularly, the localised rate of cooling, leading to macrosegregation variations in the composition of the alloy.[20] Variations in the ingot cooling rate lead to diverse macrosegregation regimes being generated in different parts of the body of the ingot. In a low carbon steel alloy, this macrosegregation results in enhanced and depleted zones of carbon (ie the *segregates*), that is a loss of homogeneity and, at the microscale, inconsistencies in the chemical and physical make-up of the alloy, all resulting in variation in the chemical and physical material properties of the final steel component. Where the segregates are enhanced over the intended level (ie the carbon content is richer) the macrosegregation is referred to as *'positive'*.

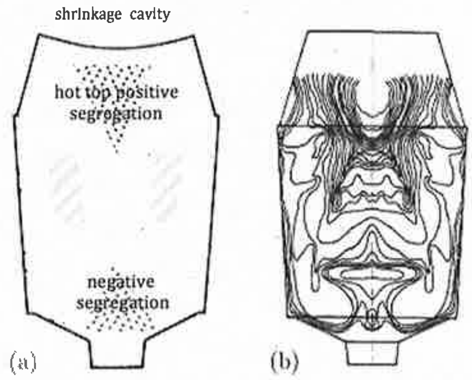

FIGURE 3A SCHEMATIC OF 180 TONNE STEEL INGOT[20]
a) MACROSEGREGATION ZONES
b) ISO-CARBON LINES

Almost all macrosegregation is undesirable for the first stage ingot manufacturing in the overall forging route because, unless the affected zones are cropped and discarded from the ingot prior to the final forging-machining processes, the variations remain in the body of the finished component.

FIGURE 3A shows the macrosegregation zones typically expected in the large, conventional steel ingot (~180 tonnes) used to produce pressure vessel components, particularly for the nuclear industry.[21] The zones of macrosegregation within the ingot can range from a few centimetres to a few metres. The chemical variations follow the tracks of the macrosegregation so any chemical inconsistencies introduced by macrosegregation should be expected to deliver different microstructures, and hence inconsistent mechanical properties.

The inclusion of segregates in finished forged components, even in limited quantities, may also lead to the formation of crack-type defects in conjunction with the application of weld-deposited cladding.[22]

Once established it is practicably impossible to remove the macrosegregation zone over the distances which the species are required to transit. FIGURE 3A shows the expected areas of positive segregation towards the top of the uncropped ingot and some negative segregation towards the bottom of the ingot.

20 Pickering E J, *Macrosegregation in Steel Ingots: The Applicability of Modelling and Characterisation Techniques,* ISIJ International, Vol. 53 (2013), No. 6, pp. 935–949

21 This particularly applies to applications in the nuclear industry where to make up a large vessel, such as the RPV, the weld lengths are minimized to reduce the presence of flaws and crack initiators, thus requiring larger, single piece forged components.

22 Comon J, *A 508 Class 3 Forgings for Pressure Vessels*, Third International Conference en Pressure Vessel Technology", Tokyo, Japan, 19-22 April 1977.

FIGURE 3B shows the basic stages of the overall forging process with an undesirable inclusion of a macrosegregation zone (RED) being repositioned as the process advances, although note that accurately forecasting the path and final dispersion of the macrosegregation zone in account of the various forging path reversal is difficult.

The early stage of the forging process at Creusot (like all other forges) includes cropping, blooming and discarding potential sections of the ingot to remove the top and bottom macrosegregation zones. This is followed by upset forming that plastically deforms the ingot under high pressure, trailed by hot forming usually involving a variety of heated and shaped formers matched to the final component shape.

In effect, the opportunity to intervene in the forging process to control and limit macrosegregation is during the casting-cooling and, separately, the blooming and discard stages – once these process stages have passed any macrosegregation zone remains captured and is progressively worked into the developing forged component shape.

i) FA3 UPPER AND LOWER HEAD COMPONENTS

To produce the FA3 lower head, the conventionally shaped ingot (similar to the ingot of FIGURE 3A) was end-cropped and bloomed with the top and bottom cropped sections being discarded; the bloomed ingot was upset forged between two parallel plates and passes to reduce the thickness but increase the length and width from the original cropped ingot of 4,460mm length to billet of 6,100 by 450mm dimension; and prior to final hot forming to the hemispherical head shell, the billet was, first, annealed at around 1,240°C for 4 or more hours and, second, rough machined to remove surface scale and slag, followed by a final heat treatment by austenitizing at around 875°C and controlled quenching.

AREVA considered that a conventionally-shaped ingot of ~160 tonnes weight was required to ensure a homogeneous structure of the final RPV head shell components (ie an ample *forging ratio* in account of the cropped discards). The adoption of a conventionally-shaped ingot was a significant departure in the manufacturing route at Creusot since AREVA had previously utilised a *'directional solidification ingot'* (LSD)[23,24] for the generally smaller forged shell components of RPVs of previous nuclear power plants.

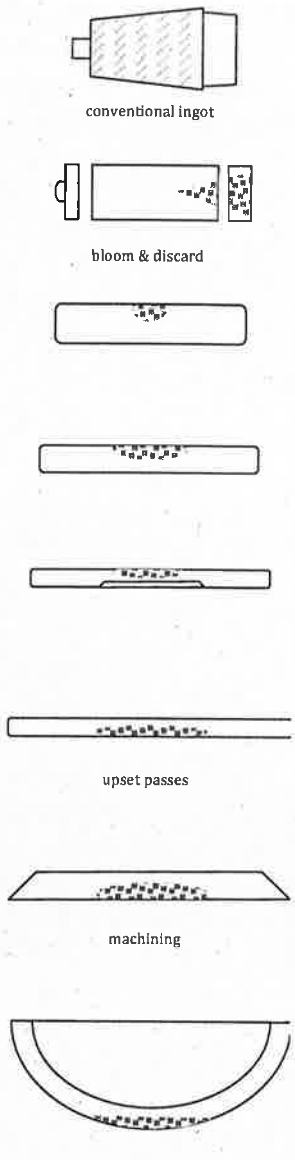

FIGURE 3B FORGING PROCESS

This significant change in the Creusot manufacturing route for the EPR heads would have required a fresh Technical Qualification (*Qualification Technique* – QT) and a *Certificate of Conformity* via a then recently enacted regulation applied to components that were at *'risk of heterogeneity of their characteristics linked to the production of materials'*,[25] being

23 The *directional solidification ingot* (*Lingot a Solidification Dirigée* - LSD) is a squat ingot of low height-to-diameter ratio cast in a top insulated mould to unify the cooling rate and bottom-poured (via a standpipe) thereby concentrating the A zone segregation to the top discard section – Creusot-Loire adopted this ingot for the RPV heads of the Framatome 1300 and 1450 MWe 4-loop PWR – the LSD development dates from around 1977 – typical LSD ingots range between 25 to 100 tonnes.

24 *Application of Directional Solidification Ingot (LSD) in Forging of PWR Reactor Vessel Heads*, Benhamou, C Poitrault, 10th International Forging Conference, Sheffield, September 1985

25 *Équipements Sous Pression Nucléaire* - ESPN Order of 12th December 2005 for Nuclear Pressurised Equipment (ESPN) FR (24FF4V) – the relevant section is *"3.2. - Technical qualification before manufacturing, the manufacturer shall identify the components that pose a risk of heterogeneity of their characteristics linked to the production of*

either in addition to or supplementing the manufacturing process to the superseded earlier LSD ingot.[26] In its reporting on this issue, the *Institut de Radiopritection et de Sûreté* (IRSN) in April 2015 noted that *"Ce procédé diffère de ceux emptoyés pour les calottes des cuves des réacteurs du parc en exploitation, A cet égard, l'IRSN observe qu'une nucléaire notable de technologie de fabrication a été"*.[27] Although IRSN identified the use of a large tonnage ingot to be the cause of the positive macrosegregation, it did not opine on whether the LSD approach provided a practical alternative and if, indeed, this manufacturing route was itself subject of a satisfactory QT.

Creusot commenced manufacturing of the upper and lower head components in or around 2004 with the manufacturing process extending through to 2007. Around that time, ASN expressed *'situation préoccupante'* (ie *"worrying situation"*) about the state of the technical documentation of the RPV QT,[28] warning AREVA of the risk of manufacturing these components in the absence of an approved QT.[29] This suggests that at the time of manufacturing the FA3 upper and lower heads, the Creusot manufacturing route had not been assessed and approved by ASN and that, it follows, no *Certificate of Conformity* was in place for the manufacture of the RPV upper and lower head shells.[30]

The final interpretation and practical application of the QT seems to have been a matter of ongoing dialogue[31] between AREVA and ASN because it was not until 2012 that AREVA submitted its proposal for the QT inspection and testing programme for the FA3 upper and lower head components – it is believed that by this date (2012) the lower head had been welded and integrally machined into the RPV as a whole and the RPV assembly pressure tested.[32] Now installed in the reactor pit of the reactor island containment, the completed RPV still does not have a *Certificate of Conformity*.[54]

For the testing of the upper and lower head shells, the original expectation for QT was that a surplus top ring would be trepanned from the semi-machined shell for separate destructive testing to determine representative chemical inclusion and various indices of

materials or the complexity of the planned manufacturing operations. All manufacturing operations shall be subject to technical qualification. This is to ensure that components manufactured under the conditions and in accordance with the procedures of the qualification will have the required characteristics."

26 RCC-M Code, *Design and Construction Rules for Mechanical Components of PWR Nuclear Islands* – this is equivalent to ASME Code, Section III, Division 1 and related sections.

27 IRSN, *Réacteur EPR Ftamanville 3 Qualification technique des calottes du couvercle et du corps de la cuve du réacteur, Pole Surete Des Installations Et Des Systémes Nucléaires*, 3 April 2015.

28 Email ASN to AREVA, 2 April 2007.

29 Email ASN to AREVA, 16 April 2007, including *"courrier de l'ASN à Areva alertant sur le risque industriel consistant à fabriquer des composants avant leur qualification technique "* noting that if process changes within the QT occurred, *"il se pourrait que la garantie de qualité des pièces fabriquées auparavant ne puisse pas être apportée, ce qui conduirait au rebut de ces pièces"*. Even if the required quality was demonstrated in the component, *"l'ASN n'aurait malgré tout pas pu mener sur la fabrication de ces pièces les contrôles visant à évaluer la conformité de leur fabrication de manière pertinente puisque les paramètres essentiels de cette dernière ne seraient pas connus au moment de sa realisation"*. In other words, ASN considered it unwise for AREVA to proceed with manufacture ahead of full QT compliance and if it did the components so produced could not be checked for quality and compliance with the ESPN because the parameters of the manufacturing processes would not have been fully recorded in the QT file.

30 Later, in 2016 when summarising the FA3 situation, ASN noted that production of most large components for the Flamanville 3 EPR, including that for the upper and lower heads of the RPV, started before the technical skills were acquired – thus, if this skills shortfall had been recognised at the time of manufacture (~2004-07) then the TQ could not have been approved nor a *Certificate of Conformity* issued.[60]

31 The prolonged dialogue between ASN and AREVA is dealt with in depth in *Report to the Advisory Committee of Experts for Nuclear Pressure Equipment* [8] – in effect, failure to agree a methodology for the TC enabled AREVA to continue to manufacture components at Creusot in the absence of any meaningful TC.

32 The first hydraulic pressure test of the RPV was undertaken on or around 14 March 2012 and a second test on or around 26 July 2013, although it is not clear if either of these tests were formally validated. Both tests seem to have been completed with the so-called AU upper head fitted since the FA3 head was under repair.

material strength. However, for its second evaluation AREVA propose to go much beyond this by destructively testing an existing but surplus to requirements EPR head forging that had been manufactured at Creusot along the same manufacturing route as the FA3 components.

Tensile and Charpy tests were carried out on the specimens taken earlier yielding the following shell through-thickness positions from the FA3 equivalent forging to yield the bending rupture energy:-

TABLE 1 CHARPY AVERAGE TOUGHNESS RESULTS AT 0°C FOR FA3 EQUIVALENT– JOULES[19]

0 INNER SURFACE	0.25	0.5	0.75	1 OUTER SURFACE
178	136	-	52[33]	73

The impact toughness for the 0.75T position of TABLE 1 at 52J is below the minimum requirement of 60J and also below the minimum average requirement of 80J across the set of tests for that location.[19]

Other testing revealed the tensile strength of the material at the 0.75T position to be equal to the minimum elongation requirement of 20%; and chemical analysis of samples taken from the outer shell surface (position 1 of TABLE 1) revealed levels of carbon up to ~0.30%, exceeding the generic ladle analysis for the ingot and in excess of the maximum carbon content specified at 0.22%.[1] Further AREVA analysis showed that the locations of the low Charpy and tensile results coincided with a distinct macrosegregation zone located at and within the crown section (FIGURE 4 □) of the FA3 equivalent head shell component.

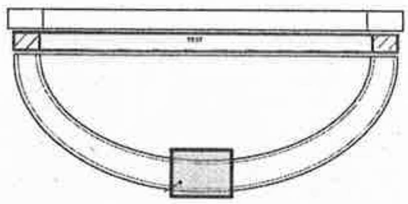

FIGURE 4 LOCATION OF SAMPLE SECTIONS FOR TC
SURPLUS TEST RING ■ MID-SHELL LOCATIONS ■

The outcome of the 2012 programme of tests on an equivalent FA3 component revealed that the test ring (FIGURE 4 □) set aside for the earlier physical testing and chemical analysis was not sufficiently representative of the material body throughout the actual FA3 upper and lower head components.[34]

There is no reason to believe that, similarly, the test rings taken for the two Taishan NPPs presently nearing commissioning in China also yielded misrepresentative material property results and, moreover, since the Taishan components followed the same manufacturing route at Creusot, the strong likelihood is that the fabricated and installed Taishan RPVs will also include the similar under-specification head components.

ii) CREUSOT COMPONENTS PRODUCED FROM 1965

As previously noted of the 400 or so forged components that have associated *'irregularities'*, 50 or so of these are installed in operational nuclear power plants in France.

33 The 1st and 2nd series test results of bending rupture energy were 36J, 52J, 48J and 47J, 62J, 64J of which the average is 52J.

34 The potential disparity between the test ring results and untested centre area of the final hot formed head component was raised with AREVA by ASN in August 2006 although there is no publicly accessible record of the response – see [56].

a) STEAM GENERATOR COMPONENTS

FIGURE 5A TYPICAL STEAM GENERATOR

A number of reports of excess carbon content in steam generator (SG) components are beginning to emerge.[35, 46] Although sparse in detail, the indication is that the SG semi-spherical head, located under the tube sheet, that is linked directly to and forms part of the primary coolant circuit boundary, contains positive macrosegregation zones of excess carbon.

A total of 18 primary coolant circuits drawn from both the 900MWe and 1,450MWE NPP series are believed to be potentially at risk – the SG forged components were sourced either from Creusot and/or the Japanese Casting and Forging Corporation (JCFC) of Japan. It is believed that macrosegregation zones are present in the central, top area of the tube sheet and, also in the top domes of a number of SGs sourced from Creusot and JCFC, possibly the Japanese Steel Works (JSW), and Sheffield Forgemasters in the UK. Recently (12 September 2016) ASN revealed that JCFC forged components were particularly prone to the presence of positive macrosegregation zones and particularly high (>0.3%) carbon excess.[79]

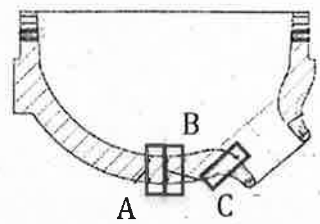

FIGURE 5B SECTION OF SG LOWER HE...

FIGURE 5B shows a cross-section through a SG lower head manifold with highlighted locations from which samples have been extracted for chemical and destructive physical testing – this particular SG bottom head was Creusot-sourced. Reported by AREVA in May 2016, the Charpy material toughness results for each of three tests and the average, taken across the shell wall thickness are:

TABLE 2 CHARPY IMPACT AVERAGE TOUGHNESS RESULTS AT 0°C FOR SG SAMPLE – JOULES

LOCATION/DEPTH[36]	0 INNER SURFACE	0.25	0.5	0.75	1 OUTER SURFACE
A	143-93-137/125	136-151-135/141	30-61-45/45	120-138-69/109	141-134-128/134
B	97-66-213/125	not available	99-69-57/75	86-85-112/94	95-60-51/69
C	182-195-226/201	196-154-157/169	150-148-129/142	172-32-104/103	166-142-213/174

AREVA state the minimum criterion for material toughness for any one and the average of the individual Charpy tests to be 60J[37] respectively, with 5 individual tests and one average failing to meet the criterion.[38] One sample taken from 0.75 shell depth at LOCATION A failed the minimum tensile elongation requirement of 20%.

35 ASN, *Certains générateurs de vapeur de réacteurs d'EdF pourraient présenter une anomalie similaire à celle de la cuve de l'EPR de Flamanville*, 23 June 2016.

36 The tally of individual results to shell depth may be in reverse order since this is not clear from the source document.

37 The testing criteria specified for the FA3 RPV requires a minimum of 80J be achieved for the average of the three tests, whereas for the SG AREVA assume a 60J average pass criterion – on the 80J average requirement 4 test series have failed.

38 The toughness and fast fracturing of ferritic steels lowers when the temperature is reduced. The fracture mode changes from ductile to brittle (fast) as the temperature descends forming a shelf-like characteristic for the particular alloy of steel – there is a transition zone between the steel acting in a purely ductile way and when it fails totally by cleavage (brittle or fast fracture). The Charpy test measures the energy required to fail a coupon test piece at specific temperatures, thus a series of Charpy tests over a range of temperatures enables the temperature transition zone to be mapped by, essentially, measuring the ratio of ductile-brittle areas of the failed Charpy specimens. However, this temperature transition characteristic changes, to the detriment of toughness, as the component ages, through thermal cycling

b) Creusot Sizewell B RPV Components

As well as providing components for French NPPs, Creusot supplied a number of forged components for overseas plants. Of particular interest are the 22 separate components sourced from Creusot to the Sizewell B nuclear power plant in Suffolk, United Kingdom[39] to make up the RPV (6 main forgings and 8 smaller forgings) and in part the steam generators (2 forgings per generator, 8 in total). The forged components for the Sizewell B RPV in order of assembly (top to bottom) comprised:-

Table 3 Sizewell B RPV Components – Manufacturing Source

	Forged Component	Supplier
1	Upper Head Dome	Creusot
2	Closure Head Flange	Creusot
3	Vessel Main Flange	Creusot
4	Nozzle Shell Course (plus 8 inlet/outlet nozzles)	Creusot
5	Core Shell Course	Japan Steel Works
6	Transition Ring	Creusot
7	Lower Head Dome	Creusot

Early in 2016 the United Kingdom Office for Nuclear Regulation (ONR) required EdF Energy, the UK operator of Sizewell B, to provide further information relating to possible 'irregularities' at-risk components being installed in the Sizewell B NPP.

However, in its explanation,[40] EdF Energy considers only the upper and lower head components (Table 3 items 1 and 7) these being those components that correspond to the FA3 carbon anomaly, but it does so without any explanation and/or justification why the other four RPV components (Table 3 items 2, 3, 4 and 6) are free of the *'irregularities'* reported to ASN.[41] On its part, ONR depends upon the AREVA claim that its *"initial screening to identify which records have potential anomalies has been completed, and that of those with anomalies, none relate to forgings supplied for Sizewell B"*.[42,43]

In specifically addressing the upper and lower head dome components (Table 3 items 1 and 7) EdF Energy[40] states that chemical analysis and physical testing for the Sizewell B

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and in nuclear applications as a result of neutron irradiation. In practice, brittle failure is influenced by the sample or component geometry, by the shape and sharpness of the initiating flaw or crack, and critically by the strain rate so the Charpy results alone can be misleading when applied to a real industrial application such as the RPV and other components of the primary pressure circuit.

39 Sizewell B is only commercial pressurised water reactor (PWR) operating in the UK – it is a 4-loop Westinghouse 1,195MWe single reactor plant commissioned to power generation in 1995 and operated by EdF Energy. Although of Westinghouse design, the RPV was supplied by Framatome in or about 1990, with Creusot production commencing in or about 1984-5 – the construction period for Sizewell B is 1987 to commissioning in 1995.

40 EdF Energy, Engineering Advice Note, *Review of Sizewell B RPV Dome Forging Components Following Flamanville 3 EPR OPEX*, E/EAN/BBHB/0373/SZB/16, EdF Energy/Structural Integrity Branch/Materials Group, March 2016

41 All of the other RPV finished components are annular rings formed during the billeting stage by hot piercing the ingot which, it is argued by EdF, removes the core area of the ingot where both positive and negative zones of segregation exist – see Figure 3 for typical distribution of segregates.

42 ONR, *Review of Sizewell B (SZB) Lifetime Records in relation to forgings manufactured by Creusot Forge*, ONR-OFP-CR-16-109 Revision 1, 14 June 2016 – AREVA provided the e-mail response via EdF Energy on 20 May 2016.

43 Interestingly, ONR reiterated[42] the AREVA caveat that *"Notwithstanding this, AREVA also claim that where anomalies do exist, none would preclude the return to service of a plant"*.

head components was conducted on the forging test ring (see FIGURE 4) although smaller but similar to that which proved to be so problematical and unreliable in the FA3 components. EdF Energy admits, that for the Sizewell B components, results from the test ring alone are insufficient to demonstrate material compliance throughout the component, stating that *"It is clear that testing of specimens extracted from the test ring would not identify a localised issue with segregation at the centre of the dome forging, since the specimens will be some distance from this region"* concluding that *"Explicit demonstration of consistency throughout the forging is not possible with these results alone"*.

EdF Energy then moves on to refer to a paper[24] presented at a conference in 1985 giving a comparison of the material properties (essentially averaged test results) of 30 RPV head shells produced at Creusot – the aim of the paper is to demonstrate, or so it claims, the consistency and absence of macrosegregation of the *'directional solidification ingots'* (LSD) manufacturing route in use from lower tonnage forgings at Creusot. EdF Energy rely upon this to demonstrate that the Sizewell B heads are also free of macrosegregation because they, too, were produced along the same Creusot LSD manufacturing route and, hence, by deduction, that the test ring results for the Sizewell B heads were therefore valid and representative of its forging as a whole.

However, the 1985 paper is too early to specifically include any results for the later manufactured Sizewell B heads and, more to the point, the statistical data presented for 30 RPV head shells is taken from the individual head test rings that are now considered unreliable.[see Table 4 and Figure 8 of 23]

In other words, the EdF Energy reasoning is *circulus in probando*, being a logical fallacy whereby the premise is just as much in need of proof as the conclusion.

c) CREUSOT-SOURCED EARLIER FRENCH NUCLEAR POWER PLANT COMPONENTS

Again, confining consideration to the upper and lower head components manufactured at Creusot, all of the domes installed in the earlier (pre-EPR) French nuclear power plants were shaped by upset forging and hot-forming discs of varying dimensions to suit the particular reactor design. Not all of these head components were manufactured at Creusot but those that were followed either the LSD or Conventional Ingot manufacturing route. Accordingly, the risk might be ascribed to each of the different first stage ingot fill manufacturing routes adopted at Creusot:-

TABLE 4 FIRST STAGE MANUFACTURING ROUTE AT CREUSOT – INGOT TYPE AND TONNAGE[8]

		N°	LSD INGOT	CONVENTIONAL INGOT
		UPPER HEAD[44]		
900MWe Series	Cruas 3 Chinon B3	1 1		195t 195t
1300MWe Series		20	58t	
N4 Series		4	63t	
		LOWER HEAD		
1300MWe Series		13	46-49t	
N4 Series	Chooz B1, B2 and Civaux 1, 2	4	55t	

44 The number of upper head components gives no account of any upper head replacement during the service life of the plant.

Setting aside Creusot forged components supplied to and installed in overseas nuclear power plants, including Sizewell B, then the potential number of at-risk RPVs installed in operating French NPPs might be:

a) CONVENTIONAL INGOT ROUTE: Assuming that the LSD route was sufficiently robust in quality assurance then, on this basis alone, the potentially at-risk nuclear power plants are those with upper heads manufactured by the Conventional Ingot route, that is the plants at Cruas 3 and Chinon B3.

b) RELIABILITY OF THE LSD INGOT ROUTE: If the LSD route was not sufficiently robust then the number of RPVs (NPPs) potentially at-risk is around 26 related to the upper head[45] and 17 related to the lower head.

The total number of components at-risk (43) in TABLE 3 does not correspond to the 50 components reported by AREVA on 26 April 2016 to be subject to *'irregularities'*, thereby implying that the Creusot 'at-risk' components are unlikely to be confined to either and/or the upper and bottom head shells of the RPV – this prognosis is indicated by a recent industry press report[46] and by ASN itself that macrosegregation flaws have recently been found in steam generators (SGs) located in the primary cooling circuits of 18 operational NPPs.[71]

TABLE 6 (see later) lists the French NPPs that are presently operating with at-risk components installed – TABLE 6 is compiled from an amalgam of sources and counts for both irregularities and at-risk steam generator defects reported by ASN.

IMPORTANCE OF MATERIAL HOMOGENEITY AND TOUGHNESS

Positive macrosegregation results in marginal increases in carbon content at a microscale. For example, in the FA3 equivalent forgings tested the macrosegregation zone created localised increases in carbon content of up to ~0.28% over the design specified 0.22% carbon content.

Even such a relatively small increase in carbon will result in a significant decrease in the bending rupture energy and the fracture toughness in those areas affected by the positive macrosegregation. On the other hand, increase of carbon content is accompanied by an increase of tensile strength thereby providing greater resistance to excessive deformation and plastic instability in the positive macrosegregation zone. In other words, positive macrosegregation places greater emphasis on the need to prevent fast fracture than that generally required to limit the ultimate tensile failure and plastic deformation modes.

There are a number of other parameters that contribute to fast fracture, particularly the ductile-brittle transition temperature at which the fracture mode switches from shear to fast fracture cleavage. Transition behaviour cannot be totally eliminated in low carbon steels and the ductile-brittle transition temperature can be reduced by various means, including lowering carbon content; the inclusion of trace elements, including phosphorus, nitrogen and hydrogen which are all detrimental and increase the tendency towards brittle fracture; a courser grain size has a marked effect on notch size, and the courser the grain size the higher will be the transition temperature.

45 Some of the original upper head components may have been replaced during the operational service period.

46 Nucleonics Week, V 57, No 25, 23 June 2016 – relates to a requirement for EdF to verify the integrity of an *'anomalous'* steam generator at Fessenheim-2 which is described in terms of excess carbon brought about by failure at Creusot to properly crop and discard the ends of the forging ingots, although ASN subsequently dismissed this.[82] ASN stated that had it been aware of the nonconformity then it would not have issued the Test Certificate in 2012 – see ASN Note d'information of 20 July 2016.

Deleterious or ageing changes during the service lifetime of the component also occur, including neutron irradiation that increasingly embrittles the material, although this is only likely to be significant in the mid-belt locality of the RPV; strain-induced and thermal ageing, both of which lead to a reduction in toughness; and the macrosegregation zone itself is a source of micro-sized flaws available to propagate into crack-like defects during the service life of the component.

At Creusot there seems to have been little acknowledgement of the importance of crack resistance of the forged components with *Le Haut Comité pour la transparence et l'information sur la sécurité nucléaire* (HCTISN)[86] noting since 2009 that Pellini testing (ie resistance to cracking) for determining the ductility temperature (RT_{NDT}) had not been undertaken on the RPV, pressuriser and SG components.

It is expected that the current round of AREVA analysis and testing will consider assessment of defect (crack) sizes, as well as the fast fracture parameters discussed above, that could prompt the RPV to fail. In fracture mechanics there is a critical crack size (length) below which the crack will not run when an applied load or stress is applied across the crack tip or root. The margin between these two defect sizes, that is i) the critical crack length and ii) the largest extant crack in the shell, is known as the *Validation Factor* (VF) for which a value approaching 2 (or greater) is usually adopted as the design basis from the onset of the manufacturing phase. It may be that EdF, who will be the licensed operator of the FA3 NPP, will seek a relaxation of the VF margin in account of the carbon anomaly acknowledged to be present in the upper and lower head components of the FA3 RPV.

For those operating NPPs that have at-risk components installed the challenge is how to reliably quantify the risk of failure in terms of the ductility transition temperature (RT_{NDT}) and VF using the limited range of non-destructive examination techniques presently available such as, for example, surface spark spectrometry.[72] Even though the surface extent of the macrosegregation zone might be determined it is, as shown by TABLE 2, variations in the <u>micro</u>chemistry within the depth of the shell that determines the actual resilience of the shell against fast fracture failure.

Simple criteria for the acceptance of an installed component might include comparison between the results of physical testing a replicate component to that of the design-basis requirement of the installed component. For example, this would require the replicate value of VF being greater than the design-basis VF and, similarly but to the contrary, the design-basis RT_{NDT} being greater than that derived from testing the replicate component.[47]

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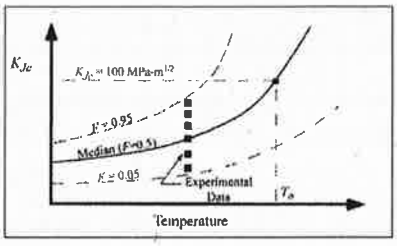
47 The evaluation of fracture toughness – see [38] – assumes a statistical approach with the adoption of a *Fracture Toughness Master Curve* from which an index temperature T_o is derived as the temperature at the median fracture toughness probability (F=0.5) – use of this Master Curve permits the fracture toughness corresponding to a particular temperature (or section thickness) to be estimated by the indexing temperature T_o and Charpy test results.



However, even on a one-for-one basis, the reliability of the replica component to accurately duplicate the macrosegregation zone throughout the shell of the installed component is doubtful, nor is it presently feasible to reliably computer model the 3-D macrosegregation zone.[20]

To deploy a single replica component to establish the presence and locality of the macrosegregation zone for each of a series of near-identical installed components would be even more challenging and of doubtful validity, This is not just for the reasons given for the one-to-one comparison above but, particularly, because according to HCTISN[86] the actual forging parameters applied during the manufacture are now untraceable since (on an unspecified number of instances) the *target* values had been recorded instead of the *actual* values used during the manufacturing of the component.

Similarly, and based on the very limited data publicly available, the reduction in VF for the SG bottom head component from Creusot and other manufacturers tentatively indicates that the VF margin is at an unacceptable level for continued operation in service.

DESIGN-BASIS –VS- TECHNICAL QUALIFICATION

Design-Basis: So far as the primary pressure circuit relates, the *Design-Basis* requirement is to specify and provide components in terms of chemical makeup and physical characteristics that are sufficient to satisfy the RPV structural containment function for all progressions of ageing and for all normal and credible abnormal operating scenarios. The design-basis adheres to the somewhat prescriptive RCC-M code[48, 49] which sets out, amongst other things, the limits and conditions of the physical attributes of the components (and systems) relevant to the functional and integrity requirements of the primary pressure boundary.

Built into RCC-M is M140 requiring, at the first level of Defence in Depth, qualification procedures to ensure that the pressure boundary components are free of defects, for example crack-like flaws. The expectation is that M140 will mostly be satisfied by post manufacturing non-destructive inspection, although there is M160 that sets out rules for a prototype part destructive testing if non-destructive volumetric examination is not possible in specific areas of the component.

This statistical approach has been adopted by AREVA for its first-round FA3 analysis - see AREVA, *Information sur l'avancement du programme d'essais des calottes sacrificicielles*, GP ESPN, 24 Juin 2016 – using Charpy tests taken from samples (destructively) removed from the Hinkley Point C upper cap a good proportion of which fail the F=0.5 criterion.

48 The first French NPPs, the 900 and 1,300MWe series, followed a design based on the universally adopted ASME code under a Westinghouse licence and then, from about 1974, the technical specifications were progressively issued with French adaptations. From 1978 much of the ASME had been superseded with very similar French RCC-M code.

49 Relevant here is Section 1, Subsection B applying to *Class 1* equipment forming and linked to the reactor primary cooling circuit (primary pressure boundary). This is the so-termed *'Break Preclusion'* equipment for which the fundamental and overriding *'design-basis'* is that the equipment will never catastrophically fail under all credible circumstances. In other words, the primary coolant circuit is assumed to remain intact and wholesome in all reasonably foreseeable normal operating and abnormal fault situations. Quality assurance controls (generally referred to as *conformity assessment procedure*)[51] for material procurement are specified under RCC M, Section 2 with the manufacturing route having to comply with a *Technical Procurement Specification* under RCC M, S2, M 140 with, for example, the Class 1 RPV components:-

TABLE 5 RPV DOME COMPONENT – SPECIFICATION AND MATERIAL GRADE

RPV COMPONENT	RCCM SPECIFICATION	EQUIPMENT CLASS	MATERIAL GRADE
Upper Head Dome	M2131	N1	16 MND 5
Lower Head Dome	M2131	N1	16 MND 5

Technical Qualification: The technical qualification (QT) endorses the design-basis, being the means by which material and component quality is ensured so that the component functions within its design-basis – put another way, QT is a record of all of the processes and actions involved in manufacturing the component showing it to conform, or otherwise, with the parameters assumed and specified by the design-basis. Thus, QT provides the confidence that enables the production facility to replicate the quality and function of the first manufactured or prototype component without the necessity to destructively test those follow-on components.

A reliable and complete QT is crucial for the consistent manufacture of large components where it is impracticable to physically examine and test every volumetric part without irrevocably damaging the component. Once that the manufacturing route has been assessed and approved, which might involve the destructive testing of the prototype component, then a consistent manufacturing route will provide conformity of follow-on components produced in the same way and under the same conditions.

QT is mandatory for the RPV (and other Class 1) components and includes assessment of the manufacturing route; a description of the inspection and testing programme involved during and following the manufacturing processes; and a qualification report and formalised record held for the final, finished component. ASN's QT requirement is based on the *European Pressure Equipment Directive* (PED – 97/23/EC) with additional requirements to reflect nuclear risk aspects. Earlier rules for product qualification are difficult to trace, although the distinct phases in the development of quality assurance controls of the primary coolant circuit components seems to be the Orders of February 1974 and October 1999, with the latter being introduced specifically to cover the design development of the then fledgling EPR NPP.

In December 2005 and in addition to the RCC-M Code, Class 1 equipment (ie the primary pressure boundary) was subject to the *Équipement Sous Pression Nucléaire* (ESPN)[50] including subsequent revisions and guidelines.[51] The general ESPN requirement is that the manufacturer shall implement a quality management QT system for the manufacture, final inspection and testing of the component and/or assemblage of components, and more generally the manufacturing facilities.

The administrative process for this is that the *French Directorate for Nuclear Pressure Vessels* (DEP), part of ASN, is the nominated *Notified Body* that undertakes, by law, a number of assessment, inspection and test activities on primary pressure circuit components and their manufacturing routes (ie inspection of the forging plants and processes). Under these arrangements, the manufacturer (AREVA) is responsible for obtaining from DEP a *Certificate of Conformity*.

For the N1 break-precluded category of components,[52] the order of 12 December 2005 clarifies the key safety requirements for nuclear pressure equipment (ESPN) and that a

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50 The French Order dated 12 December 2005 (ESPN). ESPN has extended the practical application of the methodology established by the *Pressure Equipment Directive (97/23/EC)* to nuclear pressure equipment, under *French Decree 99-1046* dated 13 December 1999, and Order dated 21 December 1999 (ESP).

51 ASN, *Conformity Assessment of Nuclear Pressure Equipment*, French Nuclear Safety Authority Guideline 8, September 2012

52 In France, nuclear pressure equipment is regulated on the same basis as the conventional pressure equipment. The ESPN determines *additional requirements* to take into account the importance for safety of level 1 components and the importance of radioactive releases in case of failure of other components. The equipment is classified in three decreasing levels N1, N2 and N3 according to the quantity of radioactivity that could be released in case of failure of the equipment and the importance for safety of this equipment - the main primary and secondary systems of the French PWR reactors classification is N1.

demonstration of conformity is via *Qualification Technique* (QT). The key requirements of the order,[51] so far as the Creusot issue relates, is that the QT should, amongst other things, identify and record:

- the risks of component heterogeneities throughout their entire volume; and
- conformity with the mechanical characteristic values specified for each type of material.

Specifically for heterogeneities the QT must therefore identify:[53]

- causes and influencing parameters;
- locations on the component;
- means of detection;
- manufacturing processes for avoiding heterogeneities;
- means of detection on the component (where, when, how, how many);
- acceptability criteria of the results of the detection; and
- procedures to control the influencing parameters during manufacture.

Importantly, QT has to be in place and a *Certificate of Conformity* issued by the *Notified Body* DEP (ASN) before manufacture of the first component commences.

AREVA'S APPLICATION OF TECHNICAL QUALIFICATION AT CREUSOT

ASN has yet to publish the QT file that accompanied the original FA3 upper and lower head manufacturing route.

At this present time (August 2016) the RPV installed in the reactor pit at FA3 does not have a *Certificate of Conformity*,[54] meaning that it does not comply European Pressure Equipment Directive 97/23/EC; *Équipements Sous Pression Nucléaire* of December 2005 (ESPN); nor satisfy the ASN prerequisite of January 2008 that all new components require a *Certificate of Conformity* prior to manufacture, thereby applying to the RPV assembly that was fabricated in total in or around 2011.

It is difficult to foresee just how the FA3 RPV will ever comply with the ESPN, particularly with the irrecoverable lapses in its QT file and the acknowledged presence of a positive macrosegregation zone in the lower head shell that now forms an integral part of the RPV. If the FA3 NPP is to proceed to nuclear commissioning ASN's January 2008 prerequisite will have to be waived, and significant dispensations (relaxation) of its design-basis and operating licence will have to be granted.

When commencing the manufacture of the FA3 head components AREVA disputed the need for a separate QT because, according to ASN, it regarded the M140 qualification of the RCC-M to wholly satisfy this requirement. Thereafter, AREVA and ASN wrangled over this issue until 2008 when ASN ruled[55] that a separate QT was required. Moreover, from

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53 ASN, *Application of the French Order dated 12/12/2005 on Nuclear Pressure Equipment, Guide N° 19*, February 2013.
54 ASN to LargeAssociates, email 16 August 2016.
55 ASN email to AREVA 19 February 2008, ACS/MFG-dép-DEP- 0083-2008 ASN-2008-09048 *'relatif au problème dans le processus de QT des GV/RO.*

1 January 2008 ASN invoked the prerequisite that prior to manufacture[56] all new components required a full and approved QT file, thus effectively setting a hold-point that manufacturing of a (series of) component(s) could not proceed until the *Certificate of Conformity* had been issued – this ruling applied only to new components and not the FA3 upper and bottom heads that had been already manufactured without a full and prior approved QT.

What is of interest is that ASN applied no further restriction on the final manufacture processes to the bottom head, including its welding into the RPV assemblage, and then the RPV installation into the FA3 reactor pit in January 2014.[57] In fact, the FA3 upper and bottom heads, although known not to have a satisfactory manufacturing audit, in the form of the QT file, were not checked for heterogeneity until 2012 and then, later in October 2014, the results of tests on the replicate upper head revealed the below par material toughness results, with ASN making these results and the non-conformity public on 7 April 2015.

Importantly, in manufacturing the upper and lower head components AREVA chose RCC-M M140 qualification instead of QT, a practice that was halted by ASN from January 2008 when it stipulated that a *Certificate of Conformity* had to be issued prior to manufacturing commencing. It follows that it is also likely that AREVA adopted the same M140 approach for quality assurance of the manufacture of other N1 primary pressure circuit components and, if so, there may be shortfalls in the QT for other components manufactured not just at Creusot but also abroad at JCFC and JSW forges – these potentially at-risk components could include the larger RPV annular rings.

Present practice holds AREVA to the prerequisite of submitting to ASN-DEP **before** the (first or prototype) component is manufactured a request for assessment of its compliance, although from the limited amount of information so far published by ASN, it is not practicable to determine if and to what extent this submission was made by AREVA for the FA3 head components.[58]

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56 In fact, ASN stated its interpretation that the TQ should be prepared and agreed ahead of manufacture *"L'évaluation de conformité requiert la production préalable de la démarche de qualification. Effectivement, le module G de l'annexe 2 du décret 99-1046 du 13 décembre 1999 stipule que la demande de vérification à l'unité, introduite par le fabricant comporte une documentation technique"* and it distinctly separates the need for a TQ from the M140 and M380 requirements *"Le processus de qualification doit apporter l'assurance que les procédés de fabrication choisis confèrent aux pièces, ainsi produites et contrôlées, l'ensemble des caractéristiques définies lors de la conception à partir de l'analyse des risques. La démarche de qualification s'inscrit dans la continuité de la justification des choix de moyens de fabrication. Elle permet de définir les essais nécessaires pour s'assurer de la justesse des choix de moyens de fabrication, en complément des essais et contrôles de recette de chaque pièce."* - see ASN letter to AREVA of 21 August 2006, *Qualification technique des approvisionnements anticipés constitutifs de la cuve EPR.* There was also some rancour between ASN and AREVA over the FA3 second primary pump housing *"Vous avez indiqué à l'ASN, notamment au cours d'une réunion le 12 juillet 2007 et par un courriel le même jour, votre intention de fabriquer le deuxième carter de pompe primaire FA3 dont la coulée est prévue le 18 juillet 2007. Vous avez également indiqué votre intention de fabriquer de nombreuses pièces des circuits principaux du réacteur avant la finalisation de la qualification technique de leur fabrication. J'attire votre attention sur le fait que ces pratiques constituent une prise de risque industriel importante pour AREVA NP du fait des considérations exposées ci-dessus: si la qualification technique des opérations de fabrication réalisée a porteriori pour ces pièces venait à apporter des éléments non pris en compte dans le programme technique de fabrication, la démonstration de la garantie de leur qualité poserait des difficultés, ce qui pourrait conduire à leur rebut. En tout état de cause, le contrôle par l'ASN de la fabrication de ces pièces, qui concourt à l'évaluation de leur conformité, ne pourra être considéré comme approprié que si le programme technique de fabrication est finalisé a priori et n'est pas significativement remis en cause par la qualification"* – see Letter, ASN to AREVA, *Projet Flamanville 3. Qualification technique des opérations de fabrication.*, 16 July 2007.

57 ASN claim that, in effect, it has no powers to stop the manufacturer (AREVA) to install the RPV and associated cooling circuit component into the nuclear island.

58 For nuclear pressure equipment of level N1, the essential safety requirement defined by ESPN as the QT requires that *"prior to manufacture, the manufacturer identifies the component that present a risk of heterogeneity in their characteristics linked to the production of the materials or the complexity of the planned manufacturing operations. All*

Interestingly, ASN considered the investigation results reported to it by AREVA, in or about 2012, related to potential heterogeneities that were *"not usually subject to such checks"* – AREVA seems to have discovered these serious flaws in the (FA3 equivalent) upper and bottom head components during the period 2010 to 2011,[51] although there are media reports of something seriously amiss much earlier in 2006.[5]

In fact, there is more definitive evidence that something was seriously amiss in or around 2008 when destructive testing of the FA3 pressuriser centre manhole knock-out revealed notable differences when compared to similar testing of the Olkiluoto 3 pressuriser. However, even though Creusot attributed the differences to the presence of residual major positive macrosegregation zone in the upper dome of the FA3 the existence of the tests and results were not then reported to ASN.[59]

In other words, the manufacture of the FA3 RPV upper and bottom head components had not, since production commenced in or about 2006 and 2007, complied with the requirements of the QT. Problems with the Creusot manufacturing route (ie the adoption of the conventional ingot manufacturing route for the RPV head forgings) remained undetected and unknown to ASN for four to five years or, if *Le Canard* is to be believed,[5] all involved parties knew of it very early on in the manufacturing sequence, in or around 2006-07. This prior knowledge hinting at non-conformity may stem from the analysis undertaken by AREVA in 2007 of swarf collected from the post-upset forging plate prior to the final hot forming process – these results indicated an over-specification of local carbon content of 0.265% and 0.277% for two samples taken from the unformed upper head plate.[60]

Whatever, in or about 2011, it seems that either AREVA or ASN, or both, realised that the forging test ring results for the chemical analyses and physical testing were unreliable and that the QT up to that date was unsatisfactory, if not entirely misleading. However, quite contrary to this knowledge, ASN stated in 2012 that it *"considers that in 2012, as a result of complying with the provisions of the ESPN orders for a number of years, the equipment manufacturers have reached a satisfactory level with respect to the 'technical qualification' requirement"*.[61]

Not surprisingly, following the apparent (see later) authoritative sanctioning of the QT by ASN, the UK ONR nuclear safety regulator when carrying out its *Generic Safety Assessment*

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the manufacturing operations form the subject of a technical qualification". To assess QT compliance, the current practice involves AREVA submitting to ASN, **before** producing the material/component identified by the AREVA as requiring technical qualification, a request for an assessment of compliance with this requirement,[8] comprising a technical document that details in particular those aspects of the material characteristics (risk of heterogeneity, toughness, physical testing, etc) – an important prerequisite of the QT is to demonstrate that the component will be in each and every respect consistent with the parameters specified and used by the design-basis.

59 ASN, *Objet: Contrôle de la fabrication des équipements sous pression nucléaires (ESPN), Thème Conformité des matériaux entrant dans la fabrication des ESPN Codes INSSN-DEP-2016-0692 et INSSN-DEP-2016-0693*, 9 May 2016.

60 ASN, *Note en vue de la réunion du 23 mars 2016 du groupe de suivi du HCTISN portant sur l'anomalie de la cuve de Flamanville 3*, 21 March 2016

61 ASN's confidence in Creusot quality assurance and QT matters around this time (ie *'for a number of years'*) was generally shared by the Nuclear Regulatory Commission (NRC) following its inspection of Creusot activities in 2009, although the NRC had reason to serve i) a *Notice of Violation* because Creusot failed to adopt appropriate defect reporting procedures[67]; and ii) a *Notice of Non Conformance* relating to failure to calibrate the temperature transducers of the Charpy notch test samples (a critical parameter in determining material toughness) – see NRC, Report Nº 99901381/2009-2010, July 2009.

(GDA) on the twin EPR NPP for Hinkley Point C, also approved the Creusot manufacturing route:[62]

> "... *NNB GenCo's*[63] *company processes for the ultrasonic inspection of forgings for high integrity components has taken account of ONR interventions and are progressing satisfactory. Similarly, NNB GenCo has demonstrated an understanding of the patterns of segregation in large ferritic forgings and has elicited a ruling by the design code owner to the effect that the forgings are code compliant. Given this, the inspector considers that NNB GenCo have made satisfactory progress in resolving the issues of macro segregation identified in the assessment of HPC PCSR 2012."*
>
> *My added emphasis*

In other words, in or about 2014 the UK regulator was unaware of the non-compliance of the Creusot manufacturing route that had been known to both AREVA and ASN since at least 2011, or earlier.[64, 65]

All of this points to possible failure of ASN-DEP to ensure that the FA3 installed RPV components complied with the 2005 ESPN,[50] that is that although it was known that the QT for these components was unreliable, possibly from as early as 2006, and certainly at least by 2011, ASN continued to espouse that all was well.

The point at issue here is twofold: should the requirement for a *Certificate of Conformity* for the parts of the RPV assemblage apply from the ESPN date of December 2005, or should it apply retrospectively from that ASN clarification date of January 2008[54] and, indeed, should the requirement that a valid *Certificate of Conformity* be in place be an absolute and supreme prerequisite, failing which the RPV already installed at FA3 could not proceed into licensed nuclear service?

Implications for Existing FA3 Head Components: For the already manufactured FA3 head components ASN seemingly turned a blind eye, enabling AREVA to incorporate the at-risk lower head into the FA3 RPV; machine and weld line, and hydro pressure test the RPV (March 2012); and install the RPV in the FA3 reactor pit (January 2014).

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62 ONR, *GDA First Project Convergence Point at Hinkley Point C – Summary Progress Report for the Design and Safety Case Cornerstone* ONR-CNRP-PR-14-034, November 2014 – see paragraph 36.

63 NNB Generation Company (NNB GenCo) is a subsidiary created by EDF Energy to build and operate two new nuclear power stations in the United Kingdom.

64 ASN's first public pronouncement of the FA3 non-compliance was not until April 2015, so ONR had not been informed by ASN at the time that it compiled its Convergence Point report [62] in or around November 2014. Also, the e-mail exchanges between EdF Energy and AREVA – see *Emails: Areva manufacturing concerns. SZB 50831R-Attachment 6* – shows that the exchange between EdF Energy and AREVA did not commence until 13 May 2016, even then it was confined to EdF Energy receiving a general statement of assurance which was eventually given by AREVA after a somewhat frosty e-mail exchanges on 20 May 2016 – there is no record of any more detailed information being exchanged between the parties. What may be of interest here is that even without this assurance and detailed information from AREVA, EdF Energy was sufficiently confident to issue the Design Authority Advice Notes – including *Implications for Sizewell B from the Flamanville 3 Reactor Pressure Vessel Manufacturing Issues*, DAO/EAN/JIDB/065/SZB/16, April 2016, [40] of March 2016 and [81] of March 2016 – all well in advance of receiving any information from AREVA in the May 2016 exchange of emails.

65 In its *Generic Design Assessment* of the proposed EPR at Hinkley Point C, the UK regulator (ONR) sent its comments on the ESPN to ASN in or around 2011-12 – as yet these comments are not publicly available – see NNB GenCo: Hinkley Point C Pre-Construction Safety Report 2012, Assessment Report: ONR-CNRP-AR-13-074, Revision 0, Version 2,14 March 2014 – *Assessment Report for Work Stream B17: Structural Integrity.* However, judging from the November 2014 resolution[62] ONR was subsequently satisfied that the QT was adequate.

For the FA3 RPV to commission to power operation, ASN will need to grant a dispensation with regard to non-compliance with the ESPN, particularly relating to its fast fracture performance; and, somehow, resolve the fact that the Creusot manufacturing route for the head components was and, apparently, remains unauthorised.

Implications for New (post January 2008) EPR Head Components: What is not clear, is whether the QT hold-point introduced on 1 January 2008[56] was fully effective from that date, that is prohibiting AREVA from later manufacturing further upper and lower heads until a *Certificate of Conformity* had been issued for that particular Creusot manufacturing route.

Although ASN has acknowledged that, specifically, the FA3 RPV does not presently have a *Certificate of Conformity*,[54] it is not known if the QT for Creusot (and the other manufacturing routes abroad) has been approved and that production of new components may now resume – on the balance of probabilities, and particularly in account that ASN has deprioritised the resolution of the FA3 carbon anomaly, it is most unlikely that manufacture of EPR RPV head, and other N1 class primary pressure boundary components, is able to proceed at Creusot and elsewhere.

There is some evidence to suggest that the QT problems at Creusot were not confined to the single RPV head manufacturing route. At shop floor level, quality control of the various manufacturing processes at Creusot are set out in what might be best described as the Creusot Forge *Quality Assurance Manual* (QAM).[66] QAM assigns a Quality Assurance (QA) and, separately, a Methods/Quality Control (QC) manager, and charges all employees with the responsibility to report to the QC any defect of a component. The QC has to document and evaluate the reported defect to determine if the identified condition is a substantial safety hazard, following which QAM requires the QA to notify the 'customer' but not necessarily the nuclear safety regulator (ie ASN).

This quirk in the reporting procedure was not highlighted until the US Nuclear Regulatory Commission's (NRC) visit to Creusot in 2009 when overseeing the now abandoned US EPR order (UA).[67] In response to the NRC Violation Notice[68] pointing out that it had not been directly informed of defective components, Creusot modified its QAM, although it is not clear that this revision also included for reporting directly to ASN-DEP on components destined for French NPPs.

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66 Section 57.2 of the QAM establishes program requirements for controlling the manufacturing process. These processes are implemented by personnel in accordance with specific and qualified technical instructions and/or procedures. The principal operations steps in the Creusot Forge manufacturing process include receiving inspection, forging, heat treatment, machining, nondestructive examination, dimensional examination, mechanical tests, and inspection after manufacturing operations have been completed. Documents used to follow-up and control manufacturing and QT operations include procedures, customer drawings, manufacturing drawings, test instructions, and the shop traveler file. The shop traveler file is the primary QT document bundle used for controlling operations and their status, especially for essential operations that are systematically included. Specifically, a QT coordinator is assigned responsibility for the shop traveler file throughout all operations, so that it identifies the customer drawings, specifications, and applicable procedures for the activity being performed, including applicable procedural and technical information for all manufacturing, analysis, inspection and testing operations.

67 In a similar situation when Creusot had in manufacture forged components for a US nuclear power plant, the NRC noted that Creusot had not performed any such reports in the past 2 years (2009), with the NRC inspectors noting that the relevant section of the QAM (Section 58.5, IN 004) stipulating the written reporting of defects to customers instead of the NRC - see NRC, Report No 99901381/2009-201, July 2009.

68 Creusot Forge, NRC – Report 99901381/2009-201, undated (c2009) – response to NRC Violation Notice – it is not clear if this relates only to reporting to the NRS or is a revision of the general QAM defect reporting procedure that would include ASN and/or DEP of ASN.

Similarly, ASN reports that differences in QT files to actual practice (ie the *'irregularities'*) at Creusot had not been transmitted to the customer and ASN itself, although dates and further details have not been made publicly available.[69, 70]

Implications for pre-EPR Components: The situation relating to a total of 50 at-risk N1 components installed in operating NPPs across France was not publicly made known until 3 May 2016, although little detail was released other than that these were subject to *'irregularities'*. Then on 23 June 2016 ASN reported a potential defect (similar to the FA3 carbon anomaly) with 18 steam generators currently in service at French NPPs, adding that other forged components (including the RPV and pressuriser) are subject to ongoing investigation.[71,72]

Obviously, the QT quality assurance measures, in various versions since the February 1974 and October 1999 Orders, failed to prevent at-risk N1 nuclear safety critical components from being installed in operating NPPs.

With respect to the risk of heterogeneity resulting from positive macrosegregation arising in the Creusot manufacturing route, AREVA's QT file for the FA3 at-risk components was, found to be *'poorly assessed and its consequences poorly quantified'*.[8] It may be that upon its acquisition of Creusot Forge in 2006[4] AREVA inherited bad practices that it did not subsequently purge and correct – ASN hinted at this lack of vigilance in another aspect of AREVA's management of Creusot Forge.[73] In other words, it is quite possible that QT inadequacies at Creusot applied to other manufacturing routes (such as the SG heads, pressuriser, etc) reaching back to 1965 – all of this may explain and be within ASN's use of the generic term *'irregularities'*.

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69 ASN, *Irrégularités détectées chez AREVA Creusot Forge*, HCTISN, 30 Juin 2016

70 *"Ces irrégularités, de natures très diverses, consistent en des incohérences, des modifications ou des omissions dans les dossiers de fabrication relatives à des paramètres de fabrication ou des résultats d'essais. Certaines informations relatives au forgeage, au traitement thermique, aux essais mécaniques ou aux analyses chimiques n'étaient ainsi pas transmises au client de Creusot Forge et à l'ASN. Dix-neuf de ces irrégularités portent sur le respect des spécifications du client et des règles de fabrication des équipements sous pression nucléaires"* - ASN Briefing, *Irrégularités détectées dans l'usine d'Areva de Creusot Forge : l'ASN fait un point d'étape*, 16 June 2016.

71 ASN, *Certain EDF reactor steam generators in service could contain an anomaly similar to that affecting the Flamanville EPR vessel*, Note d'information, 23 June 2016 – the affected NPPs are Le Blayais NPP (1), Bugey NPP (4), Chinon NPP (B1 and B2), Civaux NPP (1 and 2), Dampierre NPP (2, 3 and 4), Fessenheim NPP (1), Gravelines NPP(2 and 4), Saint-Laurent-des-Eaux NPP (B1 and B2), Tricastin NPP (1, 2, 3 and 4), added to which Fessenheim 2 NPP operation has been suspended because of the presence of a macrosegregation zone on a steamside circuit lower shell component of a steam generator. Excepting the lower shell defect of Fessenheim 2, the macrosegregation zone potentially involved 20 Creusot-source monobloc bottom heads manufactured from 1990 at 8 NPPs and, manufactured between 1990-1997, the monoblocs of 26 SGs at 12 NPPs sourced from JCFC. Similarly, the SG tube plates are also potentially at-risk components but the distribution of at-risk SG tube plates is not available, although 58 NPPs are likely to be involved with the tube plates sourced from Creusot, JSW and Sheffield Forgemasters.

72 Depending on the NPP power rating there are either 3 or 4 SGs serving each NPP. EdF is required to report back to ASN on the i) location of any zone of macrosegregation; and ii) if there are any extant defects on the surface or within the shell thickness. Of location, a crack-like flaw on the outer surface is of less concern that a similar defect on the inner surface which is generally inaccessible for non-destructive examination. For i) the non-destructive technique will probably involve spark spectrometry on the outer surface – the inner surface is inaccessible and it is not possible to accurately record the extent of any macrosegregation zone (and hence the carbon content) into the depth for the shell – any extrapolation technique to assess the in-depth carbon content is likely to require advanced acceptance by ASN. For ii) ultrasound inference techniques will detect any crack-like flaws at depth and magnetic particle will detect surface flaws - it is important to be able to monitor any growth of known pre-existing flaws. Both of these non-destructive inspection techniques will require the reactor plant to be shut down and taken to a cold depressurised state. If this monitoring is delayed until a scheduled outage of the NPP then it has to be assumed that EdF has demonstrated to ASN that there is no unacceptable risk associated with maintaining the plant in service until the inspection outage.

73 ASN, *Annual Report 2012 – Continuity of the Steps Taken to Manage Manufacturing Risks* (page 400) – relates to the presence in hydrogen in replacement SG shells.

More recently, in September 2016, ASN provided a less ambiguous definition of the *'irregularities'* to have included *"Counterfeit, Fraudulent and Substandard Items (CFSI)"* when referring to three further unspecified incidents that had arisen since the end of 2015.[78]

An example of such misrepresentation (or falsification) at Creusot of manufacturing data was revealed by ASN in May 2016 when the sacrificial test results for a replacement steam generator for which the maximum carbon concentration was recorded as 0.23%, whereas subsequently the record had to be amended to reveal a residual and major positive macrosegregation zone of higher carbon content[59] – three further replacement SGs were found also to have unacceptably high carbon content in residual areas of positive macrosegregation and have since been scrapped.

Replacement Steam Generator Programme: In September 2011 EdF embarked upon a steam generator replacement programme for the 1,300MWe series NPPs involving a total of 44 replacement SGs, 32 of which were to be supplied by AREVA and sourced from Creusot.

The AREVA supply schedule was then (2011) sixteen SGs by July 2016, eight in January 2017 and the final eight in January 2018.[74] However, the patchy progress of this SG replacement programme are given, first, by the present outage of Paluel 2 NPP where installation of the replacement SGs has been delayed by the handling mishap of an existing SG in March 2016[75] and, second, that the current outage at the Cattenom 1 NPP will not now include fitting the replacement SGs because of delivery delays.

The replacement SGs, already fully and part manufactured, are also likely to be subject to investigation for macrosegregation in addition to the at-risk SGs identified by ASN in June 2016.[see TABLE 6] Possibly included in this programme of inspection were the three or four replacement SGs scrapped because of fraudulent recordkeeping referred to above.

FINDINGS AND RECOMMENDATIONS

Delivery of Flamanville 3: It is fact that components of the FA3 reactor pressure vessel do not comply with the design-basis requirement that precludes catastrophic failure of the RPV – on this fact alone, the FA3 RPV is not fit for service.

The acknowledged increase of carbon content in the macrosegregation zone, with the associated reduction in material toughness, escalates the vulnerability of the at-risk components to the fast fracture failure mode – the presumption is that AREVA will seek to demonstrate that the remaining fast fracture VF margin is sufficient for normal and all credible abnormal modes of reactor plant operation.

The immediate outcome of the non-compliance with the design specification of the nuclear safety critical FA3 RPV is that it is certain to stall AREVA's present round of analysis and reporting of test programme until mid-2017, if not later. No doubt, the intent of AREVA's analysis and physical testing of FA3 equivalent forged components is to show that, even with account of the non-compliance, the RPV assemblage as a whole will have sufficient margin to operate at an acceptable risk of failure.

74 World Nuclear News, *EDF orders 44 steam generators*, 29 September 2011.

75 ASN, *Fall of a steam generator in the Paluel reactor 2 building*, 4 April 2016.

Even so, the RPV assemblage remains non-compliant with the 2005 ESPN, which means that the *'break preclusion'* prerequisite of the design-basis will no longer underpin the first level of defence of the FA3 nuclear safety case. Thus, to proceed into licensed operational service, ASN will have to grant a dispensation relaxing the all-important design-basis requirement of *'break preclusion'* for the FA3 NPP.

FA3 Defence in Depth: Because RPV failure is not included in the nuclear safety case there is nothing in the *third level of defence* to mitigate the consequences of RPV failure. Thus a licence dispensation allowing for RPV failure in the principle of *Defence-in-Depth* would be a very substantial departure in the Design-Basis requiring fundamental revisions of the first two levels of defence-in-depth entailing hardware and systems modifications to a number of aspects of the FA3 NPP.

Achieving FA3 Conformity by Inference Means: At this time there is no intention to undertake anything other than non-destructive inspection and examination of the installed FA3 components with, instead, the physically disruptive and destructive material sampling and testing being undertaken on supernumerary, replica components that have been through the same Creusot manufacturing route.

For the FA3 at-risk components the carbon anomaly has been linked to the size and cooling of the forging ingot stage of the Creusot manufacturing route. However, the presence and extent of a macrosegregation zone can only be fully detected, mapped and examined by destructive means, so any potential defects have to deduced via inference testing of i) a test ring taken from the surplus edges of the component and/or by destructively examining ii) a supernumerary or equivalent, replica forging that has followed through the same manufacturing route as the FA3 component.

It is now acknowledged that results from the FA3 test ring are unreliable,[34] so a greater reliance has to be placed on the i) examination and destructive testing of supernumerary, replica components and, because it would be grossly uneconomic to continue to rely on replica testing for all future components, ii) the use of predictive modelling of the presence and location of macrosegregation zones.

However, for i) there must be doubts about the reliability of such replication, especially when the formation and spread of the macrosegregation zones within the cooling ingot are subject to so many poorly defined and least understood factors. Moreover, serious doubts have been raised about the reliability of the QT record-keeping during the early stages (2005 to 2008) of manufacturing the FA3 and supernumerary upper and lower head components: In effect, AREVA did not prepare a comprehensive QT file to record all of the relevant parameters of the manufacturing route prior to embarking upon manufacturing the components and, of course, there must also be concern that the FA3 components may also have been subject to much the same *irregularities* of similar components produced earlier at Creusot. The absence of complete QT manufacturing records means that there may be variations in the individual manufacturing routes for the FA3 and supernumerary test components – nothing has been produced to show otherwise – thus there can be no guarantee that the supernumerary test components will be sufficiently reliable emulations of the FA3 at-risk components that are now fully integrated into the installed FA3 RPV.

These uncertainties place considerable reservation on the reliability of the proposed inference methodology to determine the suitability for service of the original FA3 components.

One element of uncertainty in this reassessment will be the reliability of deducing the actual carbon content from the FA3 equivalent or replicate forgings. Obviously, because these forgings are very large and expensive, destructive examination has been minimal in the past, there being an increasing dependence on modelling and non-destructive inspection (NDI) to determine the existence of macrosegregation zones.[20] However, the difficulties associated with (computer-aided) macrosegregation zone modelling are formidable and NDI techniques generally rely upon the surface condition to extrapolate into the inner depth of the shell. A key requirement of the QT is that if such macrosegregation modelling and/or NDI is deployed then it has to be proven and sound basis for predicting the absence of macrosegregation in components that cannot be non-destructively examined.

Pre-EPR Installed Component Checks by Inference Means: Existing versions of predictive modelling of the macrosegregation zones might be improved and reasonably applied to new forged components (ie any FA3 successors) on the basis that the exact manufacturing parameters will be known – for this the QT will have to be established and the particular manufacturing routes certified by the appropriate *Certificates of Conformity.*

However, for the existing 50 or so installed Creusot at-risk components (21 NPPs) with, in addition, the at-risk SG components (18 NPPs) sourced from Creusot and other forging plants, the doubtful provenance[86] of the manufacturing and QT records cast considerable doubt on the reliability of any advanced modelling of the existence and dispersion of macrosegregation zones.

Prognosis for FA3 RPV: Now that the at-risk lower head has been weld integrated into the FA3 RPV, installed in the FA3 reactor pit in primary containment and physically connected to the primary coolant circuit, the alternatives for demonstrating the suitability of the FA3 RPV for nuclear powered service are somewhat limited.

First, to restore the margin curtailing fast fracture the NPP could be derated and, particularly, a regime of pressure-temperature management rules and safeguarding procedures introduced for normal and all anticipated modes of abnormal operation. However, this option also necessitates abandoning the *'break preclusion'* of the N1 safety critical components and, even if derating could be practicably implemented, it would result in a NPP of significantly reduced generation efficiency.

The second option is to replace the at-risk components of the FA3 RPV and restore the *'break preclusion'* prerequisite of the nuclear safety case. If so, it is considered impractical to carry out such repairs whilst the FA3 RPV remains in-situ in the reactor pit of the nuclear island so removal from, repair and eventual reinstatement of the ~525 tonne RPV into the nuclear island would be a very expensive and time-consuming exercise, so disruptive to be likely to jeopardise the financial viability and continuance of the FA3 project.

ASN have acknowledged that this second option may be necessary, advising AREVA to contingency prepare for this in December 2015.[12]

Future EPR RPV Components: The same Creusot manufacturing route used for the already installed but yet to be commissioned FA3 RPV, was also used for and, hence, the same flaws are very likely to arise in the two Taishan, China EPR NPPs presently nearing commissioning, and future orders such as Hinkley Point C EPR. For these and future new orders of EPR NPPs a number of issues remain outstanding:

The flawed Creusot manufacturing route that is reliant upon cropping and upset forging of a single, large conventional ingot will have to undergo reappraisal and fresh QT. If this particular manufacturing route is found to be unreliable, which presently seems to be the case, then for future EPR head forged components a new manufacturing route will have to be developed and technically qualified – it is not immediately obvious that the *Lingot a*

Solidification Dirigée (LSD) technique developed for smaller head components can be readily upscaled for the larger EPR head components.

Of course, the resumption of production EPR primary pressure circuit components is very much dependent upon the present FA3 problems being, first, fully understood and, second, reaching some resolution. The second round investigation programme coerced by ASN on EdF-AREVA was generally reckoned to take until mid-2017 for ASN to establish a regulatory position. However, most recently (30 June 2016), ASN declared[69] that for FA3 *"characterisation en cours mais non prioritaire"* that could further delay a regulatory decision from ASN.

Any extended delay in the commissioning and satisfactory trial operation of the FA3 NPP will have serious implications for the funding arrangements supporting the UK twin EPR project at Hinkley Point C.[76] Essentially, if FA3 overruns the European Commission 31 December 2020 deadline[77] for the *Base Case Condition* to be satisfied then the UK government's Credit Guarantee will be protected and, instead, the shareholders (eg EdF and China General Nuclear Power Company) will assume the principal exposure to the viability of the EPR technology and the compliance of its means of reliable manufacture.

On their parts EdF and AREVA both continue to express confidence that FA3 will commence power operation in the fourth quarter of 2018, that is in good time to reach the Base Condition by December 2020.

Other Creusot-Sourced Components: Equally, if not more galling for the French EdF FA3 NPP operator, is the revelation that the macrosegregation defect could also apply to Creusot-sourced components already installed in operating French nuclear power plants. This startling exposé arose when AREVA reported its review findings to ASN in April 2015 that some 400 Creusot forged components manufactured in the period since 1965 are subject to *'irregularities'* and at least 50 of these are installed in NPPs presently operating across France.

Cruas 3 and Chinon B3: Both Cruas 3 (~1984) and Chinon B3 (~1987) are fitted with upper closure heads sourced at Creusot under the single, large conventional ingot manufacturing route. If, as it might be reasonably assumed, these components are subject to the same frailties as the later FA3 components (also produced from conventional ingots) then they, too, are at risk of depletion of fracture toughness in any positive macrosegregation zone remaining in the component shells.

Until the present AREVA programme of evaluation of the FA3 components has been completed, shutdown or derating of these two NPPs should be considered, particularly taking account of further degradation of material toughness due to strain-induced and thermal ageing over the respective operational service history of each NPP.

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76 HM government has agreed terms on a deal to support construction of Hinkley Point C (HPC), a new nuclear power station that could generate around 7% of the UK's electricity. The deal is with NNB Generation Company (NNBG), a subsidiary of French state-owned energy company EDF. China General Nuclear Power Corporation (CGN) will take 33.5% ownership of NNBG. The deal centres on a 'contract for difference' (CfD), whereby the Department has agreed that NNBG will receive an index-linked £92.50 per megawatt hour (MWh) (2012 prices) for the electricity HPC sells for 35 years.1 HM Treasury has also offered to guarantee up to £2 billion of bonds that NNBG may issue to finance its construction of HPC – see National Audit Office, *Nuclear Power in the UK*, Department of Energy & Climate Change, HC511, 12 July 2016.

77 European Commission, *Commission Decision of 08 October 2014 on the Aid and Measure SA.34947 (2013/C)(ex 2013/N) for Support to the Hinkley Point C Nuclear Power Station*, 8 October 2014 – the UK government's continuing commitment to this funding arrangement is given National Audit Office, *UK Guarantees Scheme for Infrastructure*. Treasury HC909 28 January 2015.

Irregularities in Creusot Components since 1965: There is very little information and data available for a number of NPPs that ASN acknowledge contain Creusot components dating from 1965 and which are known to have *'irregularities'*.

First, ASN defines *'irregularities'* to "*comprise inconsistencies, modifications or omissions in the production files, concerning manufacturing parameters and test results*"[**Error! Bookmark not defined.**] which could include a whole host of material defects, poor and/or dubious recordkeeping, mismanagement and so on – even so, components subject to such *irregularities* attached must be considered to be sufficiently *'at-risk'* to jeopardise the nuclear safety case.

Whatever the details of the *'irregularities'* it is clear that the QT requirements in force at the appropriate times of manufacture failed to 'capture' a true, factual record of the components sourced from Creusot.[86] Like the December 2005 ESPN, the QT requirements set out in the February 1974 and October 1999 Orders respectively failed to prescribe the basis of a reliable QT system at the respective times.

An example of an *'irregularity'* in the QT recordkeeping at Creusot is given by HCTISN[86] noting that *'Le défaut de traçabilité des paramètres de forge (valeur visée 37ucléaire à la place de la valeur réelle)'*, essentially that the actual forging parameters applied during the manufacture were untraceable because target values had been recorded instead of the actual values.

If, as it seems, the QT system has been inadequate (and/or abused) since 1974 or earlier, back to 1965 as implied by AREVA, then this form of quality assurance system failure is likely to have allowed a diverse range of component non-compliances to slip through unchecked. In other words, it is unlikely that the *'irregularities'* are solely confined to the presence of macrosegregation associated with the use of single, conventional forgings in the Creusot manufacturing route. Indeed, the at-risk components might include a variety of manufacturing routes and other causes of non-conformity so, until full details of the *irregularities* are publicly available, the risk and potential severity of failure of the operating NPPs can only be a matter of speculation.

A further ambiguity is that, to date, other than stating that there are 50 at-risk components installed in operating French NPPs, although EdF has identified the NPPs by name it has not declared which at-risk components are installed. The situation is further confused by recent industry media reports and a statement by ASN of 23 June 2016[71] that similar zones of positive macrosegregation have been found in semi-spherical, bottom heads of steam generators (SGs) in service at a total of 18 NPPs of the 900MWe and 1,450MWe series – these at-risk SGs are in addition to the 50 at-risk components installed in operating French NPPs previously stated by ASN.

The manufacturing routes for these SGs is sourced at both Creusot and the Japanese Casting and Forging Corporation (JCFC), with the latter involvement having the potential to widen the international scope of this problem. The fact that an overseas manufactory (JCFC) is involved strengthens the suspicion that the QT, and/or its management application, is at fault because the QT is specified, introduced and overseen by the purchaser of the components (in this case AREVA or its predecessor).[78]

78 Between 1990 to 1997 26 SG bottom heads were fabricated by JCFC, these being installed in the 3-loop 900MWe series and 4-loop N4 and from 1990 20 SGs were fabricated by Creusot for installation at 8 900MWe series NPPs – it seems, although it is not confirmed, that both Creusot and JCFC deployed the conventional ingot (and not LSD) manufacturing route.

Following a number of in situ inspections of the JCFC sourced SG manifolds (bottom heads), ASN announced (12 September) that *"JCFC channel heads: first measurements tend to show higher C% than 0.30%"*,[79] thereby raising doubtd about the toughness characteristic of JCFC sourced components in particular, although further details as to the dispersion of these SG manifolds is not given.

Indeed, for the operational NPPs at-risk it may be apposite to retrospectively apply a single, universal regime of QT once that the most appropriate QT has been determined to a) preserve the *break preclusion* principle of the Design-Basis; and b) not compromise the overriding principle of *Defence-in-Depth*. Indeed, it would be reprehensible of ASN if it dithered further on this, allowing EdF-AREVA to continue the programme of appraisal of both FA3 and the operational NPPs at-risk components to continue without first an effective and properly managed QT being in place.

Obviously, each of the in-service at-risk components has to be assessed and technically qualified afresh on a case-by-case basis. Since the presence of excess carbon in macrosegregation zones places greater emphasis on the need to prevent fast fracture failure, the evaluation of the individual operating NPPs presents a demand of increased complexity (and calculable uncertainty) needing to take into account both brittle and ductile response regimes of each at-risk component.

In fact, the general case assessment for a SG manifold failure has been completed by EdF and reviewed by IRSN on behalf of ASN. The IRSN review[80] covers CPO, CPY and N4 NPPs, concluding that EdF requires further material data for its analysis to be applicable; it disagrees with EdF that the nuclear fuel core is safeguarded, with IRSN finding that in certain fault conditions involving the catastrophic failure of a SG manifold, the fuel core could melt; and to bolster the margins mitigating against a fuel core melt situation, it recommends that EdF should immediately implement a series of (unspecified) compensatory measures at each operating NPP with the at-risk SGs installed. In effect, the IRSN review is tacit recognition that an undeclared number of CPO, CPY and N4 NPPs are presently operating an unquantified level of risk of incurring serious radiological event.

UK Sizewell NPP: The EdF-AREVA progress on analysing the safety of the operating NPPs that have at-risk components installed is yet to be made publicly available by ASN. However, the UK safety regulator (Office for Nuclear Regulation – ONR) has received a response (March 2016) from EdF Energy operator of the pressurised water reactor (PWR) NPP at Sizewell B, Suffolk – this EdF Energy response may provide an insight into the approach to be adopted by its French counterpart for the NPPs operating in France.

Interestingly, the EdF Energy response considered only 2 of the 6 major components sourced from Creusot to make up the Sizewell B RPV, thereby tacitly assuming that there was no potential for carbon excess in any of the Creusot annular forgings. In considering the Sizewell B RPV head shells, EdF Energy admitted that results from the test ring (a disposable part of the forging) were insufficient to demonstrate material compliance throughout the component, stating that *"demonstration of consistency throughout the forging is not possible with these {test ring} results alone"*.

Instead, the EdF Energy response to ONR almost entirely relied upon a 1985 conference paper describing the development of the *Lingot a Solidification Dirigée* manufacturing route, but which did not specifically refer to or contain data expressly relating to the

79 ASN, *Recent Developments in Creusot Forge Manufacturing Issues,* 12 September 2016.

80 Avis IRSN, 2016 2016-00275 *Objet : EDF – REP - Paliers CP0, CPY et N4 – Ségrégations en carbone des fonds primaires de générateurs de vapeur – Analyse de sûreté et mesures compensatoires,* 5 August 2016

Sizewell B head shells – on this basis, that is referring to a 1985 paper that was *"carried out at around the time of SZB {Sizewell B} dome forging manufacture"* and also that the manufacturing route was different to the large, conventional ingot used for the FA3 head shells, the at-risk potential of the Sizewell B Creusot forgings was dismissed, although further testing and analysis may be ongoing for the Sizewell B case.[81]

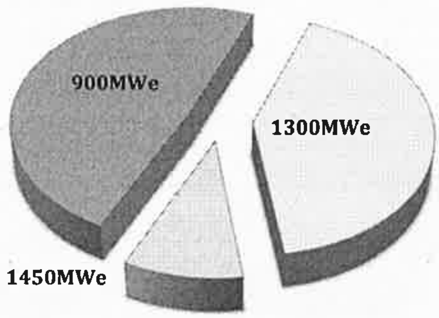
The Sizewell B response illustrates how not to approach technical qualification of an existing at-risk component. This is because it has not, particularly with the recent ASN acknowledgement that SG components are also at risk of positive macrosegregation, been irrefutably demonstrated to derive from a single, identifiable manufacturing route (for the FA3 at-risk components the large, conventional ingot instead of the LSD ingot).

Unreliable Test Ring Results: The existence of the FA3, RPV and other N1 components in operating NPPs and, possibly, SG at-risk components, together with lack of confidence shown in the recent Sizewell B re-evaluation, strongly suggest that dependence upon the forging sacrificial test ring for material analysis and testing is unreliable – indeed, for the FA3 at-risk components the test ring material was drawn from the peripheral parts of the upset forged plate that was furthest from the centre-plate zone of positive macrosegregation.

Clearly, for the FA3 and, quite possibly, earlier Creusot-sourced components there was need for supernumerary components for the process of obtaining a satisfactory QT although, that said, the uncertainties in matching a true replicate to the production component would have been and remains challenging.

Accordingly, it would be prudent to review all forged components from Creusot (including the SG flaws) that have been overly reliant upon the test ring for material characterisation analysis and physical testing.

Summary of At-Risk NPPs Operating in France: Approximately 70-75% of the total French electricity generation capacity is provided by the nuclear power sector. The split of generating capacity across the different series of French PWR NPPs is:-



FRENCH NUCLEAR GENERATION CAPACITY BY REACTOR SERIES

The operating NPPs that presently have installed at-risk components, both defined as

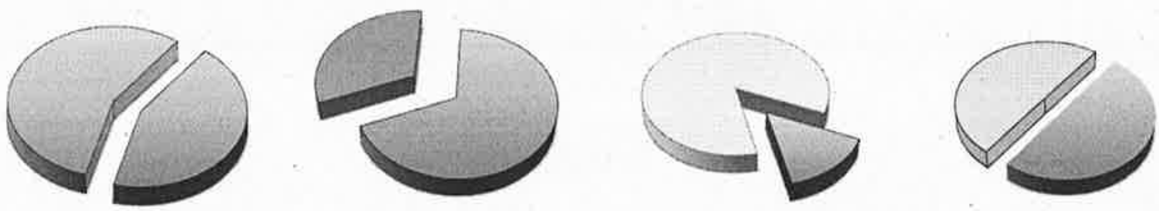
81 EdF Energy, *Sizewell B - Consideration of Reduced Toughness in the Upper and Lower Closure Heads*, EAN E/EAN/BBJB/0379/SZB/16, March 2016 – see Appendix 1 that outlines a further test and analysis programme to be undertaken by EdF Energy, although it is not clear if this has been completed or is still ongoing.

'irregularities' and steam generators identified by ASN, is as follows:

TABLE 6 AT-RISK OPERATING FRENCH NPPS [15,71]

NPP SERIES	NPP	ASN DEFINED IRREGULARITY	AT-RISK STEAM GENERATOR	UNIT MWE	FIRST COMMERCIAL OPERATION
900 MWe	Blayais 1-4	Unit 1, 3	Unit 1	910	81, 83, 83, 83
	Bugey 2-3	Unit 2, 3		910	79, 79
	Bugey 4-5	Unit 4	Unit 4	880	79, 80
	Chinon B1-4	Unit B1, B3	Unit B1, B2	905	84, 84, 87, 88
	Cruas 1-4			915	84, 85, 84, 85
	Dampierre 1-4	Unit 1, 3, 4	Unit 2, 3, 4	890	80, 81, 81, 81
	Fessenheim 1-2	Unit 1, 2	Unit 1, 2[82]	880	77, 78
	Gravelines B1-4		Unit 2, 4	910	80, 80, 81, 81
	Gravelines C5-6	Unit 3		910	85, 85
	Saint-Laurent B1-2	Unit B1, B2	Unit B1, B2	915	83, 83
	Tricastin 1-4	Unit 2, 3	Unit 1, 2, 3, 4	915	80, 80, 81, 81
1300 MWe[83]	Belleville 1 & 2			1310	88, 89
	Test 1-4	Unit 1		1300	87, 88, 91, 92
	Flamanville 1-2			1330	86, 87
	Golfech 1-2	Unit 2		1310	91, 94
	Nogent s/Seine 1-2			1310	88, 89
	Paluel 1-4	Unit 1		1330	85, 85, 86, 86
	Penly 1-2			1330	90, 92
	Saint-Alban 1-2			1335	86, 87
N4 – 1450 MWe	Chooz B1-2			1500	96, 99
	Civaux 1-2	Unit 2	Unit 1, 2	1495	99, 00

Inspection of TABLE 6 reveals of the total French nuclear generating capacity around 44% depends upon at-risk NPPs.[84] Similarly, of the various series of NPP types the 900MWe has about 68% of its generating capacity at-risk; the 1300MWe series is around 15% at-risk, and the N4 series has 50% of its generating capacity at-risk.



82 See [15] - on 17 July 2016 Fessenheim 2 had its operational licence suspended due of problems detected on one of the three steam generators. The Fessenheim 2 SG was a replacement SG manufactured at Creusot in or around 2008 – ASN has stated (e-mail 25 July 2016) that the problem is not with the bottom head component but relates to the lower shell forging. The totals of at-risk generating capacity drawn from TABLE 6 remain unchanged.

83 Potential macrosegregation problems with the series 1,300MWe NPPs are not included in TABLE 6.

84 The at-risk generated power capacity of TABLE 6 might best be described as a rough-and-ready estimation that takes no account of NPP availability, scheduled outages, etc.. Also, the possibility of the Cruas 3 and Chinon B3 NPPs having at-risk components (see TABLE 3) is not included in the appropriate totals.

The breadth and resource demands of the inspection and possible remedial programme required for the greater number of French operating NPPs is identified by TABLE 6. Until ASN provide further details, the timing, cost and potential loss of generating capacity arising from this countrywide remedial programme is open to speculation.

However, it might be reasonably assumed that EdF's human and equipment resource limitations will necessitate the inspection and assessment programmes being staggered over the pre-scheduled refuelling and/or maintenance outage programmes for individual NPPs. Judging from the number of NPPs involved such a staggered approach might be expected to take several years to complete.

If the individual NPPs continue at power until their allotted inspection date, etc, then the public will have to live with and tolerate an unspecified measure of increased risk of accident arising from failure of the installed at-risk components. On 26 April 2016, ASN charged EdF and AREVA jointly that *'as soon as possible'* they were to provide *'assessment of the consequences for the safety of the facilities'* although, to date, some four months later, nothing in this respect has been forthcoming.[85]

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85 In a Press Release of 9 September 2016 EdF referred to a *Complementary Safety Report* being submitted to SSN on 11 August, 2016 that identified 7 new findings over its *Interim Report* of 11 July, 2016 – the latter of these EdF reports is not publicly available - the first is a published, somewhat guardedly composed press release of limited information value.

APPENDIX I

CHRONOLOGY OF EVENTS AND ACTIONS RELATING TO FLAMANVILLE 3 CREUSOT-SOURCED AT-RISK COMPONENTS[86]

DATE	ACTION-EVENT	REF	DOCUMENT SOURCE
12 December 2005	ASN issues ESPN	25	*Équipements Sous Pression Nucléaire* – ESPN Order of 12th December 2005 for Nuclear Pressurised Equipment (ESPN) FR (24FF4V)
September 2006	Areva acquires Creusot Forge	4	
September 2006 & January 2007	Casting forged upper and lower heads for Flamanville 3		
2 April 2007	ASN email to AREVA expressing *'situation préoccupante'*	28	Email ASN to AREVA, 2 April 2007.
16 April 2007	ASN email to AREVA on failure to complete QT before manufacture		
December 2007	Construction works commence at Flamanville Manche for FA3 NPP		
16 July 2007	ASN states TQ should be prepared and approved prior to manufacture of fisrt component	56	Letter, ASN to AREVA, *Projet Flamanville 3. Qualification technique des 42ucléaire42 de fabrication.*, 16 July 2007
19 February 2008	ASN rules on QT required in addition to M140 of RCC-M	55	ASN email to AREVA 19 February 2008, ACS/MFG-dép-DEP- 0083-2008 ASN-2008-09048 *'relatif au 42ucléai dans le processus de QT des GV/RO'*.
July 2009	NRC report and violation notices to AREVA on non conformity	61-67-68	NRC, Report N° 99901381/2009-2010, July 2009
November 2011	Qualifying ESPN		
14 March 2012	1st hydro test on RPV		
July 2012	Proposal for additional testing on UA cap		
8 September 2012	ASN Guideline 8 on conformity assessment of pressure equipment	51	ASN, *Conformity Assessment of Nuclear Pressure Equipment*, French Nuclear Safety Authority Guideline 8, September 2012
February 2013	ASN published Guideline 19 on application of ESPN	53	Application of the French Order dated 12/12/2005 on Nuclear Pressure Equipment, Guide N° 19, February 2013
26 July 2013	2nd in-situ hydro test		
January 2014	RPV installed in reactor pit at FA3		
March 2014	ONR comments to ASN on TQ	65	NNB GenCo: Hinkley Point C Pre-Construction Safety Report 2012, Assessment Report: ONR-CNRP-AR-13-074, Revision 0, Version 2,14 March 2014 – *Assessment Report for Work Stream B17: Structural Integrity*. However, judging from the November 2014
September 2014	Non-Conformity mechanical tests to ESPN on UA cap		
November 2014	UK ONR reports acceptancd of Creusot manufacturing route	62	ONR, *GDA First Project Convergence Point at Hinkley Point C – Summary Progress Report for the Design and Safety Case Cornerstone* ONR-CNRP-PR-14-034, November 2014
c. December 2014	Anomaly detected on upper and lower heads of FA3		

86 *Anomalies dans les dossiers de suivi de fabrication au Creusot Présentation*, HCTISN, 30 Juin 2016

March 2015	Detection of malfunctions in the tensile tests made between 2009 and 2014		
3 April 2015	IRSN reporting on manufacturing route at Creusot	27	IRSN, *Réacteur EPR Ftamanville 3 Qualification technique des calottes du couvercle et du corps de la cuve du réacteur, Pole Surete Des Installations Et Des Systémes Nucléaires*, 3 April 2015
7/8 April 2015	ASN Note d'information: Technical clarifications concerning the manufacturing anomalies on the Flamanville EPR reactor pressure vessel	18	*Communiqué de presse de l'ASN du 7 avril 2015 sur les anomalies de fabrication de la cuve de l'EPR de Flamanville*
31 July 2015	ASN reveals caron anomaly of FA3 components		ASN, *Background to the discovery of the anomaly affecting the Flamanville EPR reactor vessel (excessively high carbon content in the vessel closure head and vessel bottom head)*, 31 July 2015
May-September 2015	Audit Lloyd's Register		
30 September 2015	Report of the Advisory Committee of Experts for Nucxlear Pressure Equipment	8	*Report to the Advisory Committee of Experts for Nuclear Pressure Equipment CODEP*-DEP-2015-037971 IRSN Report /2015-00010 Public Version, Session of 30 September 2015
October 2015	AREVA instructed to Lloyds Register submittred to ASN		
19 October 2015	ASN Note d'information: ASN convenes Advisory Committee on FA3 components		ASN, *ASN convened the Advisory Committee concerning the anomaly affecting the Flamanville EPR reactor vessel*, 19 October 2015
November 2015	Highlight new malfunctions in the tensile tests between 2005 and 2014 and Discover generic defects in primary pump components		
December 2015	Launch of the Action Plan Quality Plants Division Manufacturing, including Action 5: Verification Mission of the conformity of production and Action 6: 2nd phase of the audit Lloyd 's Register		ASN to AREVA, *Evaluation de la conformité de la cuve de l'EPR de Flamanville 3 Démarche de justification de la ténacité suffisante des calottes du fond et du couvercle de la cuve*, 14 December 2015
14 December 2015	ASN suggest tp AREVA that to consider all options, including replacingthe FA3 upper and lower heads	12	Email ASN to AREVA, 14 December 2015 – Under
17 December 2015	ASN Note d'information: ASN requires new test programme for FA3 components		ASN. *Flamanville 3 EPR: ASN has no objection to the initiation of a new test programme*, 17 December 2015
March 2016	Identification of records with *'irregularities'* from Le Creusot		
March 2016	EdF Energy Advice Note on Sizewell B NPP	40	EdF Energy, Engineering Advice Note, *Review of Sizewell B RPV Dome Forging Components Following Flamanville 3 EPR OPEX*, E/EAN/BBHB/0373/SZB/16, EdF Energy/Structural Integrity Branch/Materials Group, March 2016
March 2016	EdF Energy Advice Note on Sizewell B NPP	81	EdF Energy, *Sizewell B – Consideration of Reduced Toughness in the Upper and Lower Closure Heads*, EAN E/EAN/BBJB/0379/SZB/16, March 2016
21 March 2016	ASN meeting with HCTISN	60	*Note en vue de la 43ucléai du 23 mars 2016 du groupe de suivi du HCTISN portant sur l'anomalie de la cuve de Flamanville 3*, 21 March 2016

April 2016	EdF Energy on Creusot sourced components for Sizewell B	64	EdF Energy, *Implications for Sizewell B from the Flamanville 3 Reactor Pressure Vessel Manufacturing Issues*, DAO/EAN/JIDB/065/SZB/16, April 2016
25 April 2016	EREVA informs ASN of irregularities in files at Creusot		
4 May 2016	ASN Note d'information: ASN considers AREVA's April 2015 Review to be *superficial*		ASN, *AREVA has informed ASN of irregularities concerning components manufactured in its Creusot Forge plant*, 4 May 2016
9 May 2016	ASN refers to i) pressuriser top dome material tests of December 2008 to FA3 pressuriser compared to test results of Olkiluoto 3 pressuriser, revealing notable differences between the two; and ii) the scrapping of 3 or 4 replacemenrt completed ateam generators	59	*Objet : Contrôle de la fabrication des équipements sous pression nucléaires (ESPN), Thème Conformité des matériaux entrant dans la fabrication des ESPN Codes INSSN-DEP-2016-0692 et INSSN-DEP-2016-0693*, 9 May 2016
20 May 2016	AREVA email response to EdF Energy of Sizewell B components		
June 2016	Non-compliance of steam generator bottom heads, top heads and tube plates reported by ASN		
13 June 2016	EdF issue statement listing NPPs affected by *'irregularities'*	15	EdF, *Défaut d'assurance qualité sur des dossiers de fabrication d'Areva pour des 44ucléaire44s du parc 44ucléaire d'EDF: pas de remise en cause de la sûreté, 13 June 2016*
14 June 2016	ONR review of Sizewell B	42	ONR, *Review of Sizewell B (SZB) Lifetime Records in relation to forgings manufactured by Creusot Forge*, ONR-OFP-CR-16-109 Revision 1, 14 June 2016
20 June 2016	ASN Note d'information: Interim briefing on *'irregularities'*		ASN, *Irregularities detected in Areva's Creusot Forge plant: ASN interim briefing*, 20 June 2016
23 June 2016	ASN presentation on at-risk steam generators with *'irregularities'* at risk components	71	ASN, *Certains générateurs de vapeur de réacteurs d'EdF pourraient 44ucléaire une anomalie similaire à celle de la cuve de l'EPR de Flamanville*, 23 June 2016
23 June 2016	ASN Note d'information: ASN lists affected NPPs		
23 June 2016	Nucleonics Week reports Fessenheim 6 steam generator suspension	46	Nucleonics Week, V 57, No 25, 23 June 2016
28 June 2016	ASN Note d'information: Steam Generators installed in 18 NPPs at-risk		**ASN,** *Certain EDF reactor steam generators in service could contain an anomaly similar to that affecting the Flamanville EPR vessel*, 28 June 2016
30 June 2016	HCTISN presentation on *'irregularities'* at Creusot	86	
30 June 2016	ASN deprioritises FA3 characterisation	69	ASN, *Irrégularités détectées chez AREVA Creusot Forge*, HCTISN, 30 Juin 2016
~17 July 2016	Operating licence for steam generator at Fessenheim 2 suspended whilst ASN awaits further justification from EdF-AREVA		
20 July 2016	ASN Note d'information: Fessenheim 2 SG certificate suspended		ASB, *ASN suspends the test certificate for a steam generator in the Fessenheim NPP affected by one of the irregularities detected in Areva's Creusot Forge plant*, 20 July 2016
5 August 2016	IRSN evaluates EdF reappraisal of SG manifold failure and reports to ASN that 'compensatory' measures are required on operational NPPs to avoid unacceptable risk of fuel melt incident.	80	Avis IRSN, 2016 2016-00275 *Objet : EDF – REP - Paliers CP0, CPY et N4 – Ségrégations en carbone des fonds primaires de générateurs de vapeur – Analyse de sûreté et mesures compensatoires*, 5 August 2016

16 August 2016	ASN confirms that the FA3 RPV components and the RPV assembly do not have a *Certificate of Conformity*	54	ASN to LargeAssociates, email 16 August 2016
9 September 2016	EdF issue Press Release stating that *Complimentary Safety Report* on in-service NPPs submitted to ASN of 11 August 2016	85	EdF, Note d'information, *Défaut d'assurance qualité sur des dossiers de fabrication d'Areva pour des 45ucléaire45s du parc 45ucléaire d'EDF : pas de remise en cause de la sûreté*, 9 Septembre 2016
12 September 2016	ASN admit that *"Since the end of 2015, three different cases of Counterfeit, Fraudulent and Substandard Items (CFSI) related to nuclear industry raised in France"*	78	ASN, *Recent Developments in Creusot Forge Manufacturing Issues*, 12 September 2016
12 September 2016	ASN notes that *"JCFC channel heads: first measurements tend to show higher C% than 0.30%"*	79	ASN, *Recent Developments in Creusot Forge Manufacturing Issues*, 12 September 2016

Appendix II

Requests for Further Information and Replies Received

Topic	Nº Items Requested	Recipient	Request Date	Answered	Reply Date
HCTISN Meeting Note of 23 March 2016	1	ASN	10 May	Referred to HCTISN	20 May
Technical notes and presentations	6	ASN	14 July	4 of 6 items answered awaiting EdF-AREVA clearance for 2 items	12 August
Relating to projected NPP outage dates and suspension of certificate for Fessenheim steam generator	4	ASN-HCTISN	20 July	All 4 items answered	25 July
Fessenheim 2 bottom head source and date of manufacture	2	ASN	22 July	All 2 items answered	25 July
Flamanville 3 Test Certificates and Certificate of Conformity	3	ASN	27 July	2 of 3 items answered	16 August
Clarification of the request of 27 July	-	ASN	31 July		
Correspondence cited in ASN chronology of events	26	ASN	6 August	6 of 26 items answered	12 August
ASN prioritisation of FA3 characterisation, HPS test data, Certificate of Conformity for replacement SGs	10	ASN	10 September		
EdF Press Release of 10 September submitted reports to ASN	2	ASN	13 September		
ASN-NRA Presentation of 12-13 September	12	ASN	15 September		
ASN Letter to EdF of 9 May	4	ASN	16 September		