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REVIEW

IRREGULARITIES AND ANOMALIES RELATING TO NUCLEAR REACTOR PRIMARY COOLANT CIRCUIT COMPONENTS INSTALLED IN JAPANESE NUCLEAR POWER PLANTS

PART I –FRENCH CARBON ANOMALY CORRELATION TO JAPANESE NUCLEAR POWER PLANTS

Client: **GREENPEACE JAPAN**

Ref No **R3235-R1**

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This Review comprises three Parts. This 1st Part draws upon the development of the carbon anomaly flaw found in different forged steel components installed throughout the French nuclear power industry; how it has and continues to affect NPPs and nuclear safety in France; and how it is valid indicator of similar difficulties that are now arising in Japan.

The 2nd Part is ongoing with requests for further and specific information to the French nuclear regulator ASN and Japanese Nuclear Regulatory Authority to determine how these separate regulatory regimes are dealing with this developing nuclear safety issue, particularly in Japan.

The 3rd and Final Part will be a wrap-up report endeavouring to put into context the NRA response to and its amelioration of the carbon anomaly and its nuclear safety implications in the Japanese nuclear power plants.

The English language version of this Review is the authoritative version.

1ST ISSUE	REV No	APPROVED	CURRENT ISSUE DATE
05 10 2016	R3235-R1		**24 OCTOBER 2016**

PART I – FRENCH CARBON ANOMALY CORRELATION TO JAPANESE NUCLEAR POWER PLANTS

SUMMARY

In late 2014, the French nuclear design and manufacturing company AREVA notified the nuclear safety regulator, *Autorité de Sûreté Nucléaire* (ASN), of the results of material tests carried out on a component manufactured at the Creusot Forge in France. 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 nuclear power plant (NPP).

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 positive macrosegregation present throughout most of the thickness of the equivalent head shell – this is the so-called *'carbon anomaly'* that leads to unacceptable weakness of the steel alloy to fast and catastrophic failure.

Following these revelations AREVA was ordered to review past practises involved in the manufacture of the components. To much consternation, this revealed that not only was quality assurance and component conformity unsatisfactory, particularly in that the manufacturing route for the components 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, some of which were installed in operational NPPs throughout France – ASN generally coined these uncertainties as *'irregularities'*.

With immediate effect, the single NPP operator across France, *Électricité de France SA* (EdF), was required to evaluate the nuclear safety of its operational NPPs. Upon receiving EdF's very preliminary safety assessments in June 2016, ASN deemed 12 NPPs to be at risk ordering that these plants be operated under strict precautionary conditions, later rescinding this to require that all 12 NPPs to shut down.

Japanese Sourced Steam Generator Components: A common feature of the 12 NPPs identified to be at risk by ASN was that each incorporated replacement steam generators (SGs) that included large, forged components manufactured in Japan by the Japan Casting and Forging Company (JCFC) and, possibly, the Japan Steel Works (JSW). These components, the *bottom channel head*, the *tubesheet* and the top *elliptical dome*, were all believed to contain zones of macrosegregation with, possibly, enhanced carbon content. EdF initially reported that its preliminary examination suggested a maximum excess carbon content of 0.3%, that is about 50% over the design specification of 0.22%. On this basis, independent adviser, *Institut de Radioprotection et de Süreté* (IRSN) reckoned that the risk of catastrophic failure and fuel melt could be mitigated if certain further additional conditions and 'compensatory' measures were implemented until a scheduled outage would enable further examination of the JCFC components.

JCFC Bottom Channel Head – Excess Carbon: The first NNPs to enter the scheduled refuelling outage for a more thorough examination were Tricastin 1 and 3. The early non-destructive inspection results for the JCFC *bottom channel heads* at these NPPs revealed an alarming 0.39% level of carbon present, almost 100% greater than the maximum permissible level that, with its associated reduction in material toughness, rendered the component very vulnerable to fast fracture. IRSN revised its analysis (18 October 2016) in account of this very high carbon content, advising ASN to order the shut down of ALL but one of the NPPs with JCFC SG components installed – this shut down is to remain enforced until EdF demonstrate that the individual NPPs are acceptably safe for return to powered service.

With the very high levels of carbon reported in the Tricastin 1 and 3 before return to powered service operation it is almost a certainty that the SGs affected, up to a total of six, will have to be cut out of the primary coolant and secondary steamside circuits, removed from the nuclear island containment, and returned to a specialised heavy engineering workshop for substantial repair or for scrapping and complete replacement. The processes of manhandling and transporting these large, 300 to 400 tonne SGs is challenging, expensive and very time consuming. To replace the SGs, time scales are likely to be at least one to two years or more, if that is SG spare manufacturing capacity is available, and a typical NPP 3 SG set replacement costs are in excess of €100 to €150 million for a NPP outage of around 40 to 60 days, although for the Tricastin NPPs, already out of service, the outage or lost generation costs would be considerably greater. Should the other 10 NPPs with JCFC SG components also exhibit unacceptably high levels of carbon, and there is no reason to believe otherwise, then the time scales and costs to rectify will escalate, especially if new SG manufacturing capacity cannot be found to repair and/or replace a total of 37 individual SGs required for the 12 NPPs involved.

Japanese Nuclear Equipment Supply Chain: This Review examines the likelihood that the failure of JCFC and, possibly, JSW to provide code-compliant components into the French nuclear equipment supply chain has been mirrored in the Japanese nuclear supply chain - the reasons for this are severalfold:-

JCFC-Sourced Components: First and foremost, the undisputable fact is that during the period 1995 through to 2006, or thereabouts, JCFC supplied a number of flawed and under specification SG components into the French nuclear equipment supply chain. This demonstrates that, somehow, under-specification parts in heterogeneity and below par material characteristics have passed through the quality assurance controls of JCFC's manufacturing facilities in Japan. These quality controls, physical characteristics and safeguards would have been contractually specified by the customer, either AREVA and/or EdF, and formally approved by the French nuclear safety regulator ASN.

Also, the French regulatory framework remained unchanged throughout almost all of the period (1995 to 2006) that JCFC-sourced components were entering the French nuclear equipment supply chain, so it is most unlikely that AREVA would have had reason to change the component specification – it was only in the last year (in December 2005) that strengthening of the heterogeneity restraints was introduced and, even then, this was not strictly enforced by ASN until 2008, that is well after the JCFC supply to France contract had ceased.

The irrefutable fact is that under-specification JCFC components entered the French supply chain without immediate detection strongly suggests that the accompanying QT records did not comprehensively and correctly reflect the quality and material characteristics of the SG bottom channel heads. The very same QT records would have originated in the JCFC manufacturing facility and so must have also passed through JCFC's own quality assurance checks undetected.

Prior to commencing the French supply contract, during the period 1984 through 1993, JCFC supplied similar SG bottom channel head components for the Japanese NPPs at Takahama 3 and 4, Sendai 2, Tsuruga 2 and Tomari 1 and 2. Contrary to NRA's assertion that no forged SG components were manufactured in Japan, the terminology of the NPP operator's returns identifying the manufacturer and manufacturing route strongly suggests that these SG components were upset forged and, hence, at much the same risk of unacceptably levels of heterogeneity as the French counterparts.

It follows, that JCFC components similar to those supplied to the French, produced to similar standards and safeguards, would have also had opportunity to slip through any quality assurance control point operated by JCFC. Moreover, there is nothing to suggest that the Japanese regulator at the time (1984 to 1993), being the somewhat unwieldy Nuclear Safety Commission, together with its cohort the Industrial Safety Agency (NISA), was any more efficacious than the more organisationally streamlined French counterpart ASN. Indeed, there are anecdotal claims made in later years that much to the contrary applied to both the Nuclear Safety Commission and NISA, via so-called regulatory capture.

JSW-Sourced Components: There is some ambiguity about the supply of SG components to the French supply chain. These components, the SG elliptical domes and tubesheets, have also been identified by ASN to have heterogeneity in the form of positive macrosegregation and, hence, elevated risk of vulnerability to fast fracture because of reduced material toughness – AREVA has tested replica samples of tubesheet and elliptical dome, both yielding below specification results but at this time there is no information directly sourcing the replica to JSW or the French forge le Creusot.

JCFC-JSW-KSC RPV and other Components: NRA's assertions underlying its claim that *"the risk seems small"* with respect to Japanese forged and hot-formed components being flawed with macrosegregation zones are, with respect, not convincing. For example, it claims the risk is small because "*Quality control in forging process have been managed appropriately and the manufacturing records endorse the quality".*

This, surely, overlooks the established fact that the present ongoing examination of the 37 bottom channel heads supplied by JCFC to the French is now revealing astonishingly high levels (0.39% over a specified maximum of 0.22%) of excess carbon – either the original manufacturing records (which include test results and other material indicators) were never inspected by the JCFC quality control inspectors before despatch from the JCFC works, and/or these records did not comprehensively and correctly describe the quality of the components. Such a serious breach of the safeguards set down to ensure quality and consistency of nuclear safety critical components, be it by negligence or otherwise, should not be dismissed so lightly.

Similarly, for the components hot-formed from externally-source steel plate NRA seems to assume that 'strand' cast steel slabs are intrinsically free of segregate formation, whereas centreline macrosegregation and cracking is a commonly acknowledged production uncertainty at steel mills.

In its presentation of 13 September 2016 NRA refers to the Japanese standards specifying the physical, metallurgical and quality of components – these being *target* criteria that the components have to satisfy to enter the Japanese nuclear equipment supply chain. It does not, however, provide the *actual* material characteristics attained in the production of these components but, because of the seriousness of the situation in France relating to similar but substandard Japanese manufactured components, it is imperative that the actual physical and quality characteristics (ie the original test and analysis records) be examined afresh.

Findings: The Review issues a number of FINDINGS specifically addressing the issues raised in France could quite possible apply to the Japanese nuclear equipment supply chain for each of three categories of components, comprising the JCFC-sourced SG bottom channel heads; the SG tubesheets and elliptical domes possibly sourced from JSW, and, more generally, the forgings making up both PWR and BWR RPVs and, for the PWRs, the pressuriser.

JCFC PWR Bottom Channel Head: Essentially, that further clarification is required on the terms and consistency of usage by the Japanese NPP operators in reporting back the manufacturing route for these SG components although, that said, circumstantial factors strongly suggest that the bottom channel heads were upset forged like those known to have entered the French supply chain. Because of this possibility and particularly since the JCFC QT records somehow allowed the flawed French components to despatch from JCFC's works without detection, it is recommended that all of these Japanese NPP installed components be non-destructively examined (NDE) in situ.

JSW PWR Tubesheets and Elliptical Domes: These components have not been specifically identified in the NPP operator returns, which is especially surprising for the tubesheet which forms part of the pressurised boundary of the reactor primary coolant circuit – further information on the manufacturing routes for both tubesheet and elliptical dome should be reported.

A means of accessing the tubesheet top surface (where the AREVA exploratory tests found excess carbon) for NDE will have to be developed and demonstrated to be viable. If this is not possible, then it should be practicable to cut out a tubesheet from a NPP reaching the stage at which SG replacement is deemed necessary but, for this option, the risk of continuing to operate the NPP until a ready-to-be-replaced SG becomes available will have to be justified.

PWR and BWR RPV etc Forged and Hot-Formed Plate Components: Further information is required on the QT records for each of these components, particularly for the ingot cropping and discard stages The recent French experience with the Flamanville 3 EPR RPV lower and higher head components implies that the presence of macrosegregation zones was not actively sought at any of the stages following ingot cropping and discard operations, the fallacious assumption being that all positive macrosegregated had been removed along with the discard.

The QT records for all dome shells (ie RPV heads and similar) should be scrutinised for over-reliance upon test ring results which has discredited by EdF, being unrepresentative of the main body of the component because of its relative peripheral remoteness from typical localities of macrosegregation. For those components manufactured by hot-forming of steel plate the mill records for the strand or continuously cast plate should be checked for the presence of centreline macrosegregation and cracking.

Protection of the Japanese Nuclear Equipment Supply Chain: In France the presence of flawed components has attracted considerable regulatory attention because, first and foremost, there are potential severe nuclear safety issues involved and, second, it has exposed a regulatory loophole.

The flawed JCFC SG bottom channel heads so far identified in France serve a *Class 1* function in the reactor primary coolant circuit and, being *break-precluded* items, catastrophic failure by fast fracture cannot be permitted because the potential off-site radiological consequences could be intolerably severe. The flawed tubesheets, possibly supplied by JSW, are likewise identified to be in the French nuclear equipment supply chain, also serve a *Class 1* function and tubesheet failure could also lead to a significant radiological release to and consequences the public domain.

The regulatory loophole exposed the flawed JCFC components is that somehow these components been accepted into the French supply chain. To do this the flawed components also had to someway slip the through the quality assurance controls and safeguards of the JCFC works.

In other words this composite, that has resulted in the French failure, includes two elements that are entirely founded in Japan, these being i) that the defective components were wholly manufactured in Japan and ii) that the quality control safeguards that should have prevented the flawed components leaving the place of manufacture failed. The final barrier preventing entry into the Japanese nuclear equipment supply chain is iii) the Japanese regulatory system as previously administered by the much discredited Nuclear Safety Commission and NISA - in France this final regulatory barrier also failed.

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ABBREVIATIONS, ACRONYMS AND TERMINOLOGY

ACENPE	Advisory Committee of Experts for Nuclear Pressure Equipment
AREVA	French state owned company specialising in nuclear equipment and plant
ASME	American Society of Mechanical Engineers
ASN	*Autorité de Sûreté Nucléaire* – Nuclear Safety Authority
bottom channel head	A component of the SG, being to lowermost cap or bottom head of the SG which connects to the reactor primary circuit.
BPVC	ASME Boiler and Pressure Vessel Code
break precluded	Typically in a nuclear safety case the main pressurised components of the reactor primary coolant circuit are considered to be break precluded meaning that each would not be expected to catastrophically fail under all reasonably credible situations – these components include the RPV, the SG tubesheet and bottom head, pressuriser and main pipework,
BWR	Boiling Water Reactor.
C%	The percentage (by weight) of carbon present in a steel alloy – typical C% for Class 1 and/or N1 components in the primary coolant circuit is no greater than 0.22%.
carbon anomaly	the term coined by ASN to described the excess carbon found in the microstructure in a steel alloy as a result of the formation of zones of positive macrosegregates.
Certificate of Conformity	A certificate granted by ASN as part of the ESPN quality control measures.
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.
Class 1	The Japanese nuclear regulatory design and procurement codes for nuclear plant specify all components in the reactor primary coolant circuit to be Class 1 – equivalent to N1 in the French RCC-M code.
CP0, CP1, CP2	Variants of the 900MWe series of French PWR NPPs
CPGFO	JSME Committee on Power Generation Facility Code
DEP	*French Directorate for Nuclear Pressure Vessels*
discard	In the forging process the discard is the cropped portion that is discarded to remove from the bloomed billet any undesirable impurities, tec
EDF	Électricité de France S.A – French stated owned power company
elliptical dome	A component of the SG, being to uppermost cap of the SG which connects to the steamside circuit.
EPR	European Pressurised Reactor
ESPN	*Équipements Sous Pression Nucléaire* – ESPN Order of 12th December 2005 for Nuclear Pressurised Equipment (ESPN) FR (24FF4V)
FA3	The EPR NPP presently under construction at Flamanville on the north Atlantic coast of France.
forging ratio	The excess volume of an ingot being prepared or bloomed that enables undesirable sections of the billet to be cropped and discarded.
HCTISN	*Le Haut Comité pour la transparence et l'information sur la sécurité nucléaire* – High Committee for Transparency and Information on Nuclear Security
irregularities	Term coined by ASN to "*comprise inconsistencies, modifications or omissions in the production files, concerning manufacturing parameters and test results".*
IRSN	*Institut de Radioprotection et de Süreté*
J	Joule – a derived unit of energy – 1 newton meter (N-m) = 1J
JCFC	Japanese Casting and Forging Corporation
JFESC	Japanese JFE Steel Corporation previously Kawasaki Steel Corporation (KSC)
JNES	Japan Nuclear Energy Organisation – now defunct
JSME	Japan Society of Mechanical Engineers
JSW	Japan Steel Works
lower head	The lowermost component of the RPV, in the shape of a half spherical forging that is welded into the RPV assemblage
LSD	*Lingot a Solidification Dirigée* – a casting technique for ingots at Creusot Forge
macrosegregation zone	A volumetric area of the forging where the cooling process has resulted in alloying constituents, such as carbon, to coagulate at a microlevel in excess – ie positive macrosegregation – or diminish – ie negative macrosegregation

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 1450MW_e French PWR NPPs
NDI	Non-Destructive Inspection (or Examination)
NISA	Nuclear and Industry Safety Agency – now defunct
NPP	Nuclear Power Plant
NRA	The Japanese Nuclear Regulatory Authority
NRC	Nuclear Regulatory Commission – the United States nuclear safety regulator
Olkiluoto 3	An EPR NPP presently under construction at Olkiluoto Finland
ONR	Office for Nuclear Regulation – the UK nuclear safety authority
OES	Optical Emission Spectrometry
PCSR	Pre-Construction 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. The United States adopts ASME, France the RCC-M and Japan ASME and the domestic JSME – Japanese Society of Mechanical Engineers.
RPV	Reactor Pressure Vessel
RT_{NDT}	Ductility transition reference temperature
SG	Steam Generator
steamside	The steamside is the separate steam condensate circuit the feeds to and powers the turbo-alternators – steam is raised ion the steamside by routing the condensate through the SG on the outer side of the primary circuit tube bundle.
strand casting	Strand or continuous casting is where molten steel is continuously cast into a strand that is solidified under controlled conditions by water cooled pressure rollers.
Taishan 1 and 2	Two EPR NPP presently under construction at Taishan, China
tubesheet	The large dividing steel plate in a steam generator that separates the reactor primary cooling circuit from the steamside circuit that operates at lower pressure – the tubesheet is drilled with several thousand holes into which the individual steam generator tubing return loop is peened.
upper head	The topmost or lid component of the RPV
upset forging	Passing the billet under parallel plates at high pressure to plastically deform the billet

IRREGULARITIES AND ANOMALIES RELATING TO THE FORGED COMPONENTS IN JAPAN

THE CARBON ANOMALY - CHRONOLOGY

In mid 2015 the French nuclear safety regulator *Autorité de Sûreté Nucléaire* (ASN) announced[1] that it had been notified by the national nuclear power plant (NPP) operator *Électricité de France* (EdF) of a materials flaw in the steel alloy of reactor pressure vessel (RPV) of the Flamanville 3 (FA3)[1, 2] presently under construction on the north-west Atlantic coast of France. Later in 2015 and throughout 2016 ASN made public further details not only about the FA3 RPV but that similar defects and irregularities had originated from the AREVA's main heavy forging works le Creusot Forge and were presently installed in a number of French operational NPPs.

Detailed inspection of the French operational NPPs also revealed that a significant number of replacement steam generator (SG) components manufactured by Japanese sources had also entered the French nuclear supply chain during the period 1995 through to 2006. Certain of these components, particularly those sourced from the *Japan Casting and Forging Company* (JCFC) and, possibly, the *Japan Steel Works* (JSW) also included a metallurgical flaw referred to as the *carbon anomaly*.[3]

Mindful, it is assumed, that similarly flawed components might be present in the Japanese nuclear supply chain, in or around July-August 2016 ASN notified the Japanese *Nuclear Regulatory Authority* (NRA) of the situation in France. NRA reacted to the potential presence of similarly flawed parts installed in Japanese NPPs by issuing, on 24 August, a guidance[4] to Japanese NPP operators that, first, each was to report back by 2 September the manufacturing source and manufacturing route (methods) of all *Class 1* components within the pressurised primary coolant circuit. Following a further statement by ASN of 28 September, on 29 September NRA issued a second requirement for Japanese NPP operators to carry out inspections of all primary pressure circuit equipment installed in Japanese NPPs that contained forged components - each operator being mandated to report back to NRA, by 31 October 2016, the evaluated risks of all forged parts and components installed in Japanese NPPs that may potentially include zones of carbon anomaly.

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 Peninsula 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 carbon anomaly is where, during the molten casting process of the steel ingot prior to forging, there arises an accumulation of excess carbon in the granular boundaries of the alloy. Unless eliminated during the forging processes by cropping and discarding, the zone of segregates (referred to as macrosegregation) might have a surface spread from several centimetres to a meter or more on the final forged component, being present in the depth of the shell thickness. For components serving in the pressurised reactor primary cooling circuit, typically the steel is alloyed with around 0.2% carbon to achieve the optimum balance between elongation strength, ductility and toughness. Positive macrosegregation will give rise to an increase in the micro-distribution of carbon up to and possibly in excess of 0.3% that, although improving elongation strength, results in a reduction in material toughness rendering the pressurised component prone to abrupt fracture, particularly under conditions of thermal shock.

4 NRA, Instructions *from NRA to Power Companies*, 24 August 2016 – unauthorized translation

DISCOVERY OF THE CARBON ANOMALY AND IRREGULARITIES IN FRANCE

Recounting the French experience to date provides a useful insight into the discovery of carbon anomaly and how this may affect Japanese NPPs if and when, that is, such resume power operation following the enforced outages since the Fukushima Daiichi nuclear catastrophe.

Referred to as a *'carbon anomaly'*, the aberration in the FA3 RPV was found by chemical analyses and physical testing of two replica components, these being the separate upper head or lid, and the lower head or dome forged component that closes the RPV.[5] These component forgings were manufactured at the AREVA Creusot Forge in or about 2006-2007 and the larger, annular ring components, beyond the ingot tonnage capacity of Creusot, were forged in Japan by the Japan Steel Works (JSW).

The preliminary findings of the FA3 testing and evaluation programme strongly pointed to faults and inconsistencies in the manufacturing processes deployed at the Creusot Forge, particularly in the casting and subsequent upset forging from a single, top-cast ingot.[6] This process was known to give rise to heterogeneity of the steel alloy in the form of localised positive macrosegregated zones of excess carbon content, usually located at the top end of the cast ingot or billet but which could be effectively managed by cropping and discarding the affected section of macrosegregation. However, if the discard amount was not fully effective then subsequent hot working to form the component shell retained the excess carbon zone as shown typically by FIGURE 2.

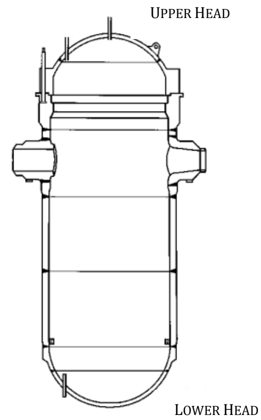

FIGURE 2 - EPR RPV SHELL

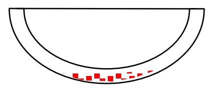

FIGURE 2 LOWER HEAD SHELL

HIGH CARBON ZONE

The next development in France occurred when AREVA was instructed 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 about 400 components with 50 of these being currently installed at French operational nuclear power plants. In response, ASN served notice on AREVA requiring its assessment of the consequences for the safety of those French operational NPPs that had installed components containing the i) *carbon anomaly* and/or subject to ii) *irregularities.*

This root and branch assessment required AREVA to examine all forged N1 [7] components installed in French operational NPPs, irrespective of component type and the source of manufacture. In ordering this assessment it must have been recognised at the time that not only was there a fundamental weakness in the Creusot manufacturing route, that was common across a number of different components and had existed for several past decades, but also the in- and post-manufacture inspection and quality control regimes had and were continuing to fail to detect what now transpires to have been manifestly obvious flaws in the final component parts.

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5 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.

6 For further details of the FA3 defects and the Creusot manufacturing route see LargeAssociates, *Review Irregularities and Anomalies Relating to the Forged Components of Le Creusot Forge*, Greenpeace France, 29 September 2016

7 French RCC-M code *N1* components are equivalent to *Class 1* Components of the Japanese *NRA Ordinance on Technical Standards for Commercial Power Reactor Facilities, Article 17*

Moreover, this very same manufacturing route had been used by Creusot Forge for the production of other forged components of the pressurised primary coolant circuits for earlier French and overseas NPPs, including the pressuriser, valve bodies, and three crucial components of the steam generators (SG).

Under the French engineering design code (RCC-M) these are classified as N1 components of the pressurised primary coolant circuit and include the complete RPV welded assemblage {1}, steam generator upper and bottom channel heads, tubesheets and elliptical top domes {2}, main pump bodies {3}, and pressuriser {4}, as shown by FIGURE 3 for a 3-loop PWR NPP.

Also, a prerequisite of the French regulatory system is that the manufacturing route, including the place of manufacture, for each N1 component type has to conform to the French regulatory regime – this conformity is assessed and approved via certification conducted by ASN,[8] and applies equally to overseas sources of N1 components, such as JCFC and JSW, both of whom would have been subject to visits and scrutiny by ASN and/or its agency the *French Directorate for Nuclear Pressure Vessels* (DEP).

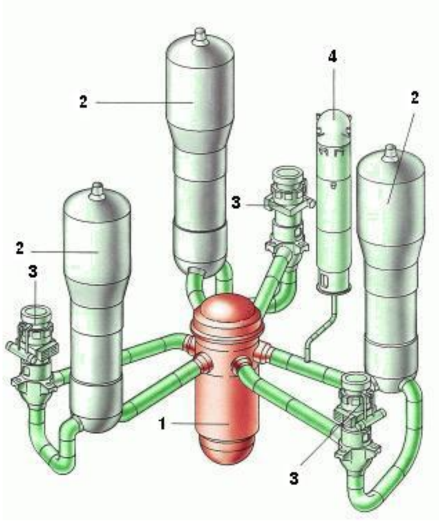

FIGURE 3 REACTOR N1 PRIMARY COOLANT CIRCUIT TYPICAL OF 3-LOOP 900 MWe SERIES

CARBON ANOMALY AND IRREGULARITIES IN STEAM GENERATOR COMPONENTS

FIGURE 4 STEAM GENERATOR

When AREVA reported its assessment, around May 2016, a number incidences of excess carbon content in steam generator (SG) components began to emerge.[9] These components included the *elliptical dome* and *annular rings* or *shells* serving the steamside circuit and, of particular concern, the *tubesheet* and torispherical *bottom channel head*. The tubesheet and bottom channel head components form part of the reactor primary cooling circuit boundary and, for the overall nuclear safety case, are considered to be *'break precluded'* components.

In July 2016, a total of 18 NPP primary coolant circuits drawn from both the 900MWe and 1,450MWe series of French PWR NPPs were identified to be potentially at risk because of the presence of macrosegregation zones of excess carbon in certain of the installed component parts – the SG forged components were sourced either from Creusot, the UK Sheffield Forgemasters and/or Japanese forges. Of the Japanese sourcing, the SG *bottom channel head* components were manufactured by the JCFC with the *tubesheets* and *elliptical domes* possibly sourced from the JSW.[10]

From test results obtained from AREVA (see APPENDICES I, II and III) the macrosegregation zones are present in the

i) central, top area of the tubesheet;

ii) outlet port of the elliptical dome; and

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8 The present (post 2005) requirement is the issue of a Certificate of Conformity by ASN under the *Équipements Sous Pression Nucléaire* – ESPN Order of 12th December 2005 for Nuclear Pressurised Equipment (ESPN) FR (24FF4V)

9 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.

10 ASN, *Major Positive Residual Carbon Segregation Forged Components of EDF's Operating Fleet*, (in French - *Ségrégations majeures positives résiduelles du Carbone Composants forgés du parc en exploitation d'EDF*) 24 juin 2016) 24 June 2016

iii) the monobloc bottom channel head.

FIGURE 5 shows a cross-section through a SG bottom channel head replicate with highlighted locations from which samples have been extracted for chemical and destructive physical testing with this particular SG test blank being Creusot-sourced. Reported by AREVA in May 2016, the Charpy material toughness results (a first measure of material toughness) for each of three tests and the average, taken across the shell wall thickness are:

TABLE 1 CHARPY IMPACT AVERAGE TOUGHNESS RESULTS AT 0ºC FOR SG SAMPLE§ – JOULES

LOCATION/DEPTH	**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

§ Appendix I reproduces the full AREVA test results of the summarised Table 1.

Referring to TABLE 1, to satisfy the design-basis of the French RCC-M design code, the minimum criterion for material toughness for any one and the average of the individual Charpy tests to be 60J and 80J[11] respectively, with 5 individual tests and one average failing to meet the RCC-M N1 criterion for material toughness.[12]

FIGURE 5A TUBESHEET

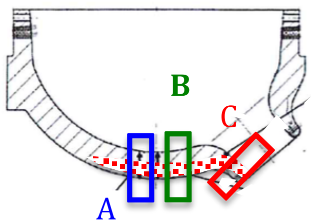

FIGURE 5B BOTTOM CHANNEL HEAD

Probably by portable spark optical emission spectrometry (OES) carried out on an NPP in situ SG, in mid-September 2016 ASN specifically referred to JCFC-sourced SG bottom channel heads in that *"first measurements tend to show higher C% {carbon} than 0.30%"*. It follows that the existence of a zone of excess carbon as high as, if not higher than 0.30% (over the 0.22% maximum content) would be accompanied by very significant reduction in the material toughness (ie the Charpy of TABLE 1). ASN also noted that the JCFC forged bottom channel head components were particularly prone to the presence of positive macrosegregation zones and particularly high (>0.32%) carbon excess.

However, IRSN later revealed[40] the excess carbon to be much higher, at 0.39%, in the bottom channel head ports of the SGs of the Tricastin 1 and 3 NPPs – this revelation of an extraordinary high level of excess carbon resulted in ordering the shutdown (18 October)

11 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. The equivalent Japanese code for Class 1 components sets the maximum carbon content at ≤0.25% (weight) and the Charpy absorbed energy at 0ºC ≥ 40J (average) 34J minimum.

12 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 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.

of all but one of the NPPs with SGs that included the JCFC-sourced bottom channel head component – see TABLE 4.

Recently (23 September 2016) ASN released further information[13] giving outline details of 83 *irregularities* identified by AREVA of which ~12% most likely related to positive macrosegregation carbon excess, although it is not possible to determine the degree of severity for each instance.

FIGURE 3 DRILLED TUBESHEET

The ASN list of 83 *irregularities* also refers to tubesheet components installed at a number of French operational NPPs. APPENDIX II shows the macrosegregation zone yielding enhanced carbon content of 0.26% in the central area of the top face – it is not known if this particular tubesheet taken from an unspecified 1300MWe series NPP was originally JSW-sourced or, which seems more likely, it is a replicate blank manufactured for testing purposes alone – in either case, the manufacturing source is not revealed by AREVA.[42]

ASN has also identified[10] the presence of macrosegregation zones (> 0.25% carbon) in the top (elliptical) domes of SGs supplied by Creusot and JSW. [9, 10] Testing of a replicate component (the manufacturing source of which is not revealed) yielded material toughness (Charpy) failures at one-quarter and one-half shell depth locations.[14] These components were installed in their parent replacement SGs during the period 1990 to 2000 for which French RCC-M M140 qualification was required.

In summary, Japanese-sourced components that have been manufactured and installed in i) the EPR NPPs presently under construction and ii) French operational NPPs are as follows (although subject to «ratification» awaited from ASN – see APPENDIX VI):

TABLE 2 JAPANESE-SOURCED COMPONENTS§ INSTALLED IN EPRS UNDER CONSTRUCTION («TENTATIVE»)

○ FLAMANVILLE 3 ⊙ OLKILUOTO 3 ✉ TAISHAN 1 ✉ TAISHAN 2

	REACTOR PRESSURE VESSEL			STEAM GENERATOR				
SOURCE	CLOSURE HEADS	ANNULAR RINGS	NOZZLE RING	ELLIPTICAL HEAD	SHELLS	TUBESHEET	CHANNEL HEAD	COMMENTS
JSW	⊙	○⊙✉	○⊙✉✉	○⊙	⊙○✉✉ 1	⊙○✉	⊙○✉✉	1 SG Conical shells only for Flamanville 3, Taishan 1 and 2
JCFC	-	-	-		«○»2			2 not conical shells

§ Omits other N1 forged components of the primary coolant circuit such as pressuriser, valve bodies, etc..

13 ASN Note d'information, *Areva NP's Creusot Forge Plant: ASN publishes the list of irregularities detected so far*, 23 September 2016

14 The elliptical dome test results were at one-quarter depth 41/53/21 and 36J average and at mid-depth 33/47/88 and 56J average set against the code requirement of ≥60J for any individual test and ≥80J for the average of three tests.

TABLE 3 JAPANESE-SOURCED COMPONENTS§ INSTALLED FRENCH OPERATIONAL NPPS («TENTATIVE»)

	REACTOR PRESSURE VESSEL			STEAM GENERATOR				
SOURCE	**CLOSURE HEADS**	**ANNULAR RINGS**	**NOZZLE RING**	**ELLIPTICAL HEAD**	**SHELLS**	**TUBESHEET**	**BOTTOM CHANNEL HEAD**	**COMMENTS**
JSW		«»	«»	YES excess carbon zone in top port & replicate fails Charpy test	«»	YES possibly excess carbon zone on and near to top	«YES[1]»	1 ASN claims JSW manufacturing route free of carbon macro-segregation issue.
JCFC		«»	«»	«»	«»	«»	YES[2] excess carbon zone in centre & replicate fails Charpy test	2 Excess Carbon believed to be extant on SGs in up to 12 NPPs – excess levels of 0.39% detected at Units 1 and 3 of Tricastin.
JFESC[3]		«»	«»	«»	«»	«»	«»	3 Kawasaki Steel Corporation (KSC)

In summary: Information on the types and sourcing of component installed in the pressurised primary circuit of French NPPs is incomplete, although there is clear evidence that Japanese-sourced components have been installed in French operational PWR NPPs. The distribution and sources of SG component parts is somewhat obscured because the SGs were most likely assembled in France being made up of components from various sources. Also, it is difficult to track the sourcing because the parties involved are not releasing further information into the public domain.

1) SG BOTTOM CHANNEL HEADS: It is clear that JCFC-sourced SG components, very certainly including the bottom channel head have been and continue to be in use in operational French NPPs – all except one of these NPPs was ordered to be shutdown on 18 October 2016. The supply date for each individual component is subject to awaited verification from ASN, although it is likely that the majority of the JCFC component SGs were installed between 1990 and 2006 in the sequence shown by TABLE 4.[15]

TABLE 4 FRENCH OPERATIONAL NPPS REPLACEMENT STEAM GENERATOR PROGRAMMES («TENTATIVE»)§

DAM1	BUG5	GRA1	DA3-SLB1	GRA2	TRI2	TRI1	GRA4	TRI3	FES1	SLB2	TRI4	DAM2	BUG4	«CHB1	DAM4	BLA1»	CIV 1
1990	93	94	95	96	97	98	00	01	02	03	04	05	06	07	08	09	UNKNOWN
			⊘⊘	⊘	⊘	⊘	⊘	⊘	⊘	⊘	⊘	▯	⊘	⊘	▯	▯	⊘
			JCFC- JCFC	JCFC	JCFC	JCFC	JCFC	JCFC	JCFC		JCFC		JCFC				JCFC
					☒		☒		☒		☒						☒

§ Years are the SG installation date in the NPP – the actual manufacturing completion year will be earlier by, say, a year or more

In TABLE 4 the NPPs shaded GREEN make up 14 of the 18 NPPs[16] subject to investigation by ASN – those appended JCFC include SGs incorporating the JCFC-

15 JSW are currently involved in supply of SG component parts – see ASN, *Contrôle de la fabrication des équipements sous pression nucléaires (ESPN) Thème : Inspection relative à la conformité des matériaux entrant dans la fabrication des ESPN Code : INSSN-DEP-2016-0697*, 30 septembre 2016

16 NPPs Chinon B2 and Civaux 1 and 2 are not shown in TABLE 4 – dates of the replacement SG installation is not readily available but most probably these SGs were replaced in or around 2010 or, later, from 2011 when a second programme of 32 AREVA procured SG replacements commenced in France.

sourced forged bottom channel heads – not included in TABLE 4 is Fessenheim 2 also fitted with a JCFC-sourced channel head, so a total of 12 NPPs containing JCFC-sourced bottom channel heads. All but one of the NNPs involved in this 2nd phase replacement SG programme are three-loop 900MWe series PWRs, with Civaux 1 which is a four-loop 1,450MWe PWR, thereby involving 37 JCFC bottom channel head components.

Of these 18 NPPs, ASN has cleared 4 (including Chinon B2 not shown) for return to unconditional power (▯); 6 (including 2 not shown) had been allowed to return to power but were subject to further investigation and evaluation (🛇) and, it is believed, *'compensatory'* measures necessary to mitigate the risk of a fuel melt incident; and 8 remained in enforced outage (🛇) whilst further examination and evaluation is undertaken by the operator EdF, added to which Fessenheim 2 is held over on enforced outage because of a separate SG component defect manufactured at Creusot.

However, on 18 October ASN ordered EdF to shutdown ☒ all of the plants that it previously permitted to operate conditionally whilst further investigations were undertaken (🛇), so now all of the French NPPs except St Laurent Unit 1 that have JCFC SG bottom channel heads installed are to be shutdown. The ASN letter of instruction to EdF,[17] when referring to the macrosegregation zones detected by ND examination of the JCFC SG bottom channel heads on Tricastin 1 and 3, notes that *'it cannot be excluded that other primary funds* {eg bottom channel heads} *from the same manufacturer have an even greater segregation'*, thus providing a measure of the potential seriousness of the situation for all NPPs fitted with JCFC SG components.[18]

2) TUBESHEETS: JSW supplied an unknown number of SG tubesheet components. It may be that the JSW-sourced tubesheet supply rate coincided with the sequence of TABLE 4 and/or the tubesheets are being introduced in the 2nd phase French replacement SG programme (from 2011). However, although ASN has acknowledged the presence of flawed tubesheets, and possibly that these are JSW sourced, it is not known if and in which NPPs these may have been installed.

3) OTHER COMPONENTS: The information for this Review mostly relates to the recent (2016) findings of ASN involving the components supplied by JCFC and JSW for the French 1st and possibly 2nd phases of the replacement SG programme outlined by TABLE 4 – these components are likely to include an unknown number of SG elliptical domes (top caps) sourced from JSW. It is not known if similar components are presently in production and/or awaiting delivery for the 2nd phase replacement SG programme currently underway.[16]

4) SUMMARY OF THE JAPANESE SOURCED COMPONENTS SUPPLIED TO FRANCE: It now acknowledged that there are three different types of SG forged steel components in the French nuclear supply chain, being present in a number of operational NPPs. Japanese-sourced components have also been supplied for the yet to be commissioned Flamanville 3 EPR, these include components of the RPV and the steam generators.

17 ASN, *Décision no 2016-DC-0572 de l'Autorité de sûreté nucléaire du 18 octobre 2016 prescrivant des contrôles et mesures sur le fond primaire de certains générateurs de vapeur de réacteurs électronucléaires exploités par Électricité de France* – Société Anonyme (EDF-SA), 18 October 2016

18 The latest information (21 October 2016) on the NPP shutdowns is that 7 NPPs are currently in enforced outage for inspection, these are Civaux 2, Dampierre 3, Gravelines 2, Tricastin 1, Tricastin 3, Saint-Laurent B2 and Bugey 4. Of the 5 reactors currently in operation, these are all to be shutdown in a phased programme of Tricastin 4 from 22 October, Fessenheim 1 from 10 December, Gravelines 4 from 17 December, Civaux 1 from 23 December and Tricastin 2 from 23 December. Any one of these NPPs will only be permitted to start pending a satisfactory SG safety case being presented by EdF.

TABLE 5 JAPANESE SOURCED FORGED COMPONENTS IN THE FRENCH SUPPLY CHAIN

FRENCH OPERATIONAL NPPs – MAINLY REPLACEMENT STEAM GENERATOR COMPONENTS			
COMPONENT	**SOURCE**	**APPLICATION**	**COMMENTS**
BOTTOM CHANNEL HEAD	JCFC	Replacement SG programme 1990 through to 2010	Confirmed – installed in up to 18 French 900MWe series NPPs,
TUBESHEETS	JSW	Possibly, in 1st and 2nd phase replacement SG programme	Awaiting confirmation from ASN – See APPENDIX VI – may have been installed in 1,300MWe series
ELLIPTICAL DOME	JSW	Possibly, replacement SG programme	Awaiting confirmation from ASN – See APPENDIX VI – may have been installed in 1,300MWe series
FRENCH FLAMANVILLE 3 EPR – REACTOR PRESSURE VESSEL AND STEAM GENERATORS[19]			
RPV HEAD FLANGE	JSW	RPV already assembled installed in reactor pit of secondary containment of nuclear island containment	
RPV NOZZLE-UPPER-LOWER SHELLS	JSW		
RPV TRANSITION RING	JSW		
SG ELLIPTICAL DOME	JSW	SGs GN321, 322, 323 and 324 already installed and connected into reactor primary coolant circuit	These components are the subject of 14 reported irregularities.[20]
SG TUBE SHEET	JSW		
SG BOTTOM CHANNEL HEAD	JSW		

It is irrefutable fact that flawed and non-compliant components manufactured by JCFC are presently installed in French operational NPPs. All of these NPPs, except St Laurent 1, are currently shut down or are to be shut down in enforced outage whilst further examination and investigation is undertaken.

Moreover, ASN's independent adviser IRSN has identified the unacceptable level of risk of a fuel core melt in certain circumstances following failure of a flawed JCFC manufactured bottom channel head,[21] strongly recommending that *'compensatory'* measures be immediately implemented to safeguard the NPP against such catastrophic failure. ASN has gone one step further than the IRSN advice to introduce *'compensatory'* measures for the continuing operation[21, 22] by, instead, shutting down all but one of the NPPs with JCFC SG components.

Several if not many[23] of these flawed JCFC components exhibit distinctive heterogeneity in the form of zones of positive macrosegregation, carbon excess and some have not been fully machined to the specified design.[29] In each of these respects the affected JCFC components are non-compliant with the French specification, design and procurement code. It follows that the QT records that accompanied these flawed JCFC components were either i) not inspected by the French authorities and/or ii) did not comprehensively record the quality of the individual components.

19 Tsuyoshi Nakamura, JSW, *Different Requirements of Codes for Manufacturing of Forgings*, 10 September 2009

20 ASN, *Liste des irrégularités détectées au sein de Creusot Forge*, 22 Septembre 2016

21 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

22 The IRSN recommendation of [21] was made in August 2016 when it was believed that the maximum excess carbon content in the SG bottom channel head components did not exceed 0.3% but once it learnt the level was 0.39% IRSN too recommended immediate shutdown of the affected NPPs.

23 The final numbers of flawed JCFC bottom channel heads has yet to be determined and disclosed by EdF and ASN.

There is nothing to suggest that French standards and requirements are in any way inferior and less demanding in quality assurance and control than the Japanese counterparts so, obviously, similarly flawed components produced from similar manufacturing routes adopted by JCFC could have entered the Japanese nuclear equipment supply chain during past years – this alone, puts those components, parts and assemblages containing JCFC products at a sufficient level of uncertainty to warrant further investigation.

5) FRENCH MANUFACTURING AND MATERIAL REQUIREMENTS: Primary coolant circuit components for installation in a French NPP have to comply with the French RCC-M code for N1 equipment.[24] Generally, prior to December 2005, the RCC-M subsection M140 for quality assurance of the manufacturing route was adopted. Post December 2005, and certainly by 2008 when an additional enforcement[25] was applied by ASN, M140 was effectively supplanted by additional compliance to the *Équipements Sous Pression Nucléaire* (ESPN) introducing a *Certification of Conformity* for the manufacturing route.[26]

   All N1 components manufactured in France and overseas for installation in France have to demonstrate compliance ASN's quality control and assurance requirements before the component can enter the nuclear supply chain – this involves on-site inspection by ASN and/or its agency *French Directorate for Nuclear Pressure Vessels* (DEP) and, post December 2005, issue of the *Certificate of Conformity*. Present French practice holds the supplier[27] to the prerequisite of submitting to ASN-DEP for assessment of conformity **before** the (first or prototype) component is manufactured.[28]

6) CARBON ANOMALY PRESENCE IN JCFC- AND JSW-SOURCED COMPONENTS: Excess carbon content, via positive macrosegregation, has been acknowledged to be present in SG bottom channel head, tubesheet and elliptical dome components. Of these:-

   a) **JCFC Bottom Channel Heads**: For the JCFC-sourced channel heads ASN has confirmed the presence of macrosegregation zones with excess carbon up to and possibly beyond 0.39%. So far as publicly accessible records reveal, these components were introduced to French operational NPPs during the 1st phase

24 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.

25 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*.

26 *Équipements Sous Pression Nucléaire* - ESPN Order of 12 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 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.*"

27 Contractual arrangements between EdF, AREVA and the individual Japanese supplier (either JSW or JCFC) are not available, although the most likely arrangement would have been with AREVA acting as the proxy supplier and dealing directly with ASN and/or DEP.

28 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 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 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.

replacement SG programme from mid 1990s through to about 2009 – see TABLE 4.

b) **JSW Tubesheets**: From destructive examination of a (1,300MWe series) tubesheet, AREVA has shown the presence of a macrosegregation zone of excess carbon (0.26%) on the normally inaccessible central area of the top surface.

However, the source of the particular tubesheet examined is not available so the risk of macrosegregation cannot be definitely allocated to JSW tubesheet components although, that said, it may be that JSW tubesheets are progressing through manufacturing stages for the present but delayed 2nd phase replacement SG programme in France.

c) **JSW Elliptical Domes**: Examination and destructive testing of a replicate elliptical dome revealed the presence of a macrosegregation zone of excess carbon (~0.29%) and tests yielded below specification material toughness (Charpy) values.

However, the source of the particular replicate examined is not available so the risk of macrosegregation cannot be definitely allocated to JSW SG elliptical dome components.

NRA INVESTIGATION OF JAPANESE OPERATIONAL NPPS

On 12 September NRA published a listing[29] of the sources of forged components presently installed at Japanese NPPs (both BWR and PWR derivatives) – this listing is reproduced in APPENDIX IV and in expanded form as follows:

TABLE 5 JAPANESE-SOURCED FORGED COMPONENTS INSTALLED IN JAPANESE NPPS («TENTATIVE»)[29, 30]

	COMPONENT	JCFC	JSW	JFESC	NON-FORGED
BWR RPV	UPPER HEAD	3	11	3	0
	ANNULAR RING	0	9	2	10
	LOWER HEAD	3	16	3	3
PWR RPV	UPPER HEAD	8	13	0	0
	ANNULAR RING	4	17	0	0
	LOWER HEAD	0	0	0	21
STEAM GENERATOR	CHANNEL HEAD	0	0	0	21
	TUBESHEET	«»	«»	«»	«»
	ELLIPTICAL TOP DOME	«»	«»	«»	«»
PRESSURISER	LOWER HEAD	0	0	0	21

THE JAPANESE REGULATORY POSITION

Of Japan's total of 42 presently available NPPs, all but 5 were commissioned prior to 1997 and there are a further 2 (Ohma 1 and Shimane 3) under or in a deferred state of construction.

29 ASN-NRA, i) *Recent Developments in Creusot Forge Manufacturing Issues* – ii) *Actions Taken in Japan*, presentations, 12-13 September 2016

30 By inspection, TABLE 5 covers 25 BWR and 21 PWR NPPs with 32 SGs being supplied for the latter. This compares with a total of 42 installed NPPs, made up of 22 ABWR/BWR and 20 PWR units.[30] Another oddity of TABLE 5 is that for the 21 PWR NPPs only 21 SG bottom channel heads were supplied, whereas the more typical primary coolant circuit arrangement each serves 3 or 4 SGs, making up a total of between 60 to 80 primary manifolds.

In Japan, until about 1997 the design and construction requirements for nuclear power were stipulated via government ordinance and were, unlike the western regulatory framework, not performance-based or particularly nuclear-specific, drawing heavily on the *Japanese Industrial Standards* (JIS). This ordinance system was administered, first, by the Atomic Energy Commission and, later from 1978, by the Nuclear Safety Commission with, like its predecessor, the Commissioners appointed by the Prime Minister

The development of detailed technical codes for engineered nuclear structures and components did not commence until the 1990s, particularly with the formation of the *Committee on Power Generation Facility Code* (CPGFO) of 1997 established by the *Japan Society of Mechanical Engineers* (JSME). Under JSME CPGFO there are several subcommittees, one of which is devoted to *nuclear power* and another on *materials,* and the nuclear power subcommittee also has a specialised subgroup on *materials* which issues a *code book* dealing with specialist topics for review and adoption by the current nuclear safety regulator NRA.[31]

The JSME principal code for materials of interest here is *Rules on Materials for Nuclear Facilities* (JSME S NJ1-2011)[32] although this was not introduced by the then regulator until 2011 or 2012, by which time the greater number of Japanese NPPs had been constructed and were in service operation. The difficulty here is in identifying the specific regulatory code or procedure adopted for safeguarding the consistency and quality of components in production at the various JCFC, JSW and other steel mills, forges and fabricators involved in the Japanese nuclear equipment supply chain. In the absence of a fully developed set of codes, particularly prior to 1997, it is not clear exactly how manufacturers, such as JCFC, defined and safeguarded quality control in the manufacturing route and, if indeed, the safeguards were prescriptive and recorded.

NUCLEAR SAFETY ISSUES

The IRSN assessment[21] that catastrophic failure of a ~0.3% excess carbon flawed SG bottom channel head could lead to a fuel core melt situation had to be drastically revised when it was discovered that the actual carbon excess was 0.39%, that is almost twice the maximum permissible level of 0.22% carbon content.[40] On the basis of IRSN's revised recommendations the two NPPs involved (Tricastin 1 and 3) will now remained shutdown until the operator EdF is able to demonstrate an acceptable revised nuclear safety case, although informed opinion is that it is very unlikely these NPPs will be permitted to restart unless the flawed JCFC components are replaced – up to three SGs may require replacement at each NPP.

An incident involving a catastrophically failed SG bottom head component with a follow-on fuel core melt could challenge the primary containment of the nuclear island, resulting in a radioactive release to and radiological consequences in the public domain beyond the NPP boundary. Similarly, a SG tubesheet failure could also result in significant radiological consequences by breaching the less well-protected containment of the steamside circuit.

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31 The JSME codes and standards are serviced entirely by volunteers drawn from industry, academic, government bodies and the regulatory agencies, about 350 individuals in total, who draw up and maintain the code books. Until 2014 the JSME generated code books were subject to technical appraisal by the *Japan Nuclear Energy Organisation* (JNES) to be endorsed by the then nuclear safety regulator the *Nuclear and Industry Safety Agency* (NISA) until, that is both NISA and JNES were disbanded in or around 2012 following severe criticism by the Diet Committee that investigated and pronounced on the Fukushima Daiichi catastrophe of March 2011. The present regulator, NRA, was inaugurated in September 2012 and absorbed the staff of JNES, presently accepts and administers the application of the JSME

32 JSME S NJ1-2011 is equivalent to the ASME BPVC Section II Parts A and D.

Obviously, if similarly flawed SG components are extant in Japanese NPPs then, if and when these NPPs are brought back into service, much the same risk of incident would apply.

Effectiveness of NDE Examination of In Situ Components

Appendices I, II and III show the levels of carbon through cross sections of a i) bottom channel head, ii) tubesheet and iii) elliptical dome.

These results can only be obtained by slicing through the component to extract test pieces that are subsequently chemically analysed to determine the % carbon content and, separately, physically tested to yield the elongation (ie ductility), toughness (Charpy) and fracture resistance (Pellini). Thus, characterising a large forged component weighing tens of tonnes, although only requiring a very small comparative volume of test pieces (ie a few tens of kilogrammes) results in the destruction of the entire component.

There are a number of inference techniques available to detect the presence of a positive macrosegregation zone on the surface of in situ installed components. For example. portable spark optical emission spectrometry (OES) yields a reliable indication (typically within ±10% accuracy) of the carbon content on the surface material but not, crucially, the carbon levels in depth of the shell of the component – see Appendices I and III. Ultrasound scanning can indicate the presence of a zone of macrosegregation but it cannot yield the excess carbon content.

Of course, all of these transducing techniques require access space and some may be rendered ineffective in the presence of a radiation field. Certain components are simply inaccessible, for example the SG tubesheets for which there is no possible access whatsoever to the top surface where macrosegregation may be at its greatest – see the through-section test results of the destructively tested bottom channel head replica blank of Appendix II.

All that is available to characterise an in situ component is to produce a replica that is then destructively analysed and tested – part of the condition imposed by ASN on EdF for demonstrating the severity of the Tricastin 1 and 3 SG in situ components is the requirement that replica forged blanks are produced under the same manufacturing route conditions as the in situ originals.[17] However, unless the detailed conditions and parameters of the original manufacturing conditions are faithfully reproduced then the newly prepared blank may not sufficiently replicate the original. Recreating the original manufacturing route may be particularly challenging for components entering the Japanese nuclear supply chain prior to and during the transition to a performance based regularity framework of the mid- to late-1990s.

NRA's Present Position on Flawed Components in the Nuclear Supply Chain

In advance of each Japanese NPP operator returning its evaluation of the risk of '*forged*' components by 31 October 2016, NRA stated[29] that

" The risk that the forged component may have the zones with higher carbon concentration is being evaluated. But the risk seems small in Japan because

- *Quality control in forging process have been managed appropriately and the manufacturing records endorse the quality.*

- *JSW's forging materials are free of positive macro-segregation zones according to CODEP-DEP-2015-037971.*
- *KSC's papers (in Japanese) on "quality of their nuclear forging materials" are available.*

➢ *Forging process would eliminate the high carbon concentration zone.*

- *The axial central zone of the ingot, which has relatively high carbon concentration, is removed during the forging process of ring components.*
- *In general, the risk in containing high carbon concentration increases with the thickness or weight of the forged components increase.*
- *Forged channel head is not used for any steam generators in Japan . . ."*

Certain of these NRA claims are, with respect, somewhat disingenuous because:

➢ ***QC in forging process is managed appropriately - manufacturing records endorse quality***

The quality of the JCFC-sourced SG bottom channel heads supplied to France under the 1st phase replacement SG programme of 1995 through to 2010, or thereabouts, certainly suggests otherwise: This is because failure of quality control of the JCFC manufacturing route resulted in unacceptable levels of heterogeneity (ie positive macrosegregation and associated carbon excess) in its supply of SG bottom channel heads for installation at French NPPs.

Moreover, the *Technical Qualification* (QT) records accompanying each JCFC component could not have reflected the heterogeneity, nor the crucial reduction in material toughness and, thus, the records did not *endorse the quality* of the component. It is not at all clear how, if the manufacturing records accompanying the JCFC components correctly and comprehensively described the component quality (ie the heterogeneity), that the component was, first, allowed to despatch from the JCFC works and, second, enter the French nuclear equipment supply chain without detection.

To demonstrate manufacturing conformity, the French nuclear regulatory framework required, prior to December 2005, that at least the RCC-M M140 material quality be achieved (verified by a *Test Certificate*) and, post December 2005 additional compliance with the ESPN[26] and, with that, a *Certificate of Conformity* should have been issued. ASN has stated[29] that in the JCFC-sourced (and Creusot) bottom channel head components there is a *"high probability of carbon segregation in the center and in the nozzles"* and that "*JCFC channel heads: first measurements tend to show higher C% than 0.30%".*[33] Subsequent (18 October) NDE surface measurements at Tricastin 1 and 3 NPPs revealed this excess carbon to be much higher at a totally unacceptable 0.39%.

The point here is that, in producing the French components, JCFC failed to meet the exacting standard and consistency of manufacture required by the French RCC-M N1 design and procurement code, this being equivalent to the Japanese Class 1 prerequisite for pressurised nuclear components. The conventional ingot casting and offset forging processes assumed to be followed by JCFC for the Japanese BWR RPV upper and lower heads and PWR RPV upper heads (see TABLE 6 items tagged 'FORGED') must have been very similar to those processes adopted for manufacturing the French SG bottom channel heads so, it follows, the BWR and PWR RPV upper and lower heads could be similarly at risk of falling short of the material characteristics (toughness) and quality (heterogeneity).

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

Put another way, it would have been absurd for JCFC, to have significantly departed from its established practice for forging not that dissimilar RPV component (ie the heads) just for the French SG bottom channel head supply contract. If so, the undesirable heterogeneity present in the bottom channel heads supplied to France might well be expected to be at risk of occurring in the RPV domes provided by JCFC to Japanese NPPs.

- ***JSW materials are positive macro-segregation free according to CODEP-DEP-2015-037971***

The CODEP report[34] is authored by the *Advisory Committee of Experts for Nuclear Pressure Equipment* (ACENPE), this being the working group referred to by the French nuclear regulator ASN for opinion on the sub-standard manufacture by le Creusot Forge of the Flamanville 3 EPR RPV upper and lower head components. ACENPE refer to the JSW positioning of the cropped discard segment of the conventional ingot in its forging of the Olkiluoto 3 EPR RPV upper and lower heads, compared to the le Creusot Forge approach for the Flamanville 3 heads that, according to ACENPE, enabled JSW to crop out and discard the positive macrosegregation zone.

However, this comparison has to be made in the context of the challenge of casting the conventional ingot for the larger EPR head components and, particularly, in terms of the *forging ratio* (ie ratio of the bloom weight discarded). For Flamanville 3 le Creusot Forge was nearing its ingot casting tonnage capacity, choosing a 160 tonne conventional ingot which pared down the forging ratio,[6] whereas for Olkiluoto 3 its larger ingot casting capability enabled JSW[35] to forge the component from a larger ingot with the benefit of a more ample forging ratio.

It seems, therefore, that ACENPE's comments strictly apply JSW's manufacturing of the Olkiluoto 3 RPV heads at around 2003 and not to earlier times when the JSW ingot capacity may not have afforded such an ample forging ratio for albeit generally smaller RPV components – on this basis alone earlier JSW RPV head forged components (see TABLE 5) cannot be guaranteed to be free of positive macrosegregation zones.

- ***Forging process would eliminate the high carbon concentration zone***

It is incorrect for NRA to assert that Japanese forging practices would eliminate positive macrosegregation because, irrefutably, the JCFC bottom channel head and, possibly, JSW tubesheets and elliptical domes for the 1st phase French replacement SG programme, included heterogeneity in the form of positive macrosegregation zones.

- ***Risk of excess carbon increases with thickness/weight of forged components***

As previously explained, it is the adequacy of the *forging ratio* that is an important determinant – as forge manufactories develop and increase the ingot casting tonnage and manhandling capacities there is greater scope for raising the cropping and discard volumes.

There is evidence that the ingot size (switched from 90 to 120 tonnes during the JCFC production run) of the JCFC SG bottom channel heads in the French nuclear supply chain influenced the severity of the macrosegregation zone, although this was not a decisive factor in ASN's decision to shut down the French NPPs on 18 October 2016.[40]

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34 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.

35 Yoshihiro Ookomori, *Recent Trends and Developments in the Heavy Open-Die Forging in Japan*, Steel Castings and Forging Association of Japan, c2014-5

- ***Forged channel head is not used for any steam generators in Japan***

The means of production from *'plate'* for the SG channel heads destined for Japanese NPPs is not further defined by NRA, although it is reasonable to assume that the steel plate is manufactured by continuous or strand casting and that the final component is hot formed from this.

Positive macrosegregation also occurs on the surface and in the slab depth during the strand casting sequence, particularly in the slab centreline accompanied by interdendritic cracking,[36] oscillatory marking, and combined porosity and cracking.[37] In strand cast slabs centreline segregation is one of the most unpredictable defects,[38] generally resulting in the middle part of the strip or slab having a chemical composition (and structure) different from the average width, which results in differing properties in the mid-section of the slab.

The NRA claims that the type of SG components, particularly the bottom channel heads, could not have entered the Japanese nuclear supply chain because, simply, this particular manufacturing route (cast ingot and upset forging) is not adopted in Japan. However, the returns of the operators to the NRA's first round inspection requirement[4] suggest that 6 NPP sets of SGs were manufactured by JCFC using the cast ingot forging process – see TABLE 6 APPENDIX V.

DISPOSITION OF POTENTIALLY AT-RISK FORGED COMPONENTS THROUGHOUT JAPANESE NPPS: The NRA's original instruction of 24 August 2016 required Japanese NPP operators to i) identify those Class 1 NPP components produced by the forged steel manufacturing route and, once confirmed, ii) to evaluate the possibility of the presence of positive macrosegregation zones and excess carbon. The first part of this instruction i) was to be completed by 2 September and ii) the evaluation of excess carbon reported by 31 October 2016.

1) JCFC SG BOTTOM CHANNEL HEAD COMPONENTS

TABLE 6 of APPENDIX V is an unofficial collation (and translation) of the returns of the NPP operators to the first-round NRA requirement to report back by 2 September 2016.[4] TABLE 6 shows the main Japanese sources (JCFC and JSW) that have fed the Japanese nuclear supply chain with heavy, engineered components for installation in the reactor primary coolant circuit.

First, consider the PWR variant NPPs noting that no details are provided for the SG *tubesheet* and *elliptical top dome* components and, also contrary to the NRA's inventory[29] (TABLE 5) that JCFC did **not** supply any forged *bottom channel heads* using the cast ingot route, TABLE 6 indicates that JCFC supplied 6 NPPs with (cast)[39] forged bottom channel heads at the date of the respective NPP installation – these NPPs are shown <u>underlined</u> in TABLE 7.

It is useful to consider in conjunction with TABLE 6 the replacement SGs that have occurred in the Japanese PWR NPPs - so far as reliable records are available, replacement SGs installed in just over one-half of the Japanese PWR NPPs occurred as follows

36 Mostafa Omar El-Bealy, *ng of Steel*, Materials Sciences and Applications, 2014, 5, 724-744, August 2014

37 Elfsberg J, *Oscillationsmärkesbildning vid kontinuerliga gjutprocesser (Oscillation Mark Formation in Continuous Casting Processes)*, Royal Institute of Technology, October 2003

38 Mihály Réger, et al, *Control of Centerline Segregation in Slab Casting*, Acta Polytechnica Hungarica, Vol. 11, No. 4, 2014.

39 In the columns dealing with the SGs of TABLE 6 it is the use of the terminology 'CAST' compared to 'PLATE, FORGED' that strongly suggests that the JCFC channel heads were forged from a cast ingot rather than from a previously (strand rolled) slab.

TABLE 7 KNOWN REPLACEMENT AND (ASSUMED) REMAINING ORIGINAL SGS IN JAPANESE PWR NPPS («TENTATIVE »)§

1984-7	1989	91-93	94	95	96	97	98	99	00	01	02	03	04	05	06	07	08	09
TAKA 3 TAKA 4 SEND 1 SEND 2 TSUR 2	TERN 1 TOMA 1	TOMA 2 TERN 2 OHI 3 OHI 4	**GENK 1** **MIHA 2** **OHI 1** **TAKA 2** GENK 3 IKAT 3	**MIHA 1**	**MIHA 3** **TAKA 1**	**OHI 2** GENK 4		**IKAT 1**	**GENK 2**	**IKAT 2**				«»	«»	«»	«»	TOMA 3 TERN 3 «»
			GRA1	DA3- SLB1	GRA2	TRI2	TRI1		GRA4	TRI3	FES1	SLB2	TRI4	DAM2	BUG4			
				⊘⊘	⊘	⊘	⊘		⊘	⊘	⊘	⊘	⊘	▯	⊘			
				JCFC	JCFC	JCFC	JCFC		JCFC	JCFC	JCFC		JCFC		JCFC			

§ Years are the SG installation date in the NPP – the actual manufacturing completion year will be earlier by, say, a year or more

All of the replacement SGs (shown RED) identified in TABLE 7 were, according to the operator returns summarised in APPENDIX V, hot formed from pre-prepared plate or slab steel. PWR NPPs less than 30 years are assumed, on a rule of thumb basis, to have the original SGs still installed (shown GREEN), and borderline NPPs of about 30 years service age are shown BLUE.

Immediately below the Japanese returns of TABLE 7 is an extract of TABLE 4 giving the chronological order of the JCFC SG cast channel heads supplied to the French nuclear industry – these are the flawed JCFC components now subject to ongoing investigation by the French regulator ASN. The JCFC supply of French replacement SGs (from 1995 through to 2006) follows on almost directly from its supply of new SG installations in Japanese NPPs (from 1984 through to 1991) with, quite probably, a typical lead time for manufacturing a total of 6 replacement SGs for Dampierre 3 and St Laurent 1 filling in the intervening gap between 1991-2 and 1994-5.

FINDING 1a: Since the bottom channel head components for different variants of the PWR NPP design are not that dissimilar, in both detail and overall size, it is a reasonable supposition that the JCFC channel heads supplied to the Japanese PWR NPPs French might have also been flawed with zones of positive macrosegregation, excess carbon and resulting weakening of the material toughness characteristic.

IRSN's note of 18 October[40, 41] hints at one difficulty confronted by JCFC being the size of cast ingots changing from 90t to 120t gross, suggesting that the smaller ingot did not provide a sufficient *forging ratio* to eliminate the macrosegregation zone volume as discard.

FINDING 1b: The bottom channel heads of the SGs of NPPs *Tomari 1* and *2*, *Tsuruga 2*, *Takahama 3* and *4*, and *Sendai 2* should each be non-destructively (ND) examined to confirm the manufacturing route, be it forged directly from a cast ingot or, alternatively, hot formed from steel slab – the NRA should issue guidance on the consistent use of terms defining the various manufacturing routes filed in the returns of 2 September 2016.[4]

40 IRSN, Note d'information, *Parc nucléaire d'EDF en fonctionnement : Anomalies et irrégularités constatées lors des investigations consécutives à l'anomalie concernant les calottes de la cuve du réacteur EPR de Flamanville*, 18 October 2016

41 The French experience was that, at first, the smaller 90t ingot components had a 100% (4 of 4 SGs) heterogeneity failure rate over the 120t ingot which had a ~63% (7 of 11 SGs) heterogeneity failure rate, although eventually on 18 October ASN withdrew all NPPs with SGs that included JCFC-sourced bottom channel heads.

FINDING 1c: The outer, accessible surface of the bottom channel head should be subject to ND examination to determine if any significant degree of heterogeneity is present – this might be achieved by OES although any decarburised surface layer renders this particular technique ineffective. The results of OES should be compared to the QT records held for each component giving particular regard to the ingot tonnage and the *forging ratio*.

FINDING 1d: The NRA should make publicly accessible the methodology and results of inspections of the bottom channel head components completed during all past Periodic Review assessments.

FINDING 1e: In addition, it would be useful, to compare the QT records for the JCFC forge manufacturing route with the actual condition of the JCFC-sourced bottom channel heads that have entered the French nuclear supply chain – this comparison should be publicly accessible.

FINDING 1f: The prescriptive measures put in place to ensure quality assurance of the manufacturing route (ie the equivalent of the French RCC-M140 and, separately, ESPN) should be identified.

2) JCFC-JSW SG TUBESHEET AND ELLIPTICAL DOME COMPONENTS

TABLE 6 of APPENDIX V provides no details whatsoever of the tubesheet and elliptical head components fitted to all Japanese PWR SGs (original or replacement).

FINDING 2a: In its investigation of the Japanese-sourced tubesheets and elliptical domes now present in the French nuclear supply chain there is clear reference to the presence of positive macrosegregation zones and excess carbon. However to the contrary, in its joint presentation with NRA of 12 September 2016, ASN stated that the JSW manufacturing process could not result in positive macrosegregation flaws. The French regulator should be asked to clarify this apparent dichotomy.

FINDING 2b: All tubesheet and elliptical dome components, irrespective of manufacturer (JCFC, JSW and/or KSC) should be subject to FINDING 1b above, although it is acknowledge that access to the top surface of the tubesheet is not possible.

FINDING 2c: The outer surface of the tubesheets and elliptical domes should be subject to FINDING 1c and, in addition, a proven means of ND examining the tubesheet top surface should be demonstrated. For hot formed plate steel components the QT records for the slab or plate steel supplying mill should be re-examined.

FINDING 2d: The NRA should make publicly accessible the methodology and results of inspections of the tubesheets and elliptical domes completed during all past Periodic Review assessments.

FINDING 2e: FINDING 1e should apply as appropriate.

FINDING 2f: FINDING 1f should apply as appropriate.

3 PWR PRESSURISED REACTOR PRIMARY COOLANT CIRCUIT AND BWR RPV

TABLE 6 of APPENDIX V provides scant description of the manufacturing routes for the various RPC components.

FINDING 3a: Other than the pressuriser of the PWR NPPs, the pump and valve bodies, and RPV closure heads (lids) of both PWR and BWR NPP variants for which the previous findings should generally apply, ND examination of the installed RPV present practicable difficulties.

FINDING 3b: The QT records for each component should be thoroughly scrutinised for any inconsistency that might suggest the, somehow, heterogeneity in the installed components – this should apply to cast ingot forged and hot formed plate components.

FINDING 3c: Noting that the heterogeneity in the bottom head of the French FA3 RPV was not discovered for several years following the start of the production process, painstaking regard should be given to the ND examination of all installed components – for the JCFC manufactory particular consideration should be given to how the SG bottom channel heads destined for the French nuclear supply chain could leave the JCFC works undetected and whether this loophole in quality control could have also existed in the RPV manufacturing route. Similar scrutiny should be applied to the mill records for hot formed plate steel components.

FINDING 3d: The NRA should make publicly accessible the methodology and results of inspections of the RPV and pressuriser completed during all past Periodic Review assessments.

FINDING 3f: FINDING 1f should apply as appropriate.

OVERALL FINDINGS:

A) Where NDE of the external surface of any Class 1 (N1) component reveals the presence of surface heterogeneity in the form of positive macrosegregation and/or the formation of excess carbon, the operator should prepare a revised nuclear safety case for that particular component and the potential consequences for the NPP overall arising from its failure – the demonstration of such a revised safety case may require testing and metallurgical analysis of replica blanks of the component under review.

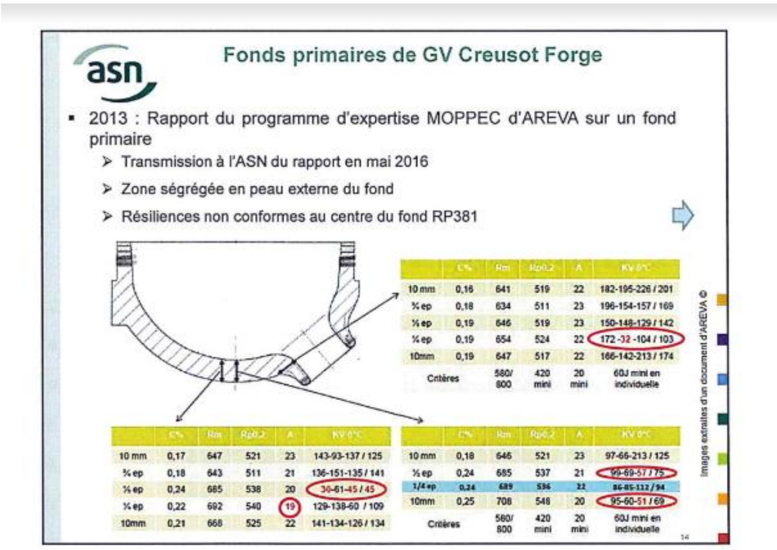
B) The outcome of the actions undertaken under Findings 1) to 3) inclusively should be reviewed by an authoritative and competent organisation such as Japan Society of Mechanical Engineers, particularly, the subcommittee on Nuclear Power's subgroup on materials, or its equivalent and only when this review has been completed it should be considered for endorsement by NRA.

LARGEASSOCIATES

CONSULTING ENGINEERS,
LONDON

APPENDIX I

AREVA TEST RESULTS FOR A CREUSOT-SOURCED STEAM GENERATOR MONOBLOC MANIFOLD [10]



Fonds primaires de GV Creusot Forge

- 2013 : Rapport du programme d'expertise MOPPEC d'AREVA sur un fond primaire
  - Transmission à l'ASN du rapport en mai 2016
  - Zone ségrégée en peau externe du fond
  - Résiliences non conformes au centre du fond RP381

	C%	Rm	Rp0,2	A	KV 0°C
10 mm	0,16	641	519	22	182-195-226 / 201
¾ ep	0,18	634	511	23	196-154-157 / 169
½ ep	0,19	646	519	23	150-148-129 / 142
¼ ep	0,19	654	524	22	172 -32 -104 / 103
10mm	0,19	647	517	22	166-142-213 / 174
Critères		580/ 800	420 mini	20 mini	60J mini en individuelle

	C%	Rm	Rp0,2	A	KV 0°C
10 mm	0,17	647	521	23	143-93-137 / 125
¾ ep	0,18	643	511	21	136-151-135 / 141
½ ep	0,24	685	538	20	30-61-45 / 45
¼ ep	0,22	692	540	19	129-138-60 / 109
10mm	0,21	668	525	22	141-134-126 / 134

	C%	Rm	Rp0,2	A	KV 0°C
10 mm	0,18	646	521	23	97-66-213 / 125
½ ep	0,24	685	537	21	99-69-57 / 75
1/4 ep	0,24	689	536	22	86-85-112 / 94
10mm	0,25	708	548	20	95-60-51 / 69
Critères		580/ 800	420 mini	20 mini	60J mini en individuelle

Images extraites d'un document d'AREVA ©

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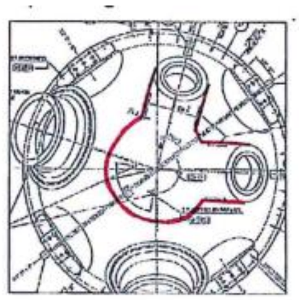


APPENDIX II

1) AREVA TEST RESULTS FOR A UNKNOWN-SOURCED STEAM GENERATOR TUBESHEET [42]

REDACTED BY AREVA AT SOURCE

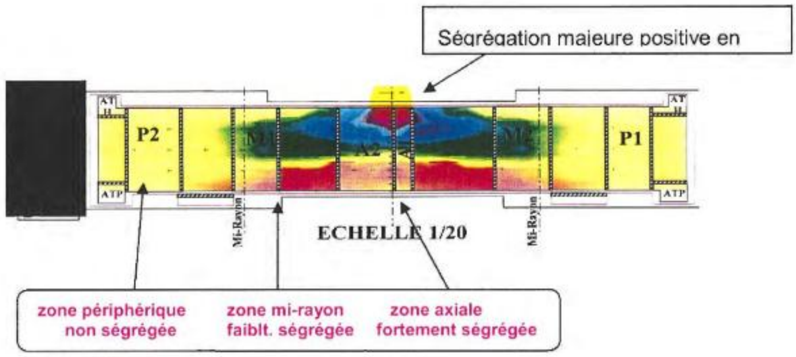
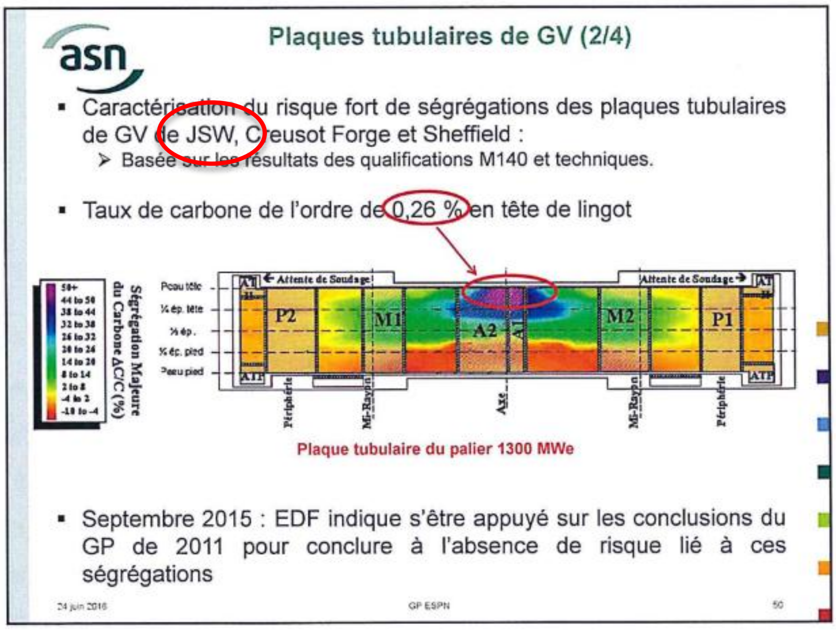


FIGURE 5: PLAQUE TUBULAIRE 1300 MWE – CARTOGRAPHIE DE CARBONE

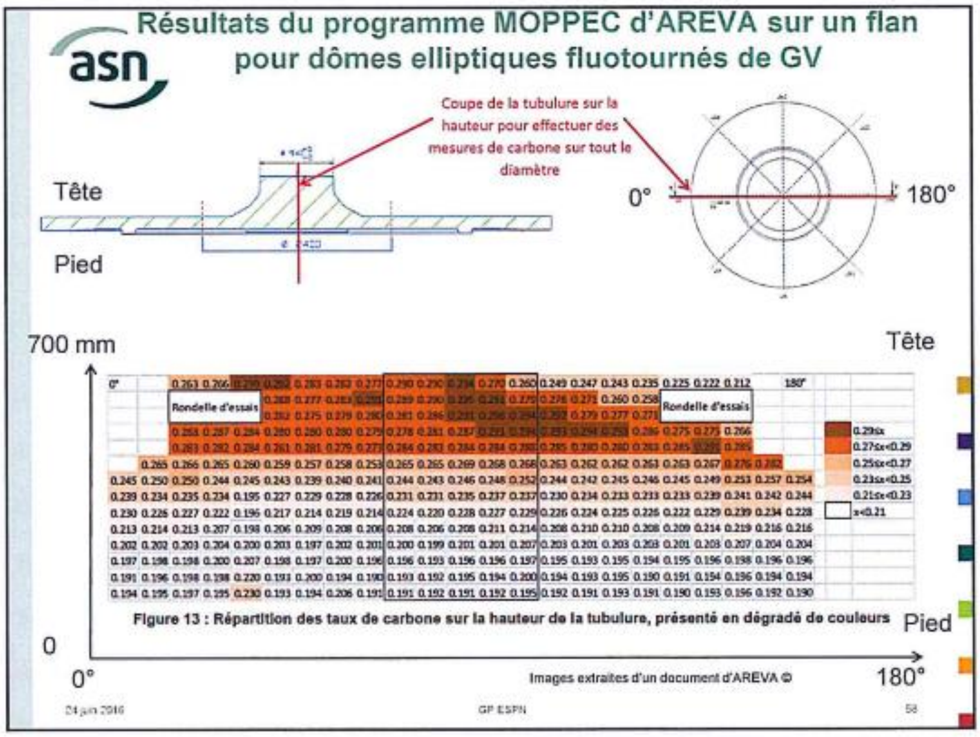
2) ASN COPY OF AREVA TEST RESULTS FOR A UNKNOWN-SOURCED STEAM GENERATOR TUBESHEET [10]

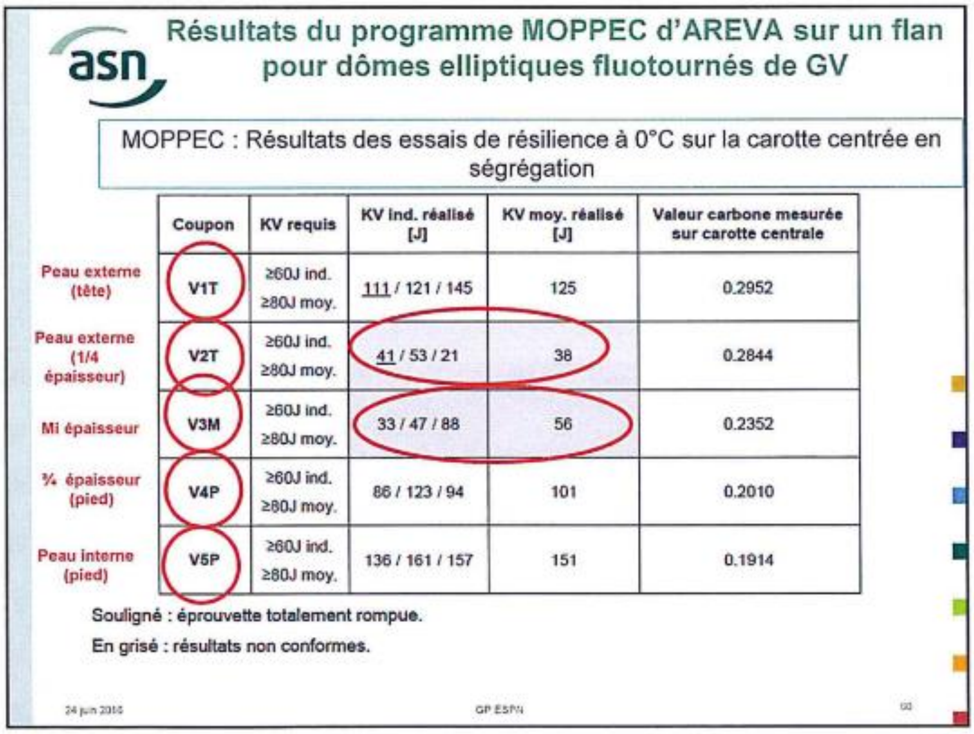


42 AREVA, *Calottes de cuve FA3 – Conception et fabrication*, DO2-PEE-F-15-007 Rev A, 24 April 2015

APPENDIX III

ASN TEST RESULTS FOR A UNKNOWN-SOURCED SG ELLIPTICAL DOME[10]





	Coupon	KV requis	KV ind. réalisé [J]	KV moy. réalisé [J]	Valeur carbone mesurée sur carotte centrale
Peau externe (tête)	V1T	≥60J ind. ≥80J moy.	111 / 121 / 145	125	0.2952
Peau externe (1/4 épaisseur)	V2T	≥60J ind. ≥80J moy.	41 / 53 / 21	38	0.2844
Mi épaisseur	V3M	≥60J ind. ≥80J moy.	33 / 47 / 88	56	0.2352
¾ épaisseur (pied)	V4P	≥60J ind. ≥80J moy.	86 / 123 / 94	101	0.2010
Peau interne (pied)	V5P	≥60J ind. ≥80J moy.	136 / 161 / 157	151	0.1914

APPENDIX IV

NRA LISTING OF FORGED COMPONENTS INSTALLED IN JAPANESE OPERATING NPPS[29]

Preliminary Responses from JP Utilities

- Number of Forged Components Used in Japan
  - ( ): Steel plate parts are supplied by a different manufacture

Equipment	Component	JCFC*1	JSW*2	KSC*3	Non-forged
BWR Pressure Vessel	Top head	0 (3)	8 (11)	3 (0)	0
	Ring	0	4 (9)	0 (2)	10
	Bottom head	**3**	16	3	3
PWR Vessel	Top head	**6** (2)	10 (3)	0	0
	Ring	2 (2)	7 (10)	0	0
	Bottom head	0	0	0	21
Steam Generator	Channel head	0	0	0	21
Pressurizer	Bottom head	0	0	0	21

*1 JCFC: Japan Casting & Forging Corporation
*2 JSW: The Japan Steel Works, Ltd.
*3 KSC: Kawasaki Steel Corporation, which is currently JFE Steel Corporation

NRA, Japan
Nuclear Regulation Authority

(5 /8) NRPL2016082602

APPENDIX V

TABLE 6 COLLATION OF PART i) RESPONSES FROM JAPANESE NPP OPERATORS

			JCFC (日本鋳鍛鋼)					JSW（日本製鋼所）				
PLANT	OPERATOR COMMISSION DATE	TYPE	STEAM GENERATOR	REACTOR PRESSURE VESSEL			PRESSURISER	STEAM GENERATOR	REACTOR PRESSURE VESSEL			PRESSURISER
			BOTTOM CHANNEL HEAD [1]	UPPER HEAD	LOWER HEAD	CORE SHELL COURSE	HEAD	BOTTOM CHANNEL HEAD [1]	UPPER HEAD	LOWER HEAD	CORE SHELL COURSE	HEAD
Hamaoka 3	Chubu (1987)	BWR							PLATE, FORGED ※	FORGED		
Hamaoka 4	Chubu (1993)	BWR							PLATE, FORGED ※	FORGED	PLATE, FORGED ※	
Hamaoka 5	Chubu (2005)	BWR							PLATE, FORGED ※	FORGED	PLATE, FORGED ※	
Shimane 2	Chugoku (1989)	BWR										
Shimane 3	Chugoku (deferred)	BWR							PLATE, FORGED ※	FORGED	FORGED	
Oma 1	J Power [2022]	BWR							PLATE, FORGED ※	FORGED	FORGED	
Tomari 1	Hokkaido (1989)	PWR	CAST						FORGED	PLATE	FORGED	PLATE
Tomari 2	Hokkaido	PWR	CAST						FORGED	PLATE	FORGED	PLATE

	(1991)											
Tomari 3	Hokkaido (2009)	PWR							FORGED	PLATE	FORGED	
Shika 1	Hokuriku (1993)	BWR		FORGED	FORGED							
Shika 2	Hokuriku (2006)	BWR							PLATE, FORGED ※	FORGED	FORGED	
Tsuruga 2	JAPCO (1987)	PWR	CAST	FORGED						PLATE	FORGED	
Tokai 2	JAPCO (1978)	BWR							PLATE, FORGED	PLATE	PLATE	
Mihama 3	Kansai (1976)	PWR							PLATE, FORGED	PLATE	FORGED PLATE	PLATE
Takahama 1	Kansa (1972)	PWR							PLATE, FORGED	PLATE	FORGED PLATE	PLATE
Takahama 2	Kansai (1975)	PWR		FORGED						PLATE	FORGED PLATE	PLATE
Takahama 3	Kansai (1985)	PWR	CAST						FORGED	PLATE	FORGED PLATE	PLATE
Takahama 4	Kansai (1985)	PWR	CAST						FORGED	PLATE	FORGED PLATE	PLATE
Oi 1	Kansa (1979)	PWR		FORGED						PLATE	FORGED PLATE	PLATE
Oi 2	Kansai (1979)	PWR		FORGED						PLATE	FORGED PLATE	PLATE
Oi 3	Kansai (1991)	PWR							FORGED	PLATE	FORGED	
Oi 4	Kansai (1993)	PWR							FORGED	PLATE	FORGED	
Genkai 2	Kyushu (1981)	PWR		FORGED						PLATE	FORGED PLATE	

Genkai 3	Kyush (1994)	PWR		PLATE, FORGED[2]		FORGED			PLATE, FORGED[2]	PLATE		
Genkai 4	Kyushu (1997)	PWR		PLATE, FORGED[2]		FORGED			PLATE, FORGED[2]	PLATE		
Sendai 1	Kyushu (1984)	PWR				FORGED PLATE[3]			FORGED	PLATE	FORGED PLATE[3]	
Sendai 2	Kyushu (1985)	PWR	CAST			FORGED PLATE[3]			FORGED	PLATE	FORGED PLATE[3]	
Ikata 1	Shikoku (1977)	PWR							FORGED	PLATE	FORGED PLATE	PLATE
Ikata 2	Shikoku (1982)	PWR		FORGED						PLATE	FORGED PLATE	PLATE
Ikata 3	Shikoku (1994)	PWR							PLATE, FORGED	PLATE	FORGED	
Fukushima Daini 1	Tepco (1982)	BWR							PLATE, FORGED	PLATE	PLATE	
Fukushima Daini 2	Tepco (1984)	BWR		PLATE, FORGED ※	FORGED							
Fukushima Daini 3	Tepco (1985)	BWR							PLATE, FORGED	FORGED	PLATE	
Fukushima Daini 4	Tepco (1987)	BWR		PLATE, FORGED ※	FORGED							
Kashiwazaki-Kariwa 1	Tepco (1985)	BWR							PLATE, FORGED	FORGED	PLATE	
Kashiwazaki-Kariwa 2	Tepco (1990)	BWR										
Kashiwazaki-Kariwa 3	Tepco (1993)	BWR							PLATE, FORGED ※	FORGED	PLATE, FORGED ※	

Kashiwazaki-Kariwa 4	Tepco (1994)	BWR							PLATE, FORGED ※	FORGED	PLATE, FORGED ※	
Kashiwazaki-Kariwa 5	Tepco (1990)	BWR										
Kashiwazaki-Kariwa 6	Tepco (1996)	BWR							PLATE, FORGED ※	FORGED	PLATE, FORGED ※	
Kashiwazaki-Kariwa 7	Tepco (1997)	BWR							PLATE, FORGED	FORGED	PLATE, FORGED	
Higashidori 1	Tepco (2005)	BWR							PLATE, FORGED[4]	FORGED	FORGED[4]	
Onagawa 1	Tohoku (1984)	BWR							PLATE, FORGED	PLATE	PLATE	
Onagawa 2	Tohoku (1995)	BWR							PLATE, FORGED ※	FORGED	PLATE, FORGED ※	
Onagawa 3	Tohoku (2002)	BWR							PLATE, FORGED ※	FORGED	PLATE, FORGED ※	
Higashidori 1	Tohok (2005)	BWR							PLATE, FORGED ※[4]	FORGED	PLATE, FORGED ※[4]	

Appendix VI

LargeAssociates Request for Further Information from ASN

Memorandum

Large and ASSOCIATES

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To:	Roger Spautz – Greenpeace Fr	M3235-A1
From:	**John H Large**	8 October 2016
Cc:	Shaun Burnie	
Subject:	**Hadlow College -** 341 Shooters Hill Road, Shooters Hill DA16 3RP	

So that I might pursue the R3233 and R3235 projects further, would you please arrange to submit the following itemised requests for further information to *Autorité de Sûreté Nucléaire*:-

"…

1) French Nuclear Power Plants (NPPs) on Enforced Outage

A) Of the 18 NPPs referred to in the ASN *Note d'information* of 28 June 2016 please identify by NPP name which of these has been

i) permitted to resume full power operation unconditionally, or may return to full power unconditional operation following the present scheduled outage;

ii) permitted to resume full power operation conditionally and, for these,

a) give the conditions imposed; and including

b) details of any *'compensatory'* measures;

iii) refused permission to resume power operation and shall remain shut down until additional investigations have been completed, of which

a) specify the detailed nature, objective and, if completed, the results of the *'additional investigations'* undertaken by EdF to date.

B) For all items of A) above please state the date upon which the individual replacement steam generator(s) were installed and licensed for pressurized operation.

C) For all items of A) above please state if at the time of first powered operation that

i) for those SGs installed prior to December 2005, if the SG(s) and its component parts satisfied the *Qualification Technique* (QT) and was thus considered to be fully compliant with all aspects of the RCC-M code;

ii) for those SGs installed after December 2005, if in addition to RCC-M compliance, the SG and its component parts were issued with a *Certificate of Conformity* in accord with *Équipements Sous Pression Nucléaire* – ESPN Order of 12th December 2005 for Nuclear Pressurised Equipment (ESPN) FR (24FF4V);

D) For all items of B) above please identify which NPPs have *installed bottom channel* head parts supplied by

i) Creusot Forge;

ii) Japan Casting and Forging Company (JCFC);

iii) Japan Steel Works (JSW); and/or

iv) any other supplier.

E) For all items of B) above please identify which NPPs have installed *tubesheet* parts supplied by

i) Creusot Forge;

ii) Japan Casting and Forging Company (JCFC);

iii) Japan Steel Works (JSW); and/or

iv) any other supplier.

F) For all items of B) above please identify which NPPs have installed *elliptical top dome* parts supplied by

i) Creusot Forge;

ii) Japan Casting and Forging Company (JCFC);

iii) Japan Steel Works (JSW); and/or

iv) any other supplier.

2) SG Tubesheets

A) Referring to the tubesheet featured in Figure 5 of the AREVA document *Calottes de cuve FA3 – Conception et fabrication*, DO2-PEE-F-15-007 Rev A, 24 April 2015 please

i) confirm or otherwise that this tubesheet is the same as the tubesheet shown on page 50 of the ASN presentation *Ségrégations majeures positives résiduelles du Carbone Composants forgés du parc en exploitation d'EDF*) 24 juin 2016;

ii) that it is a

a) predrilled blank tubesheet; but otherwise

b) a replicate of the manufacturing route adopted for 1,300MWe series French NPPs;

iii) provide the manufacturing source of the tubesheet (ie Creusot, JSW, etc);

iv) if similar replicate tubesheets have been provided by all suppliers (Creusot, JSW, etc) for similar analysis;

v) if the *'additional investigations'* of item 1), A), iii), a) above include for investigation of the in situ tubesheets; if so

vi) please state if and how tubesheets installed in SGs at all French 1300MWe NPPs are to be non-destructively inspected and evaluated for possible heterogeneity as shown by the AREVA result of item 2), A) above; and

vii) if the tubesheets installed in other operational NPPs are to be subject to similar *'additional investigations'*,

3) SG Elliptical (top) Domes

A) Referring to the elliptical dome featured in page 54 of the ASN presentation of the ASN presentation *Ségrégations majeures positives résiduelles du Carbone Composants forgés du parc en exploitation d'EDF*) 24 juin 2016, please provide the information relating to elliptical dome components as requested above under item 2), A), i) to vii).

4) SG Bottom Channel Head

A) Referring to the bottom channel head generally featured in page 10 et sec of the ASN presentation of the ASN presentation *Ségrégations majeures positives résiduelles du Carbone Composants forgés du parc en exploitation d'EDF*) 24 juin 2016, please provide the information relating to bottom channel head components as requested above under item 2), A), i) to vii).

B) Please state the manufacturing route for the bottom channel heads sourced from JCFC, be it

i) single, conventional cast ingot and upset forging; or

ii) hot formed from strand cast (or similar) steel slabs.

5) Irregularities and CFS Items

i) Please state if any bottom channel heads, tubesheets, elliptical domes supplied by either JCFC, JSW or any other Japanese sources have been subject to *'irregularities'* and/or *Counterfeit, Fraudulent and Substandard Items* as defined by ASN.

6) EdF Interim and Complementary Safety Reports

i) 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 – please provide full, unredacted copies of these EdF reports (it is not clear if the 1st report is an already published press release).

Finally, it would be helpful if you would adhere to my itemized numbering in your response.

…"

Also, it would helpful if you could remind ASN of past outstanding requests that are awaiting a response, these are:

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	5 of 6 items answered – heavily redacted copies provided - awaiting EdF-AREVA clearance for 1 item	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	7 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		