# REVIEW

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

## CONCLUDING PARTS II & III – POTENTIAL FLAWED COMPONENTS RESIDENT IN JAPANESE NUCLEAR POWER PLANTS

Client: **GREENPEACE GERMANY**

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**LARGEASSOCIATES**

**CONSULTING ENGINEERS, LONDON**


This Review comprises three Parts.

The 1st Part considered the situation of the French nuclear equipment supply chain where it is acknowledged that flawed components had been supplied by at least one Japanese manufacturer.

This combined 2nd and 3rd Part examines the prognosis that similar flawed components, manufactured in Japan are either in operation (eg Sendai) or in those plants that have been mothballed since the Fukushima Daiichi catastrophic events of March 2011 but which are being readied for restart in the near future.

To access certain source material a password is - please apply to Shaun Burnie (sburnie@greenpeace.org) for a secure password – then access http://www.largeassociates.com/CZ3235/3235search.html

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

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## PARTS II & III – POSSIBILITY OF FLAWED CLASS 1 COMPONENTS RESIDENT IN 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 vulnerability of the steel alloy to fast and catastrophic failure. Following these revelations ASN ordered a review of the past practises involved in the manufacture of the components. The review revealed that not only was quality assurance and component conformity unsatisfactory, but also that a number of flawed components had been 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 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. The reason for the enforced shutdown of these NPPs was that each had installed steam generators (SBs) that included components with extraordinary high levels of carbon and much reduced material toughness.

**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 Corporati*on (JCFC) and, possibly, the *Japan Steel Works* (JSW). The SG components supplied by JCFC, the *bottom channel heads*, have all now been shown to be at very high risk of containing residual zones of macrosegregation with enhanced carbon content. EdF initially reported that its preliminary examination suggested a maximum excess carbon content of 0.3%, which is about 50% over the design specification of 0.22%. On this basis, ASN's 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 immediately implemented until a scheduled outage would enable further examination of the JCFC components.

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.

In late November IRSN assessed a second submission from EdF that further detailed its generic *Demonstration Approach* to show if it would be feasible to operate the JCFC SG channel head installed NPPs safely with the imposition of restrictions and *'compensatory'* measures, which is the option permitted under French statute for components that do not comply with the design basis specification. Although IRSN accepted EdF's generic Demonstration Approach, it advised ASN that EdF's assessment was incomplete, from which ASN issued a Directive of 5 December 2016 to EdF listing thirteen requirements to demonstrate the validity of restarting the NPPs that had JCFC SG components installed. Part of this ASN Directive was that a 120 tonne ingot, along with number of full scale sacrificial replicates of the bottom channel head would be manufactured afresh by JCFC for carbon content mapping, chemical analysis and physical testing.

It is not absolutely clear at the time of writing this Summary whether selected French NPPs with JCFC components are to be permitted to restart in advance of the replicates being analysed and tested or, indeed, if the other prerequisites of the 5 December Directive are to be resolved.

This Review traces the programmes of inspection, testing and reassessment of the nuclear safety case now underway in France, the final outcome of which is not expected until mid-2017 – in the interim, all NPPs with JCFC components are to remain shutdown. As ASN's investigations develop more information is coming to light about fraudulent recordkeeping at the French le Creusot Forge and there is an unnamed overseas forge also implicated in fraudulent activities; it is believed that three or four completed replacement SGs awaiting installation have been scrapped because of the carbon anomaly; and tests on SG components, the *tubesheet*s,

*elliptical domes* and *bottom channel heads*, for the 2nd Phase replacement programme are currently underway in France – some of these components may or may not have been supplied by JSW.

**PART I** of this Review concludes there to have been a regulatory loophole that somehow allowed the heavily flawed JCFC components to be accepted into the French nuclear equipment 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, the composite that has resulted in the French failure includes possibly three elements that are entirely founded in Japan, these being i) that the defective components were wholly manufactured in Japan; ii) that the quality control safeguards that should have prevented the flawed components leaving the place of manufacture failed; and iii) that the manufacturing, analysis and test records were either not examined by ASN or AREVA for certification purposes and/or, if they were, the records did not correctly portray the component conformity and characteristics.

**Parts II** and **III** of this Review examine the prognosis that similarly flawed components manufactured in Japan could have passed into the Japanese nuclear equipment supply chain undetected by the Japanese nuclear regulator of the time (1980s and early 1990s).

In August 2016 the Japanese nuclear safety regulator, the *Nuclear Regulatory Authority* (NRA), set out its requirements for checking through the Class 1, forged components resident in Japan's NPPs. There was a later joint meeting and presentation between NRA and ASN in September in which the NRA elucidated its requirements for the reporting on large, forged components resident in Japanese NPPs. The reporting was in two stages comprising, first, the NRA interviewing each of the NPP operators and then receiving the operators' assessment of those Class 1, forged components thought to be at risk of macrosegregation zone inclusion; then, second and if found necessary, an evaluation of the risk by the operator of the particular NPP at risk; and, apparently, at their own volition, submissions from JCFC, JSW and JFE on the manufacturing processes involved at their respective forges.

The NRA itself was not incorporated until 2012, that is after almost all of the Japanese manufactured forged, Class 1 components would have entered the Japanese supply chain. The period of concern is when the regulatory framework was under the auspices of the *Japan Nuclear Energy Organisation* (JNES) and the then nuclear safety regulator the *Nuclear and Industry Safety Agency* (NISA), both organisations much discredited and disbanded by the Diet Committee following the Fukushima Daiichi catastrophe. Perhaps surprising therefore that the NRA permitted the operators to rely wholly on the original manufacturing records and not to specifically inspect and test the in situ candidate components.

The screening process to determine if the components were at risk comprised 4 steps. The first 3 steps required the operator (eg Kyushu) to arrive at a judgment on whether or not any residual macrosegregation originated from and/or was eliminated at a manufacturing stage, and if the levels of heterogeneity present in the component were acceptable. If none of these three simple criteria were satisfied then the final step D required assessment to be undertaken via physical analysis (ie chemical analysis, cutting out samples, etc) and/or reference to a formulaic approach such as a carbon prediction of the original cast ingot.

Obviously, each of the first 3 steps relates entirely to the original manufacturing process of which the utility NPP operators had, nor could be expected to have, any experience and expertise. Indeed, all that the operators could be expected to do would have been to refer to the original manufacturing records that had been handed on to them many years if not decades earlier by the forging manufacturers, that is the likes of JCFC, JSW and (the predecessors of) JFE.

On their parts, the forging manufacturers (JCFC, etc) submitted somewhat ambiguous descriptions of the manufacturing processes, neither being component-specific or having any meaningful chemical analysis or physical testing results – where limited data was included in the original documents it was redacted. Interestingly, JCFC although providing some mainly text narrative about the SG flawed bottom channel heads exported to France (and in doing so demonstrating that its ingot heterogeneity formulaic model was unreliable), it did not at all refer to the SG components, including the bottom channel heads, that it had manufactured for Japanese NPPs. Similarly, JSW and JFE did not furnish any details on the SG components that they had respectively manufactured for installation in Japanese NPPs.

So, overall, the submissions of the operators and forging manufacturers have not resolved the uncertainties of whether, possibly, flawed components entered the Japanese nuclear equipment supply chain. Indeed, whereas the NRA dismissed the possibility of heterogeneity in Class 1 components, mainly on the basis of the methods of manufacture, the submissions of JCFC, JSW and JFE clearly showed that macrosegregation heterogeneity formed in the pre-forged ingots and, moreover, that JCFC and JSW used a carbon content prediction model in account of this.

The Review concludes that the matter of the risk of flawed components being present in Japanese NPPs has yet to be satisfactorily resolved. Unlike the French who have an extensive inspection and testing programme in hand at operational NPPs, the NRA has yet to require in situ inspection and physical testing of the installed components and/or replicates thereof.

Relying solely upon past manufacturing records, some now from three decades past, without undertaking even the most rudimentary of crosschecks by chemical analysis and material physical testing, potentially overlooks the real possibility that zones of degraded toughness are present in installed components – all of the major components of the primary coolant circuit of both PWR and BWR light water reactor variants are forged and thus vulnerable to residual segregate zones. The possibility that such zones exist, raises the issue of the reactor operational safety case which, as currently underway in France, will be need to be reviewed and revised. In view of these uncertainties, and potentially severe component failure, the prudent tactic would be to follow the approach adopted by the French nuclear safety regulator ASN in requiring physical testing of all relevant components installed in Japanese light water moderated reactors.

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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, etc. |
| 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 that connects to the steamside circuit. |
| EPR | European Pressurised Reactor |
| ESPN | *Équipements Sous Pression Nucléair*e – 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 Sûreté* |
| 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 |

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| 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 1450$MW_e$ 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 |

During the Summer of 2016, the discovery of shortfalls in the material characteristics of key components in the French nuclear equipment supply chain triggered serious concerns about the nuclear safety of at least 18 French nuclear power plants.[1] Associated with 12 of these French nuclear power plants (NPPs) is the installation of forged components supplied by the *Japan Casting and Forging Corporation* (JCFC) and, possibly, with details awaited from the French nuclear safety regulator *Autorité de Sûreté Nucléaire* (ASN), further doubts relating to components supplied by the *Japan Steel Works* (JSW).

The material shortfall arose from the presence of a flaw in the granular structure of forged steel components generally referred to as the *'carbon anomaly'*. Essentially this arises when areas of segregates formed during the ingot casting stages of the forging process are not cropped and discarded from the forging billet. Certain of the segregate zones are rich in carbon (greater than the ~0.2% in weight for the specified carbon steel alloy) thereby degrading the material toughness and rendering those parts of the forging susceptible to fast fracture and catastrophic failure.[2] FIGURE 1 shows the relationship between decreasing toughness with increasing carbon content resulting, in this hypothetical example, a fall of about 50% in toughness of the carbon content range of 0.22% to 0.39% reported for the JCFC forged components in the French nuclear equipment supply chain.

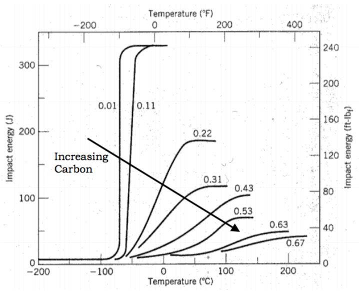


FIGURE 1 TOUGHNESS -V- CARBON CONTENT

LargeAssociates first reported on the developing situation in France in September 2016[1] raising doubts about the possible presence of similarly flawed components embedded in the Japanese nuclear equipment supply chain.[3] Salient developments in France since the previous LargeAssociates reporting have been:

- **ASN verifies JCFC sub-standard components (lower heads) installed in 12 French NPPs**

  For the period from 1989 though to 1997 AREVA-EdF installed a total of 36 replacement steam generators (SGs) over 12 operational French NPPs[4] containing now acknowledged seriously flawed bottom channel heads supplied by JCFC. This information was confirmed by ASN on 27 October following requests from LargeAssociates.[see Table of Ref 4]

- **French NPPs with JCFC components ordered to be Shut Down**

  As further understanding of the *'carbon anomaly'* present in the 12 affected NPPs developed, in October 2016 ASN ordered 7 NPPs to shut down for immediate inspection of the JCFC bottom channel heads following which, on 18 October 2016, ASN required[5] the remaining 5 NPPs to be shut down by late December 2016 – all of these plants were to remain shut down until the single French NPP operator *Électricité de France SA* (EdF) has demonstrated that it is safe for each NPP to return to power.

  At that time (October 2016) the general consensus was that the investigation and test programmes for this batch of shut down NPPs alone will occupy EdF and AREVA until at least Spring of 2017, thereafter EdF will have to prepare a licensing safety case for assessment by ASN and its advisors, *Institut de Radioprotection et de Sûreté* (IRSN)


FIGURE 2 STEAM GENERATOR

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1 LargeAssociates, *Review Irregularities and Anomalies Relating to the Forged Components of Le Creusot Forge*, Greenpeace France, 29 September 2016 - http://www.largeassociates.com/CZ3233/Note_LargeAndAssociates_EN_26092016.pdf

2 In engineering terminology the material characteristic is the *'toughness'* and the failure mode is referred to as *'fast'* or *'brittle fracture'*.

3 LargeAssociates, *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*, October 2016 - http://www.largeassociates.com/CZ3235/R3235-A1%20FINAL%2024-10-16.pdf

4 ASN Response to LargeAssociates request for further information of 15 September 2016 – Table under Slide 7a - http://www.largeassociates.com/CZ3235/3235search.html

5 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)* - file:///Users/largeassociates/Downloads/2016-DC-0572%20(3).pdf

and the *Advisory Committee of Experts for Nuclear Pressure Equipment* (ACENPE).

However, in late November IRSN[6] assessed a second submission from EdF that further detailed its generic *Demonstration Approach* to show if it would be feasible to operate the JCFC SG channel head installed NPPs safely with the imposition of restrictions and *'compensatory'* measures, which is the option permitted under French statute for components that do not comply with the design basis specification. Although IRSN accepted EdF's generic Demonstration Approach for outer surface excess carbon levels up to 0.32%, it advised ASN that EdF's assessment was incomplete, from which ASN issued a directive[7] of 5 December 2016 to EdF listing thirteen requirements, including the manufacture afresh of full scale JCFC replicates, to demonstrate the validity of restarting the NPPs that had JCFC SG components installed.

- **IRSN Analysis of Risk**

In August 2015 IRSN advised[8] that, based on EdF's preliminary inspection results of a carbon excess level of 0.3% over the specified maximum of 0.22%, the resulting reduction in steel toughness raised an unacceptable fast fracture risk and vulnerability of catastrophic failure of the JCFC components. Subsequent EdF examination revealed much higher levels of excess carbon at ≥0.39% in the JCFC components of the shutdown Tricastin 1 and 3 NPPs.[9] This prompted ASN to immediately order the phased shutdown of the 5 remaining operating plants and, whilst continuing in operation, that strict 'compensatory' measures be implemented to mitigate the risk of rapid fracture failure.[9]

The presence of fast fracture vulnerable components (the JCFC SG channel heads) in the pressurised circuit introduces the need to include two 'new' abnormal operating situations to the nuclear safety case. For example, if the reactor circuit is subject to high rates of transient change, say when the reactor is scrammed in response to a small leak in the primary circuit and when cold make-up water is injected into the circuit, there is risk that the normally hot SG channel head will encounter a cold slug of water thus thermally plunging the head temperature into the catastrophic brittle failure regime.[10, 24]

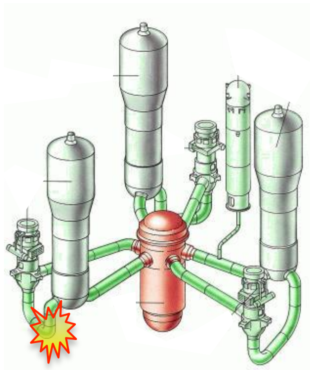

FIGURE 3 LOCA THERMAL TRANSIENT

There is a not dissimilar risk of failure when the head encounters a hot slug of water travelling round the primary coolant circuit, for example, during reactor start-up transients.

The introduction or, at least, greater emphasis that needs to be placed on the operating safety envelope for NPPs known to have installed fast fracture vulnerable components requires considerable effort and is time consuming. Accordingly, EdF's justification of continuing operation of these NPPs is likely to take several months to review by IRSN and

6 IRSN, *Avis de l'IRSN sur la sûreté des réacteurs de 900 MWe équipés de générateurs de vapeur dont les fonds présentent une teneur anormalement élevée en carbone*, Note d'information, 6 December 2016 – the 0.32% limit means that above this level EdF's generic Demonstration Approach is not considered valid.

7 ASN, *Serviceability of the steam generator channel heads manufactured by JCFC*, CODEP-DEP-2016-047228, 5 December 2016

8 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 - http://www.largeassociates.com/CZ3235/3235search.html

9 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 - http://www.irsn.fr/FR/Actualites_presse/Actualites/Documents/IRSN_NI_Centrales-EDF-Anomalies-Generateurs-Vapeur_20161018.pdf

10 The toughness and resistance to 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 when failure is by elongation, and when it is brittle and failing totally by cleavage (brittle or fast fracture). 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 material toughness characteristic results alone can be misleading when applied to a real industrial application such as the RPV and other components of the primary pressure circuit.

ACENPE, this being before ASN is able to assume a regulatory stance on this unique operating situation.

There are two options for the presently shutdown JCFC channel head NPPs: First, in the interim if, say, individual NPPs are permitted to restart (ie those under the 0.32% carbon threshold)[6] operating under restrictions and *'compensatory'* measures,[11] then much, but not all of the nuclear generating capacity will be restored in France, although under 'compensatory' operation the restarted NPPs may have quite severe restrictions placed on the load-following and frequency regulation roles. If, on the other hand, if all or some of the 12 French JCFC NPPs affected remain shut down possibly until mid-Summer 2017 before restarting is permitted or, on the other hand, if the uncertainty and risk introduced by these flawed JCFC components is assessed to be so dire then the NPPs may have to remain shutdown until the steam generators, as a whole, are replaced – a process that could incur two to three years delay as acknowledged by EdF in its 5 December 2016.[12]

- **ASN reckoning on the probability of JCFC flawed components**

  At first (2015) EdF argued that the flaw was most probably confined to a few 'rogue' JCFC components but as inspections at the enforced shutdown NPPs got underway the first results confirmed the presence of macrosegregation on all of the bottom heads as each was inspected. In other words, the flawed component rate was 100%.[4]

- **ASN Raises doubts about JSW supply of flawed components**

  Two avenues of possible inclusion of flawed components from Japan Steel Works (JSW) are raised by ASN: the first is related to a number of *'irregularities'* (generally taken to be incorrect records) found for JSW supplied components for the Flamanville 3 steam generators and, the second, to significant areas of excess carbon segregates located in a) the tubesheets and b) the elliptical head component of the steam generators for the 2nd phase of the replacement steam generator programme for the French 1,300MWe series of NPPs.[12] In May 2016 AREVA agreed to scrap three or four steam generators awaiting installation in the 2nd phase programme because of the 'late' discovery of excess carbon on the bottom channel head components. Although JSW supplied some of the tubesheets, elliptical and bottom head components, it is not possible to definitely identify any of these JSW supplied parts to include the zones of excess carbon, although further information is awaited from ASN in this respect.[13]

  However, there are hitherto unpublished documents that implicate the presence of flawed JSW components in the French nuclear equipment supply chain. The first of these documents[14] relates to omissions and/or non-compliance or conformity with manufacturing protocols for the reactor pressure vessel parts; for each of the four steam generators the elliptical domes, bottom channel heads and tubesheets; and the pressuriser. And a second document[15] involves, amongst other N1 pressurised components, three steam generator components:-

  > "*. . . Vous avez indiqué, dans les dossiers de qualification technique de plusieurs composants, que vous ne pouviez garantir les valeurs de caractéristiques mécaniques indiquées dans l'arrêté ESPN en tous points et avez transmis à l'ASN des justifications de l'absence de conséquences de cette différence. Ces justifications*

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11 At the time of writing 7 December 2016, it is not at all clear if individual units of the 12 NPPs fitted with JCFC bottom channel heads will be permitted to restart in advance of the 13 prerequisites demanded of EdF.[7]

12 ASN, *Major Positive Residual Carbon Segregation Forged Components of EDF's Operating Fleet, (in French - Ségrégationsmajeures positives résiduelles du Carbone Composants forgés du parc en exploitation d'EDF) 24 juin 2016)* 24 June 2016 - http://www.hctisn.fr/IMG/pdf/1_d_ASN_seg_majeures_cle0a15eb.pdf - see also HCTISN meeting of 5 December 2016.

13 LargeAssociates, M3235-A1, A2, A3 *Requests to ASN for Further Information* October 2016 - http://www.largeassociates.com/CZ3235/3235search.html

14 ASN to AREVA, *EPR FA3 Qualification technique Pièces Coulées avant 2008*, 3 May 2010

15 ASN to AREVA, CODEP-DEP-2011-067787, *Implementation of regulatory requirements on the mechanical properties of materials some components for the EPR Flamanville 3 and replacement of steam generators*, References: [1] the GP Referral ESPN CODEP-DEP-2011-059746 of 15 November 2011

*concernent des vannes d'isolement vapeur (MSIV) destinées à l'EPR Flamanville 3 et certains composants de générateurs de vapeur. . ."*[16]

Of particular interest is *Annex 3*[15] which advances the risk of sudden rupture of the tubesheet and the 'reproducibility' of successive tubesheets; and the absence of test results for the bottom channel heads,[17] although these may relate only to those components manufactured at the French le Creusot Forge.

Since ASN communicates only with the principal French contractor, AREVA acting as the contracted party to the nuclear licensee EdF, in this licensing correspondence [15, 17] JSW is not specifically named as the supplier of the Flamanville 3 steam generator components (channel head, elliptical dome and tubesheet). However, JSW is identified as the supplier in other ASN presentational documentation,[12] and JSW itself acknowledges that it supplied these SG components for the Flamanville 3 NPP.[18]

- **ASN reveals evidence of Document Alteration at Parliamentary Hearing**

Under examination by the *Parliamentary Office for Evaluation of Scientific and Technological Options* (L'OPECST)[19, 20] in October 2016 ASN presented, as not atypical examples, two instances of alteration of the manufacturing and test result records at the le Creusot Forge. The latter example (FIGURE 4) shows the test results for the crucial material toughness (and % elongation) being blatantly altered seemingly in order to meet the individual and average toughness requirement of 60J and 80J respectively.[21] If the component had been originally presented with these unaltered test results then there can be no doubt that it would have been rejected and scrapped.

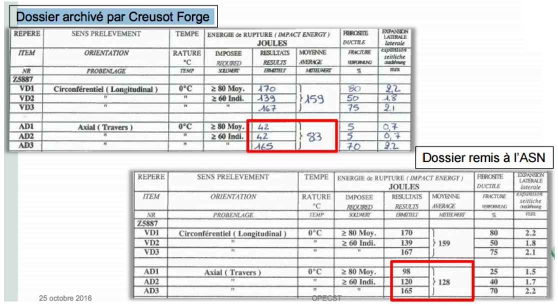



FIGURE 4 LE CREUSOT FALSIFICATION OF TEST RECORDS

ASN also revealed that le Creusot personnel identified those files holding the master and unaltered records because they were secretly marked on the folder covers with *'crossed bars'*, this being known only to certain le Creusot personnel.[22] The files potentially subject to such *'irregularities'* are believed to number several thousand being currently under ongoing investigation. It is understood that ASN has referred the matter to the French public prosecutor.

So, by mid-October 2016 it is now acknowledged that the French nuclear equipment supply chain very definitively included JCFC supplied components with excess carbon flaws. Because all of the JCFC components inspected to date include this flaw it is more than likely that <u>all</u> other JCFC components supplied for the 1st phase steam generator replacement programme (1989 though to 1997) that have yet to be examined will also be flawed in this way.[4] The general engineering prognosis is that N1 nuclear safety critical components with such an excess of carbon (≥0.39% over the specified maximum of 0.22%) are not fit for purpose and will have to be permanently withdrawn from service. IRSN has recommended that 0.32% carbon, particularly in the region of the return leg nozzle, is the upper limit over which EdF's generic Demonstration Approach is

16 *". . . you indicated in the records of technical qualification of several components, that you can not guarantee the mechanical characteristics of values in the order in every respect and ESPN have passed ASN justifications for the lack of consequences of this difference. These justifications are for steam isolation valves (MSIV) for the EPR Flamanville 3 steam generators and some components. . . "*

17 Here there may be some confusion with those components manufactured at Creusot Forge and not by JSW,

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

19 Proceedings of l'OPECST - http://videos.assemblee-nationale.fr/video.4345585_580f80fe66839.opecst--controle-des-equipements-sous-pression-nucleaires-25-octobre-2016

20 ASN, *Anomalies et irregularities sur les équipements sous pression nucléaires*, OPECST 25 Octobre 2016 - file:///Users/largeassociates/Downloads/20161025_OPECST_ESPN%20(4).pdf

21 The actual results of 42, 42, 165 joule giving an average of 83J but failing on two individual results, being altered to 98, 120, 165 with average of 128J , thus passing on all three individual results.

22 ASN, *Compte-rendu d'evenement significatif a caractere generique defauts d'assurancequalite chez creusotforge sur des dossiers de fabrications de composants d'e|pduparcenexploitation*

invalid, even so NPPs below this threshold will be required to operate under restrictions and with 'compensatory' measures in place.

Of importance here is that these flawed JCFC components somehow managed to pass through all of the French quality control checks stipulated by ASN. These ASN QA requirements would have been implanted as part of the extended French nuclear safety regulatory regime (such as RCC-M140)[23] at the JCFC Kitakyushu works. The flawed components would also have passed through JCFC's own quality controls, prior to dispatch from the JCFC works to enter France undetected to be, first, incorporated into the overall steam generator assembly, the whole issued with a N1 Test Certificate (of RCC-M140 conformity) and, then, installed in operational NPPs.

Now that the presence of the flawed JCFC components is known, ASN requires the French operator EdF to carry out a number of actions:-

1) presentation of the records held for the JCFC manufacturing route, including the material characterisation data (M140 analysis and test results);
2) physical examination of the installed JCFC components, including exploratory spark optical emission spectrometry (OES) to determine the carbon content at the surface, ultrasound and dye penetrant tests to check for surface flaws and, it is believed that EdF has or will be Charpy (toughness) testing a number of coupon pieces cut from the original test rings at the time of the original manufacture;
3) complete a risk assessment for the reduced toughness characteristic (fast fracture vulnerability) of the steel failure of the JCFC SG components and taking into account two new, hitherto considered unnecessary operational scenarios[24] involving thermal shock (both hot and cold extremes) of the JCFC SG bottom channel head component; and
4) the manufacture afresh of a 120 tonne ingot and several full scale sacrificial, replicate bottom channel head components at the JCFC Kitakyushu works for carbon mapping, analysis and physical testing.

The present situation in France is that 7 NPPs with JCFC SG components installed have shut down and are to remain shut down until ASN grants permission for each to resume criticality. Additionally, a further 5 NPPs, also fitted with JCFC SG components, are all to be shut down in a phased sequence by December end 2016 and, similarly, the JCFC components are to be in situ examined and the NPPs remain shut down until ASN grants permission for these to restart. These 12 NPPs may be permitted to continue in operation or restart, as appropriate, under restricted operation and the 'compensatory' measures recommended by IRSN, either within a week or so of early December 2016 or, much later, in mid 2017 if and when the ASN Directive to EdF of 13 prerequisite conditions has been satisfied.

Also, it is believed that replacement steam generators installed during the 2$^{nd}$ phase replacement SG programme (1,300MWe series NPPs) which may or may not include SG bottom channel head, elliptical dome and tubesheet components supplied by JSW are also subject to in situ inspection.

23 As part of the extended French nuclear regulatory requirement it is normal for place of manufacture of all N1 category components destined for the French nuclear equipment supply chain to be inspected and certified by an agency of ASN.

24 The cold shock scenario is the most challenging for a bottom channel head that is vulnerable to fast fracture failure. In this abnormal operating condition a small breach or *loss of coolant accident* (LOCA) occurs on a hot leg feeding to the steam generator, the resulting pressure drop creates steam formation in the RPV head and in the tube bank of the SG, with the primary circuit temperature dropping from around 290$^{o}$C to 250$^{o}$C and with the steam filled volute of the circulator pump effectively cavitating as steam develops in the return leg of the primary circuit. As a result of cold emergency make-up water being injected into the return leg of the primary circuit, the injected cold water floods into the RPV annulus and, on the return leg, reverses flow past the cavitating pump to encounter the hot steel of the bottom channel head – at this point in the sequence the outlet nozzle of the channel head temperature rapidly collapses to around 30$^{o}$C compared to the inlet side of the channel head manifold being maintained at around 180$^{o}$C – this temperature difference and rapid strain rate plunge return nozzle area of the channel head into the brittle regime, thereby exposing it to fast fracture and the catastrophic opening of the primary coolant circuit via a major LOCA breach.

## JAPANESE NUCLEAR EQUIPMENT SUPPLY CHAIN

Involvement of the Japanese *Nuclear Regulation Authority* (NRA), on a formal basis at least, commences in August 2016, that is before the prescheduled 12-13 September meeting between ASN and the NRA in Tokyo:-

- **Joint Statement of ASN and NRA – Tokyo, 12-13 September 2016**

  In September 2016 ASN met with the Japanese NRA, issuing a two-part statement by way of a slide presentation.[25]

  On its part, ASN stated the seriousness of the JCFC flaws but played down the potential for non-compliant JSW components. Subsequently ASN moderated its opinion about JSW's manufacturing processes 'guaranteeing' the exclusion of macrosegregation zones and freedom from heterogeneity when questioned over the basis of this.[4]

  ASN also noted that a number of counterfeit, fraudulent and substandard items (CFSI) had entered the French supply chain since the end of 2015. Later ASN confirmed[4] that of these recent CFSIs one was Creusot Forge, a second was at another but unnamed French forge, and the third was at an unnamed overseas supplier.[4] There are, essentially, two possibilities for this CFSI 'overseas' supplier, these being JSW or Sheffield Forgemasters of the UK, JCFC being ruled out because it is believed it does not have present (2015-16) supply contracts for French NPP components.

  On its part, almost unashamedly, NRA stated that the probability of segregated forged components having entered the Japanese nuclear equipment supply chain was very low for a variety of reasons, including claimed high standards of production and that many of the components were manufactured by hot forming of precast slab or plate steel and so being inherently free of macrosegregation zones.[26] NRA presented a tabulation of the manufacturers and manufacturing processes for a various components, although it did not detail the various components of the steam generators for the Japanese PWR NPPs.

  Even in advance of any data being submitted to it by the Japanese NPP operators, the NRA discounted the possibility of the presence of residual zones of macrosegregation largely on the basis that the manufacturing techniques pursued in Japan did not include processes that yielded macrosegregation and, thus, eliminating the source of segregate formation at the onset[see TABLE 6 of Appendix V of 3] – all of this somewhat disingenuously turning a blind eye to the established fact that JCFC had produced and supplied some 36 or so SG bottom channel head component to France, each of which has been shown to be seriously flawed with macrosegregation zones and heterogeneity.

  An unscheduled outcome of the meeting between ASN and NRA appears to have been the mid-October visit by NRA personnel to ASN in Paris, although the discussion topics between these two national nuclear regulators, nor a joint statement, has been revealed by either of the parties.

On 17 October 2016 NRA published a document comprising the separate submissions of JCFC, JSW and JFE (JFE Holdings). This document[27] provides information on the manufacturing processes adopted at each of these nuclear pressurised equipment manufacturers.

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

26 It was subsequently shown that for the greater number of component types, mainly hemispherical shells were hot formed from slab produced by upset forging conventional billets.

27 NRA, 仏国原子力安全局で確認された原子炉容器等における炭素偏析の 可能性に係る調査の状況等について -平成28年10月19日 原子力規制庁 - in Japanese.

- ## Japan Casting and Forging Corporation - JCFC

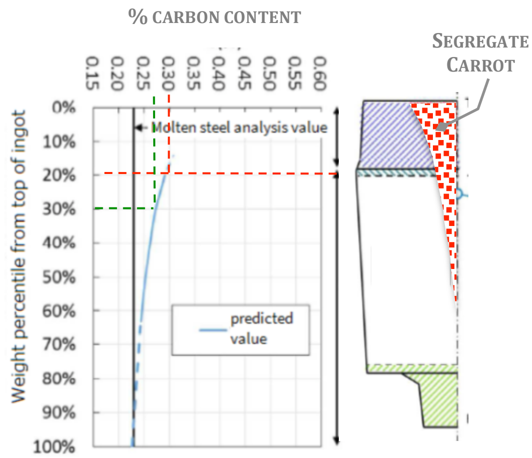



FIGURE 5 JCFC CARBON PREDICTIVE MODEL FOR 135T INGOT

COMPONENTS SUPPLIED TO THE FRENCH: For large, multi-tonnage components JCFC upset forges a single, conventional ingot, followed by machining to the final component design specification. For example, the gross ingot tonnage for the SG bottom channel heads supplied to France was 120 tonnes, although it is believed that the first four channel heads were forged from 90t ingots.

During the ingot casting and cooling stage, in the riser and higher section of the ingot, a carrot-shaped positive macrosegregation zone develops with an accompanying increase in the local carbon content. To determine the amount of the ingot to be cropped to discard the formation of positive macrosegregation in the (top) riser portion of the ingot JCFC, like other forges, adopts a formulaic approach based on its past experience.

Essentially, the model adopted assumes an increasing carbon content in the centre portion of the riser and higher part of the ingot body over the ingot ladle analysis composition – this deviation is shown by the blue characteristic ——— (FIGURE 5) for the vertical centreline or axis of the ingot, there being a decline in excess carbon content as the sampling point moves further away from the centreline.

In this example for a 135t ingot, the carbon content of the ladle melt is 0.23% but the actual carbon content at an equivalent weight *'topside'* depth of 20% is around 0.30% (- - - -) so, if the ingot (on right) was topside cropped at 30% of weight from the top of the ingot, the maximum carbon content remaining in the bloom would be 0.27% (- - - -) reducing further into the depth of the bloom.

At the bottom of the ingot the formation of a shorter depth of negative macrosegregation characterised by a reduction in the carbon content – this is also cropped and discarded in the final bloom to be upset forged.

This discard approach invariably leaves some of the positive macrosegregation zone on the bloom to be upset forged. However, the upset processing (ie high pressure forging through rollers, etc) works and distributes the macrosegregation zone on the surface of the developing forging blank so that, as a relatively thin layer, it may be partially machined off prior to the blank being hot formed and then, finally, again machined reduced when the forged component is finished machined.

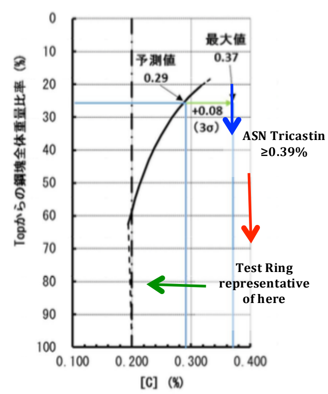



FIGURE 6 JCFC PREDICTION APPLIED TO FRENCH SG BOTTOM HEAD

For the SG bottom channel head components supplied to the French the gross ingot size was 120t of which the topside discard was 20% and the machined-off amount about 6%. JCFC's predictive model (FIGURE 6) for this size ingot at 26% total topside discard (cropping + machining) was reckoned to yield a 0.29% carbon content. Actually, JCFC measured a maximum of 0.37% compared to ASN's reported ≥0.39% on the SG bottom channel heads of Tricastin Units 1 and 3.

These results are disturbing in a number of respects:

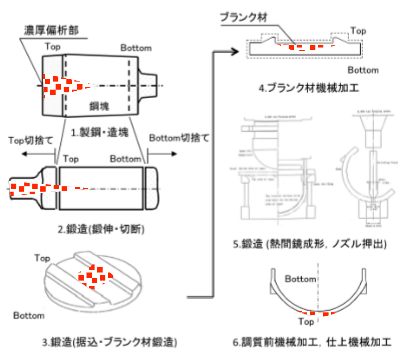



FIGURE 7 MACROSEGREGATION ZONE ORIENTATI

First, if this predictive model had been applied to the manufacturing of the French SG bottom channel heads, and there is no firm reason to believe it would have not have, then the projected level of 0.29% carbon content and the manifestly obvious heterogeneity would have certainly not have met the AREVA specification – in other words, the component would have been scrapped.

Second, it is not clear when and from where the JCFC measured (or test) value of 0.37% was taken. If this result had been obtained at the time of manufacture, say from chemical analysis of swarf collected from the first or second machining rounds, then the component should have been scrapped.

FIGURE 7 shows the changing orientation and position of the macrosegregation zone followed through in the JCFC forging process most likely adopted for the SG bottom channel heads. Where a portion of the macrosegregation zone is retained, the situation represented by FIGURE 7, the carrot root extends into and is retained in the bloomed ingot (Stage 2); then with the bloom rotated clockwise by 90°, the upset forging spreads the macrosegregation zone over the top face pre-machined and rough-machined blank (Stages 3 and 4); finally with the rough-machined blank flipped over for hot forming, to be retained on the outer surface of the finished component (Stage 6).

FIGURE 8 is illustrative of a finished SG bottom channel head showing the macrosegregation zone located on the outer surface that was originally the top part of the bloom. The test ring, shown for clarity separated from the head, is trepan cut from the head in a later stage of the head production – from this test ring are taken samples for chemical analysis and physical testing for material toughness (Charpy) and ductility (% elongation). In other words, in chemical analysis and physical characteristic the test ring is representative of the <u>lower</u> part of the cropped bloom (see FIGURE 7) and will not indicate any residual macrosegregation located on the outer surface of the channel head.

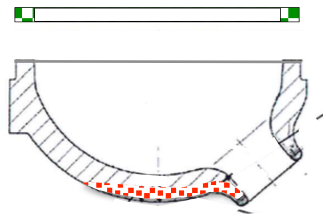


FIGURE 8 BOTTOM CHANNEL HEAD & TEST RING

There are two possible explanations as to how the 36 SG bottom channel heads passed through the JCFC quality controls to be installed in French operational NPPs: It could be that JCFC overly relied upon, first, its formulaic approach that was predicting incorrect carbon levels in the ingot and, then second, it assumed that the material samples extracted from the test rings were representative of the finished components as a whole. This latter assumption could only be correct if the components were free of heterogeneity, although subsequent tests in France have conclusively shown that they are not.

The alternative explanation is that AREVA and the French nuclear safety regulator ASN agreed that these components were, even with the extraordinary high, localised levels of carbon, fit for purpose. However, there is no record that the ASN ever agreed to such a scheme, thereby sanctioning the entry of seriously flawed components into the French nuclear equipment supply chain.

Finally, of course it is possible that the manufacturing records accompanying these JCFC components did not reflect the actual conditions and test results that would have, at that time, precluded acceptance of the JCFC components. As noted previously, the example of le Creusot Forge fraudulent records presented by ASN to the French parliamentary committee[19] managed to deceive ASN into accepting similar le Creusot components as fit for service.

COMPONENTS SUPPLIED TO THE JAPANESE NPPS: In Japan two variants of the light water moderated reactor have been commissioned over past years – these are the pressurised water reactor (PWR) and the boiling water reactor (BWR). The PWR variant, like its counterpart in France, includes a primary coolant circuit that links together the reactor pressure vessel (RPV), pressuriser, steam generators and pumps, whereas the BWR is simpler in equipment with the main RPV just served by circulatory pumps – all of these major components for PWR and BWR components are large forged carbon steel parts.

According to the returns[28] of the Japanese power utilities that have installed JCFC components (SG, RPV and other Class 1 components) there is nothing untoward about the certification of chemical analysis and physical test results.

However, the results presented are taken from the original manufacturing records for the components so, it follows, where the same formulaic predictive modelling was adopted in conjunction with the unreliability of the test ring, there will be some element of risk that components with zones of heterogeneity entered Japanese nuclear equipment supply chain undetected. It follows, that these components are now installed in NPPs that are either presently operational or awaiting permission to resume criticality.

For its NRA submission JCFC categorises the manufacturing routes into 6 Cases ordered by i) the manufacturing process and ii) ingot weight. For example, Cases 1, 2 and 3 used for the manufacture of RPV upper heads, is a 'traditional' forging process using 210t, 260t and 400t ingots are schematically represented by FIGURE 9:-

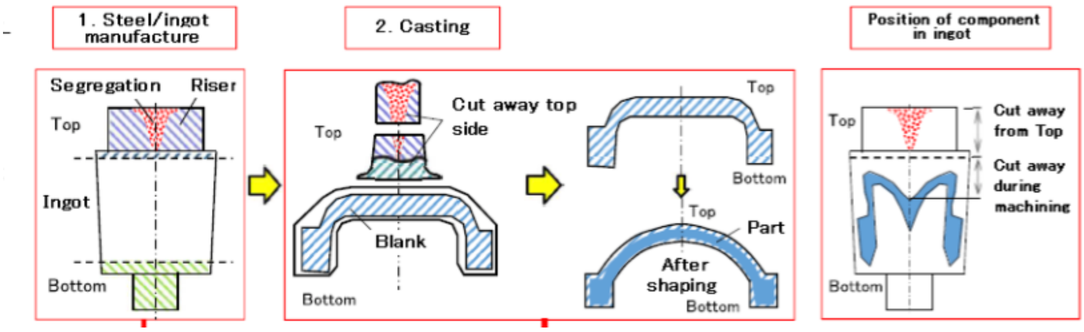



FIGURE 9 - CASES 1, 2 AND 3 - TRADITIONAL FORGING PROCESS – RPV UPPER HEAD
TAKAHAMA 2 - GENKAI 2 - OI 1, 2 - IKATA 2

The Case 4 category, used for the RPV upper head of Tsuruga 2 from a 260t ingot, is also a forging process although certain of the interim processes have been redacted in the JCFC submission.

RPV bottom heads for Fukushima Daini 2 and 4, and Shika 1 were manufactured from 260t and 90t ingots by Cases 5 and 6 respectively, again by forging. Case 5 differs from all other cases inasmuch that the bloomed ingot is turned on its side so that any remaining positive and negative macrosegregation zones are located as 'ears' of a lozenge-shaped intermediate stage as shown schematically by FIGURE 10.

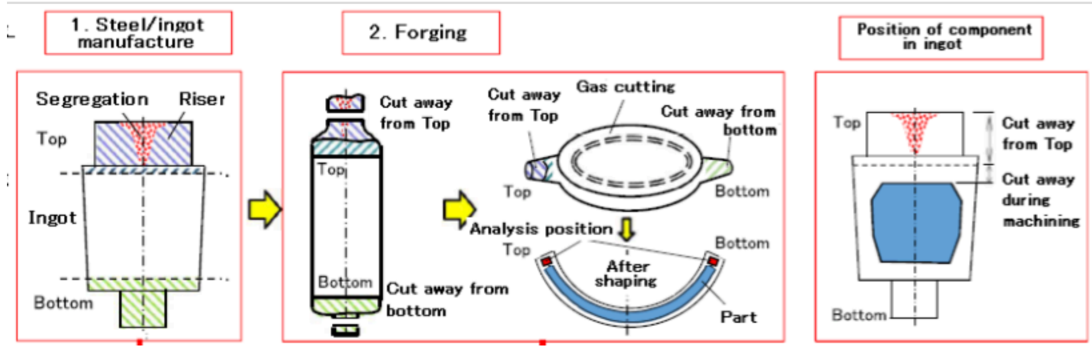



FIGURE 10 CASE 5 LATERAL FORGING PROCESS - 260T INGOT FOR FUKUSHIMA DAINI 2 AND 4

Another seemingly unique feature of Case 5 is that JCFC makes no reference to its predictive modelling to determine the discard proportion of the ingot

- **Japan Steel Works - JSW**

JSW also utilises its own formulaic approach to determine to optimal discard to minimise the presence of residual macrosegregation zones in the bloom.

For the PWR RPV head components JSW works the bloom *'top-down'* so any residual macrosegregation zone is present on the inner surface layers of the forged component, thereafter being scalped out by rough and finish machining operations – this 'reversal' of the finished component position in the billet is shown by FIGURE 11. There is nothing in this *'top-down'* forging process that


FIGURE 11 JSW TOP-DOWN PROCESS

absolutely precludes the formation and integration of a positive macrosegregation zone in the bloomed ingot.

Also, it is of interest to note that in its submission JSW acknowledges that positive macrosegregation exists in the ingot and there is a residual amount remaining in the RPV bottom head component:-

> *"... Carbon segregation tends to occur at Top side of the ingot core. The riser is cut away in order to remove this region, The ingot core is moreover cut away using a hollow punch. The final component is located in a region where there is no increased component concentration zone, therefore, carbon segregation in excess of 0,26 wt.% does not remain"*

This directly contradicts the September NRA statement[25] that due to the production technique *"JSW's forging materials are free of positive macro-segregation zones"*. Indeed, to the contrary, JSW acknowledges the presence of segregate heterogeneity because it relies upon a predictive formula to remove segregate zones at the intermediate plate machining stages.

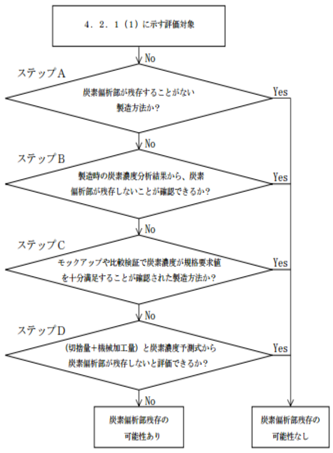
Although it is established that JSW supplied SG components into the French nuclear equipment supply chain,[18] unlike JCFC, the JSW submission to NRA makes no reference whatsoever to these N1 components (namely the tubesheets and bottom channel heads for the Flamanville 3 NPP and, possibly, for the 2nd phase replacement SG programme of the French 1,300MWe NPPs).

- **JFE Holdings - JFE**

  Similar to both JCFC and JSW, JFE manufacturers its Class 1 components by upset forging, although for its hemispherical shell or head components the bloom is worked *'side-on'* so that any residual positive and negative zones of macrosegregation appear at opposite ends of the test ring of the finished component.

In fact, all of the Class 1 components supplied by these manufacturers (JCFC, JSW and JFE) involved forging processes in their manufacture. Even those ascribed as made of plate being, solely on this basis, screened out on the claim that it was not possible to include residual segregate zones, were forged from a single, conventional ingot that itself in cooling was at risk of the formation of positive macrosegregation zones and hence local carbon enhancement. Such components should have been inspected at the break in the forging sequence and, appropriately, 'officially' certified to be free of segregates.

In each of their 17 October returns to the NRA,[27] the individual forgers (JCFC, JSW and JFE) do not reveal the actual levels of enhanced carbon segregates remaining in the components supplied. Where enhanced carbon is acknowledged to exist, the actual levels are redacted – the top-limit of ≤0.26% acknowledged by JSW, over the specified ~0.22% generally accepted for RPV and primary cooling circuit components, represents about a 30% loss of material toughness at the 0°C reference temperature.




第4－1図　評価フロー

FIGURE 12 NRA SCREENING STEPS

- **Returns from Japanese Utilities of 31 October 2016**

  The NRA required the NPP operators to provide an assessment of the Class 1 (equivalent to the French N1 category) forged components that had been installed in their respective NPPs. These returns were completed by each operator on a pro forma template, with the respondent following a simple, four-step screening logic.[28]

  Each of the first three steps (A, B and C) required the operator respondent to make a judgment on whether or not any residual macrosegregation originated from and/or was eliminated at a manufacturing stage, and if the levels of heterogeneity present in the

28 NRA, Response of the Nuclear Power Generating Utilities, 31 October 2016 - http://www.largeassociates.com/CZ3233/ASNRequestsandAnswers/000168565kyushuelectric.pdf

component were acceptable. If none of these three simple criteria were satisfied then the final step D required assessment to be undertaken via physical analysis (ie cutting out samples) and/or reference to a formulaic approach such as a carbon prediction of the original cast ingot.

The first three steps of this approach are inappropriate for a number of reasons:

First and foremost, the initial three steps relate entirely to the manufacturing process of which the utility operators had, nor could be expected to have, any experience – all that the operators could have done would have been to refer to the original manufacturing records that had been handed on to them individually by the forging manufacturers, that is the likes of JCFC, JSW and (the predecessors of) JFE.

In detail, for example:-

STEP A sets aside annular components (such as the RPV centre body sections and outer shells of steam generators) simply on the assumption that all macrosegregation would be removed from the bloom by the punch-through central axis discard. However, the recent discovery of the heavily segregated zone of the lower shell of a SG (manufactured by Creusot Forge in France) of the French Fessenheim 2 NPP places considerable doubt on such an overriding assumption being correct.[29] Similarly, the assumption that steel plate or slab will be inherently free of macrosegregation zones is incorrect because any residual zones have to be first detected and then removed before further forging operations are undertaken – this applies to both plate reduced from stamp-forging a conventional ingot and, also, slab produced by continuous strand casting and the like.

STEP B assumes that sufficiently representative samples have been taken *after* the component has been forged and shaped. However, for such large forgings the opportunity does not arise to take samples directly from the component because doing so would render the component itself unusable. Instead, there is almost total reliance on the quality and consistency of the manufacturing route and sampling from the test ring, where appropriate, although the location of the test ring may be remote from those parts of the forging that are vulnerable to heterogeneity.

STEP C relies upon the manufacturing route being, first, comprehensively and consistently prescribed in the successive production of identical components and that the whole series or train of components will be characterised by the analysis and testing of a replicate component. In other words, if the first component produced is satisfactory, as demonstrated by what may or may not be destructive analysis and testing, then it is presumed that all following components will be segregate free and satisfactory. This consistency of manufacturing safeguard clearly failed for the JCFC bottom channel heads now in the French nuclear equipment supply chain since <u>all</u> have shown unacceptable levels of heterogeneity.[5]

STEP D allows for assessment of the presence of macrosegregation zones to be determined by carbon level predictive formula, such as those adopted by JCFC and JSW, which are very sensitive to ingot size at the bloom discard stage – quite obviously, the JCFC formulaic predictive approach for the French SG bottom channel heads completely failed (see FIGURE 6).[30]

29 ASN, Note d'information of 20 July 2016

30 Essentially, each ingot size (tonnage) has a unique characteristic so the predictive formula has to be tailored to ingot size and ladle analysis. The larger the ingot tonnage then, generally, the greater the in-reach of the segregate carrot-root and hence the greater the topside discard % weight – for the 120t ingot used for the JCFC bottom channel heads the blooming and machining topside discard was about 26% of total ingot weight but for larger tonnage ingots at, say, 260t the total discard is around 80% of the initial ingot weight.

Example of the manipulation of this 4-step process is given by the Kyushu Electric Power return.[31]

In this Kyushu submission, believed to be very typical of the other NPP operators, all of the SG bottom head components (Genkai 2, 3 and 4 and Sendai 1 and 2) have been cleared from further investigation at STEP A. Although details given for this early clearance are very sparse, it is presumed that the segregation zones will have been predicted and physically removed from the bloom during the early forging discard processes although, that said, no evidence of the discard weight or predicted and distribution of the associated carbon levels is presented. Of particular interest is the screening out of the SG channel heads manufactured by JCFC for Sendai 2 NPP because it is assumed that these would have been manufactured by much the same forging processes as the JCFC SG bottom channel heads exported to France that are now known to be flawed with a residual macrosegregation zone.

The STEP A, B and C screening processes, all of which refer to an unreferenced *'manufacturing manual'*, are also accompanied by a much simplified summary of the analysis and physical test results, including ladle analysis, carbon concentration, and single and average (over 3) test Charpy toughness results all taken from the original manufacturer's records.

In very much the same vein, Kyushu reports that the other forged components were each filtered positively from the 4-step screening process, relying upon reference to the *'manufacturing manual'*, concluding that *"it was possible to confirm that there is no possibility of carbon segregation regions remaining in any of the components evaluated by Kyushu Electric Power".* Other than relying upon the manufacturing records made some years before the 1984-5 commissioning date for Sendai 1 and 2 NPPs, Kyushu does not report on any recent examination/inspection of key, forged components installed at the Sendai NPPs, thus bypassing the opportunity for non-destructive examination (NDE), or indeed analysis and physical testing of sample blanks that are normally held in reserve from the time of manufacture of the various components of the reactor primary coolant circuits.

Kyushu and the other power utilities reproduce values for the Charpy (toughness) and other material characterisation test results of samples taken at the time of the forging process. Supposedly, these values each individually relate to different specific components installed at different NPPs. However, there appears to be an odd, somewhat 'clinical' consistency in the results viewed as data sets, although the explanation of this is not possible without access to fuller details of the data and its original acquisition.[32]

If, as acknowledged by JCFC and JSW, the first stages of ingot casting and cooling were accompanied by the formation of macrosegregation zones in all of their respective manufacturing processes, then the individual component submissions should have included certificates verifying that the zones of segregates had been removed at the appropriate intermediate stages of the forging process – this could have been in the form of the certified *'forging ratio'*; a record of the discard weight; and chemical analysis of swarf and other small discards yielded during the interim rough and final finish machining stages, none of which has been provided in the submissions of power utilities.

- **Response of NRA to Diet Members Questions**

Diet Member Ms Mizuho Fukushima put to the NRA a series of requests[33] for further and supporting information on general and specific issues relating to the potential for *'carbon anom*aly' flaws – the NRA response[34] was curt and non-informative, some might opine derisory.

31 Kyushu Electric Power, 31 October 2016 – this was the only return of all of the power utilities made available in English, albeit not a complete and authorized translation. That said, the tabulated, pro forma layout of the other power company returns indicate much the sameness with the test results and other number entries being readily understood.

32 NRA, *Results of investigation on the possibility of segregation of carbon in nuclear reactor containers etc. confirmed by French Nuclear Safety Authority*, November 22, 2016

33 Diet Member questions and response from to NRA (in Japanese), 4 November 2016

34 ibid (in English), 4 November 2016

**FINDINGS**

The issue is whether there is sufficient evidence or doubt that flawed Class 1 components destined for the pressurised primary coolant circuit could have entered the Japanese nuclear equipment supply chain. These components, flawed or otherwise, are now resident in Japanese NPPs that are presently operational (Sendai 1 and 2, and Ikata 3) or those that might restart in the near future.

On one hand, the JCFC components destined for the French supply chain were seriously flawed with substantially weakened material toughness, to the extent that these components are not fit for purpose. The French JCFC contract closely followed-on JCFC contracts supplying much the same steam generator components to the Japanese supply chain – manufacturing these components involved much the same forging processes and quality control checks at the JCFC works as the French component counterparts manufactured at the same forging works.

On the other hand, the JCFC French components were eventually discovered because concerns were raised about parts of the new-build Flamanville 3 reactor and how these were manufactured at the French le Creusot Forge – such was the concern over Creusot Forge's quality controls extending beyond the Flamanville 3 forged components, that where practicable extraordinary checks and inspections were carried out on all N1 forged components at the French operational NPPs. Normally, outage inspections for NPPs are based on the assumption that the components would have been thoroughly inspected for and certified to be free of residual zones of macrosegregation during manufacturing and supply stages – if flawed components had slipped through the safeguards and checks at the manufacturing stages, then these components are, as applied in France, likely to remain undetected in operational NPPs.

In other words, the example of France shows that the only way to realistically determine the presence of such flawed components in operational NPPs is to undertake extramural inspections and tests, otherwise the flawed components, if such exist, are likely to remain in situ undetected.

In Japan, the NRA has chosen at this time not to require physical inspection of the JCFC components installed in Japanese NPPs. Instead, presently it is relying solely upon referring to the original manufacturing records and an albeit very crude 4-step screening system. This is quite contrary to the experience in France where it is now irrefutably established that reliance upon the manufacturing records alone is wholly insufficient.

As investigations progress in France, doubts are also being raised about JSW components (SG tubesheets, channel heads and elliptical heads) and, it is expected that these JSW components will now be subject to a rigorous, independent physical examination to determine the presence, if any, of residual zones of segregates. For JSW (and JFE) components supplied to the Japanese nuclear equipment supply chain, NRA requires only a response from the nuclear power utilities drawn from the past manufacturing records.

**IN CONCLUSION:** The NRA has yet to decide if an appropriate programme of physical examination/inspection, analysis and testing is to be undertaken to determine the future nuclear safety of Japanese NPPs. However, at this time, the NRA is relying solely on the original manufacturing records provided by the forged component suppliers (JCFC, JSW and JFE) and what seems to be little more than the NPP operators (Kyushu, etc) trawling through much the same original records.

Relying solely upon past manufacturing records, some now from three decades past, without undertaking even the most rudimentary of crosschecks by chemical analysis and material physical testing, potentially overlooks the real possibility that zones of significantly degraded toughness are present. The possibility that such zones exist, raises the issue of the need to review the reactor operational safety case which, as currently underway in France, would need to be reviewed and revised. With such uncertainties, and potentially severe radiological consequences, the prudent tactic would be to follow the approach adopted by the French nuclear safety regulator ASN in requiring physical testing of all relevant components installed in Japanese reactors. Obviously such a testing programme would need to be prioritised to those NPPs in operation (Sendai units 1 and 2 and Ikata 3) in the first instance being a priority, to then be extended across all of Japanese NPPs.

Even so, a more satisfactory approach would be for an independent assessor to carry out such inspections and tests considered appropriate to determine the fit-for-purpose state of the Class 1 pressurised primary coolant circuit presently resident in Japanese NPPs, irrespective of their current operational status – this would be proportionate and commensurate with the effort now underway and overseen by the French nuclear safety regulator ASN on components supplied by the same Japanese forges (both JCFC and possibly JSW).

**JOHN LARGE**
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# APPENDIX I

## NPPs WITH JCFC AND CREUSOT FORGE BOTTOM CHANNEL HEADS INSTALLED

| RÉACTEUR CONCERNÉ | MANUFACTURING SOURCE | DATE OF MANUFACTURING |
|---|---|---|
| **CHINON B1** | Creusot Forge | 2000 |
| **CHINON B2** | Creusot Forge | 2006-2007 |
| **St LAURENT B1** | JCFC | 1989 |
| **St LAURENT B2** | Creusot Forge | 1997 |
| **DAMPIERRE 2** | Creusot Forge | 2000 |
| **DAMPIERRE 3** | JCFC | 1991 |
| **DAMPIERRE 4** | Creusot Forge | 2000 |
| **TRICASTIN 1** | JCFC | 1994 |
| **TRICASTIN 2** | JCFC | 1994 |
| **TRICASTIN 3** | JCFC/Creusot Forge | 1995/1994 |
| **TRICASTIN 4** | JCFC | 1997 |
| **BUGEY 4** | JCFC/Creusot Forge | 1995/1994 |
| **GRAVELINES 2** | JCFC | 1992 |
| **GRAVELINES 4** | JCFC | 1993-1994 |
| **FESSENHEIM 1** | JCFC | 1996 |
| **CIVAUX 1** | JCFC | 1990 |
| **CIVAUX 2** | JCFC | 1992 |
| **BLAYAIS 1** | Creusot Forge | 2005-2006 |

source: ASN 27 October 2016[4]

This Review is generally confined to the 12 NPPs with JCFC components installed, although it should be noted that concern has been expressed about nuclear safety of the 6 NPPs with bottom channel head components produced by le Creusot Forge also shown in the above table. It may be that the additional precautionary measures also are in place at these NPPs.