Carbon Macrosegregation in Large Forgings

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Background / Origin of Issue

Background on Origin of Issue

- Flamanville 3 (FA3) *European Pressurized Reactor* (EPR) is under construction in France
- FA3 RPV closure head and bottom head were fabricated by Creusot Forge in 2006 and 2007
- The French Nuclear Safety Authority (ASN) introduced new fracture toughness regulations for primary system components in 2005 ("ESPN order")
  - New rule requires fabricator to consider possible heterogeneity and to show that heterogenous areas meet fracture toughness requirements
  - ASN was concerned that specimens taken here may not be representative of dome region
- FA3 RPV heads were fabricated before acceptable technical qualification methods for meeting this new regulation were established

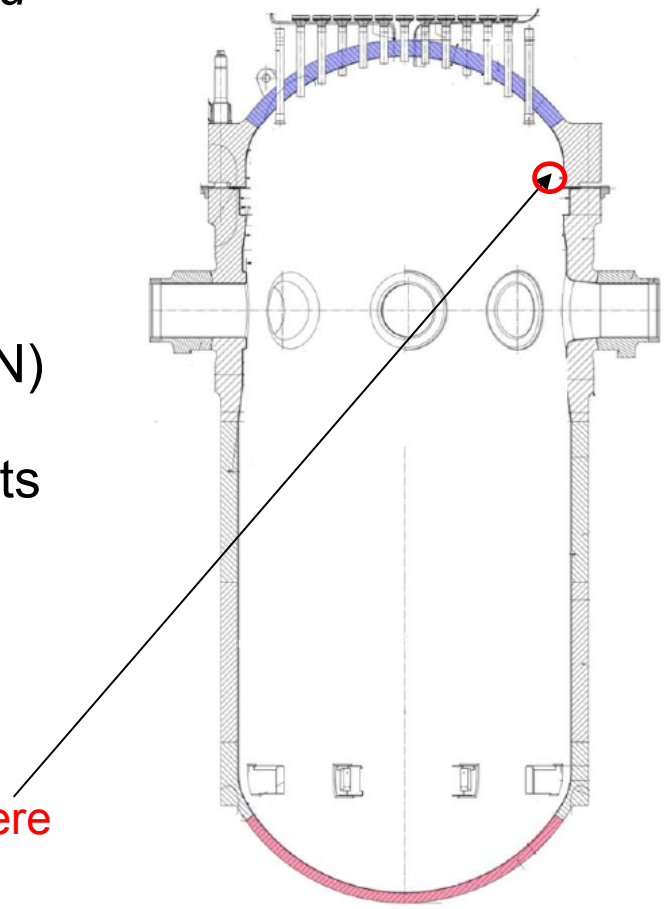
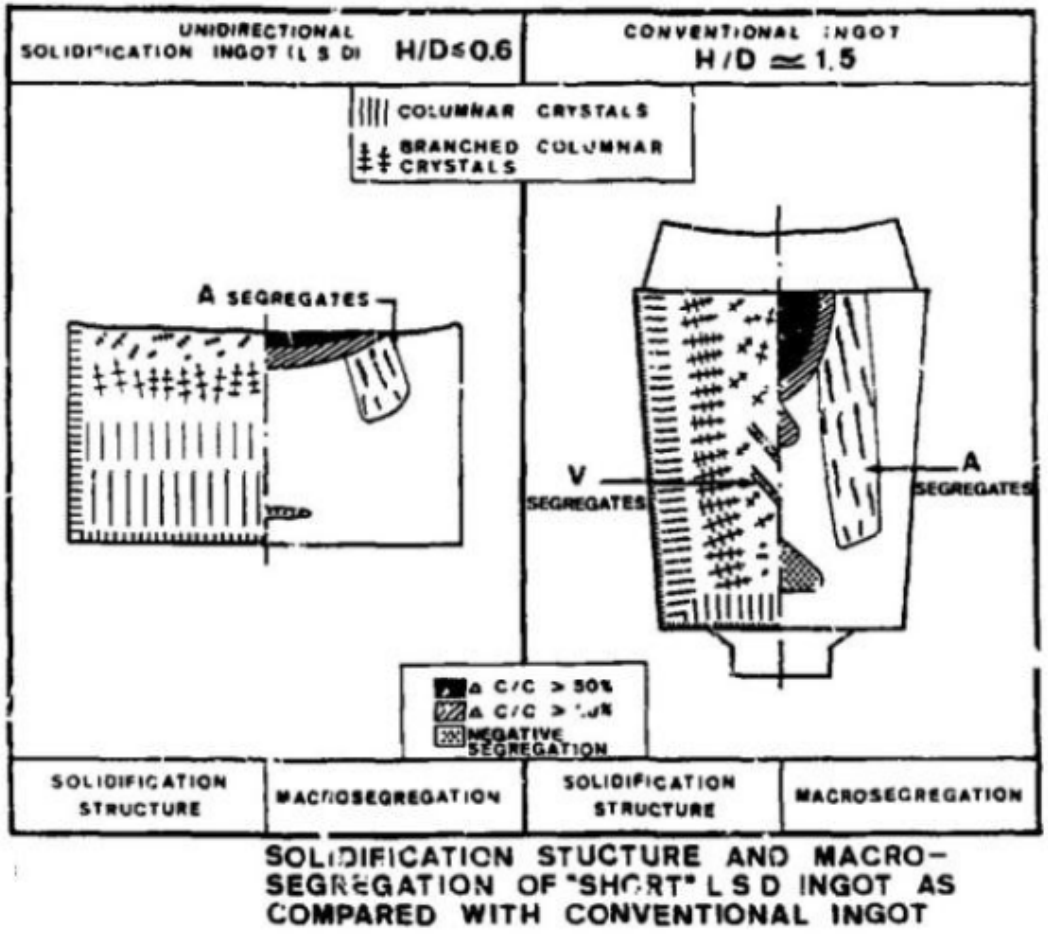


Diagram of Flamanville 3 EPR RPV from CODEP-DEP-2015-037971 , "Analysis of the procedure proposed by AREVA to prove adequate toughness of the domes of the Flamanville 3 EPR reactor pressure vessel (RPV) lower head and closure head"

Fabrication of FA3 RPV Heads

- Typically, Creusot uses a ***single directional solidification*** ingot (*Lingot à Solidification Dirigée,* LSD) which reduces carbon macrosegregation
- The size of the EPR head exceeded Creusot's industrial capacity to fabricate an LSD ingot, so a **conventional ingot** was used
  - Known to be more susceptible to carbon macrosegregation than LSD ingot

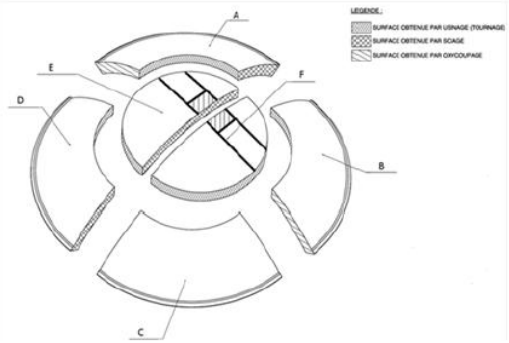


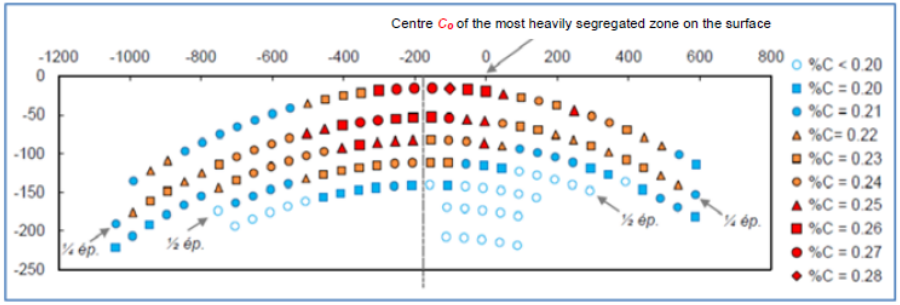
SOLIDIFICATION STUCTURE AND MACRO-SEGREGATION OF "SHORT" L S D INGOT AS COMPARED WITH CONVENTIONAL INGOT

Figure from CODEP-DEP-2015-037971 showing morphologies of segregates in LSD ingot (left) and conventional ingot (right)

Low Toughness from Qualification Tests

- In 2012 AREVA and ASN agreed how AREVA should demonstrate compliance with 2005 regulation
- AREVA destructively tested 2 other EPR heads fabricated by Creusot Forge using same method as FA3 heads
  - Impact tests at 0°C averaged 52J, below the minimum 60 J
- An investigation was conducted to determine cause of low toughness in dome
  - Carbon measurements at surface using portable spectrometry revealed large area of positive macrosegregation (high carbon)





Map of carbon content in similar head;
Figure from CODEP-DEP-2015-037971

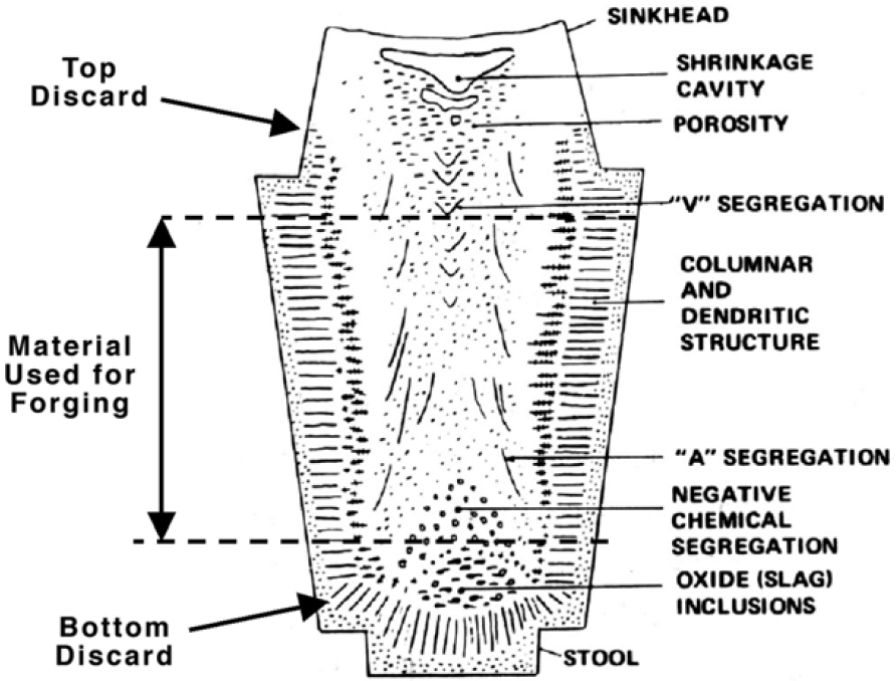
Carbon limit in France = 0.22 wt.%; by comparison, A508 Cl 2 limit is 0.27 wt.%; A508 Cl 3, 0.25 wt.%.

Consequences of Discovery of High Carbon in Flamanville 3 Head

Immediate Response	Consequence
AREVA launched a program to justify the acceptability of the FA3 heads by analysis	At end of 2016 AREVA submitted justification package; ASN review to last at least 6 months
French regulator asked if in-service components forged from conventional ingots could have this condition	Other components were identified as potentially susceptible (S/G channel heads) ⇒ **High Carbon issue**
AREVA launched a Quality Review of Creusot Forge	AREVA discovered multiple discrepancies in components manufactured by Creusot Forge ⇒ **Creusot QA records issue**

What is Macrosegregation?

- Macrosegregation - the segregation of alloying elements in an ingot over large length scales (cm or m)
- Macrosegregation occurs during solidification of an ingot
  - Interdendritic fluid flow in the mushy zone, “thermosolutal convection”
- Carbon (C) segregation is positive at the top of the ingot and negative at the bottom
  - Radiation-sensitive elements Cu and P co-segregate with C
- Phenomenon has been recognized and studied for many years – e.g., 9 reports 1926-1940 from the Heterogeneity of Steel Ingots Sub-Committee of Iron and Steel Institute (U.K.)



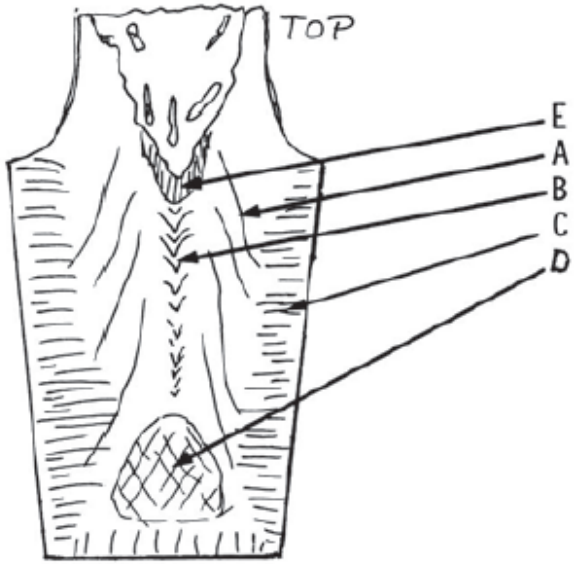
Controls to Minimize Macrosegregation in Ingots

- Carbon macrosegregation (CMAC) is characteristic in conventional ingots and tends to increase with ingot size
- ASTM standard for A 508 requires that “Sufficient discard shall be made from each ingot to secure freedom from piping [formation of cavities] and excessive segregation.”
  - “Excessive segregation” is not defined
- Specification A 508 imposes several more stringent requirements than the general requirements for forgings in ASTM A788 (Steel Forgings, General Requirements):
  - Steel must be vacuum degassed
  - Forgings must be quenched & tempered
  - Large forgings require testing (tensile & Charpy) at both ends; and at each end, 180° apart
  - In addition to ladle analysis, a product analysis is required
  - Permissible variations in carbon allowed by A788 are not allowed by A 508

Efforts to Minimize Macrosegregation in Components

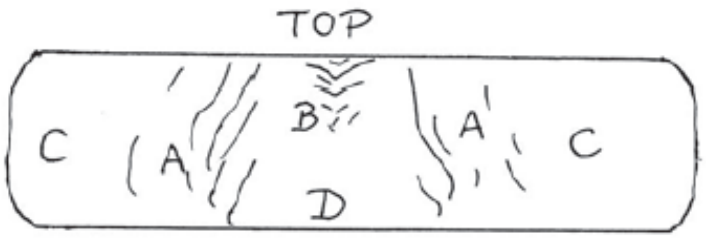
- As industrial demand for larger forged components has increased, the size of ingots has increased – and with it, the potential for macrosegregation
- Some fabricators have developed methods to minimize CMAC:
  - Japan Steel Works (JSW) multiple pouring method
    - PVP2004-3056: "JSW applies a multiple pouring method in which carbon content is differentiated in each heat for an ingot over 140 ton to minimize carbon segregation in large-sized ingot."
  - Creusot Forge "LSD" ingot design
    - See *"Application of New Types of Ingots to the Manufacturing of Heavy Pressure Vessel Forgings"* by Pierre Bocquet *et.al.*, ASTM STP 903, 1986.
- The degree of carbon segregation in any particular component will depend on
  - measures taken by the steelmaker to minimize segregation in the ingot
  - amount of top discard
  - thermo-mechanical path taken to forge the component
    - Example – trepan for ring forging removes area of highest segregation

Location of Macrosegregation in the Final Component Depends on How a Conventional Ingot is Forged

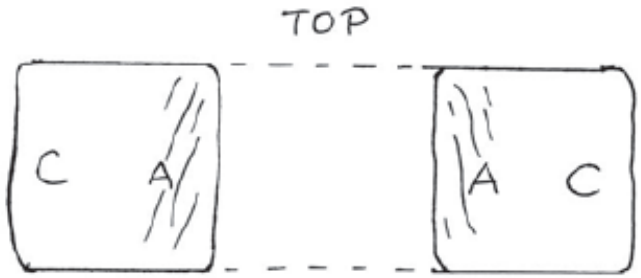


Heavily segregated pipe region
A-segregate
V-segregate
Columnar grains
Region of negative segregation

Figures from
"Macroscopic Segregation in Ingots and Its Implications in Modelling of Structures Made From Heavy Sections"
by S.F. Pugh, U.K. Atomic Energy Authority, 1982



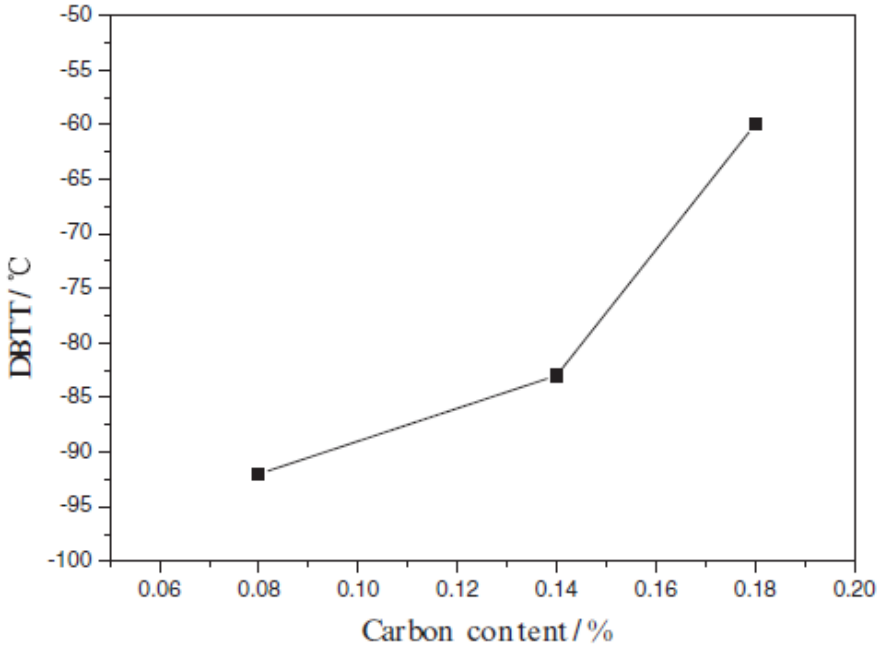
Upset disk, such as might be used for fabrication of an RPV Head or steam generator channel head



Forged ring; note the center has been removed (trepanned)

Effects of Carbon on Notch Toughness and Shelf Energy

- Increasing carbon content from 0.2 to 0.3 wt.% increases strength but decreases notch toughness and shelf energy



Note: This data is for bainitic steel.

→ Increasing C by 0.1 wt.% increases RT_{NDT} by ~32°C

Industry is evaluating the long-term need for additional data

Figure from: **"The Influence of Carbon Content and Cooling Rate on the Toughness of Mn-Mo-Ni Low-Alloy Steels" by H. Liu and H. Zhang.**

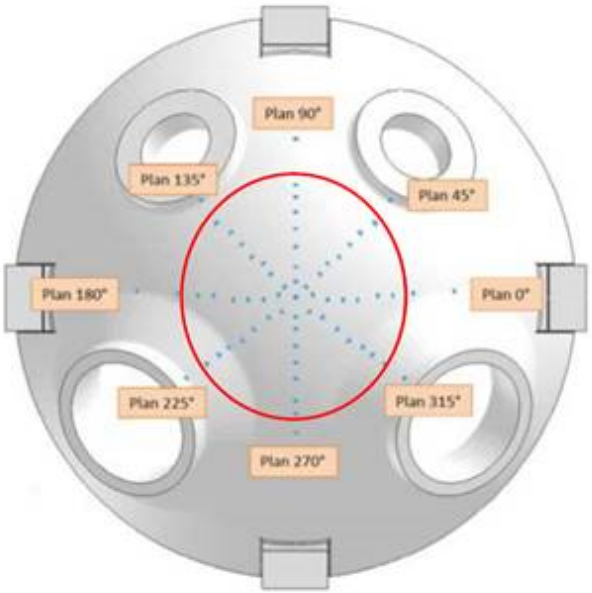
Carbon Issue in France

EDF/AREVA Review of Other Heavy Forged Components

- ASN requested that AREVA and EDF determine if other heavy forged components could be susceptible to high carbon by reviewing all heavy forged components
  - Concern is for components (e.g., vessel heads & shells, etc.) forged from conventional ingots (no concern for LSD ingots)
  - Three fabricators provided components forged from conventional ingots to PWRs in France: Creusot Forge, Japan Steel Works (JSW), Japan Casting and Forging Corporation (JCFC)
    - JSW process not susceptible (PVP2004-3056)
- EDF found 18 PWRs that have S/G channel heads forged from conventional ingots by Creusot and JCFC with high probability of carbon macrosegregation

Evaluation of Steam Generator Channel Heads (1/2)

- ASN required EDF to perform the following activities for the S/G of the 18 PWRs with Creusot and JCFC channel head forgings:
  - Surface measurements for carbon content
    - Spark Optical Emission Spectrometer (S-OES)
  - UT inspection
  - Fracture analysis
- Some carbon measurements on the steam generator channel heads from JCFC were as high as 0.39 wt.%
  - Carbon on Creusot-forged channel heads not as high, <0.32 wt.%
- EDF has 12 PWRs with steam generators containing forgings from JCFC
  - ASN required all units to have carbon measurements performed



Details of fracture analysis are based on IRSN Notification 2016-00369

Evaluation of Steam Generator Channel Heads (2/2)

- Fracture analysis was based on:
  - Postulated surface cracks on outside (hot shock transients) and inside surface (cold shock transients)
  - Assumed carbon 0.4 wt.% on outside surface (max. measured on JCFC heads), 0.26 wt.% on inside surface
  - Accounted for reduction of toughness by shifting RT_{NDT} by 180°C on outer surface, 70°C on inner surface
  - Performed deterministic analyses for various hot shock and cold shock transients (due to LOCA, accidental valve openings and pump starts, etc.)
- Conservative deterministic fracture analyses by EDF demonstrated the channel heads have no risk of fracture
- However, due to the high shift-carbon relationship assumed in the analyses, EDF agreed to adopt compensatory operational measures in order to limit thermal shock to S/G channel heads
- All affected PWRs have been authorized to restart

Impact of Carbon Issue in Japan

Impact of High Carbon Issue in Japan

- Concerned that some carbon measurements on forgings supplied by JCFC were ~0.39 wt%, ASN informed Japan's regulator
- On August 24, 2016, Japan's Nuclear Regulation Authority (NRA) ordered that all PWRs & BWRs check large forged nuclear components - including the reactor pressure vessels, steam generators and pressurizers - for high levels of carbon in the steel
- NRA required 2 actions:
  - For major components, report product form and fabricator
  - For forged components, evaluate the risk that the component may have zones with higher carbon concentration than allowed by Japan standards

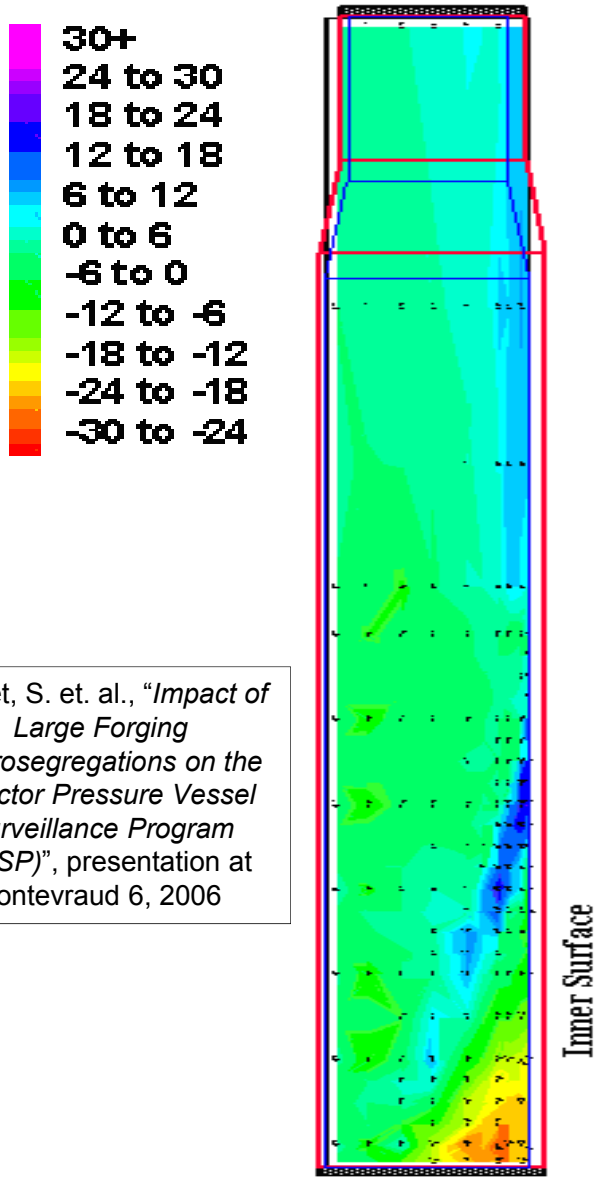
Resolution of Issue in Japan

- On October 31, 2016, all Japanese nuclear utilities reported there is no possibility of carbon anomalies in any reactor coolant system (RCS) heavy components
- NRA accepted the utility reports
- NRA also released a preliminary report on the forging practices of Japan Casting & Forging Corp. (JCFC), Japan Steel Works (JSW), and JFE Steel Corp. (formerly, Kawasaki Steel Corporation)
  - "Status of an Investigation on the Potential Carbon Segregation in Reactor Vessels Confirmed by ASN," The Secretariat of the Nuclear Regulation Authority, dated October 19, 2016
  - Each fabricator provided a summary of forging process(es) and the steps taken to avoid high carbon

EPRI Activities to Address Carbon Issue

Safety Significance for RPV

- In late 2016, MRP started a project to assess the risk associated with postulated carbon macrosegregation in RPV ring forgings
  - Risk is evaluated using probabilistic fracture mechanics (PFM) analyses to determine the conditional probability of vessel failure (CPF) or through-wall cracking frequency (TWCF) for ring forgings with postulated macrosegregation
- RPV shell analyses complete
  - Draft report currently undergoing peer review
  - Final report publication: 6/30/2017



Saillet, S. et. al., "*Impact of Large Forging Macrosegregations on the Reactor Pressure Vessel Surveillance Program (PVSP)*", presentation at Fontevraud 6, 2006

Evaluation of RPV Forgings

- Risk evaluation efforts:
  - Deterministic and probabilistic fracture mechanics analyses
  - Evaluation of the limiting forging material: RPV beltline ring forging material with the highest RT_{MAX} at 80 years in the U.S. PWR fleet
  - Normal cooldown along the Appendix G PT limit curve: 547°F to 300°F at 100°F/hr., then 300°F to 60°F at 50°F/hr
  - Postulated PTS events: 61 transients from the NRC's Alternate PTS evaluation of a 3-loop PWR
  - Carbon macrosegregation distributions for head and ring forgings
  - Postulated copper and phosphorous cosegregation
  - Embedded and small surface flaws
  - $RT_{NDT(U)} = RT_{NDT(Uo)} + C_o \bullet 560 \bullet (\Delta C/C_o)$
    - 560°F/wt.% C is change in $RT_{NDT(U)}$ as a function of change in carbon content; average of data from 7 sources
- Preliminary results
  - The risk criteria (CPF < 10^{-6}, and 95% TWCF < 10^{-6}) will be maintained through the end of an 80 year operating interval at postulated carbon macrosegregation levels greater than the maximum measured values

Additional Evaluations Recommended by Ad Hoc Cmte

- In February 2017, the utility executive leadership of the Primary Materials Management Program (PMMP) requested MRP to expand scope of efforts to address other potentially affected components
  - RPV heads, steam generator channel heads, etc.
- A utility-led Ad Hoc Committee to address the carbon macrosegregation issue was formed
  - Met on March 17 and April 24
  - Recommended approach that is summarized on next slide

Approach for Assessing CMAC Issue for Large Forgings

Activity	Description
A. Extension of RPV PFM analyses to qualitatively bound other components	This work is in progress; report due in June 2017 (will be included in RPV report).
B. Document technical basis for the hypothesis that RPV integrity bounds other components	Review of historical documents relative to hypothesis that materials in the RPV beltline are bounding for the entire RCS.
C. Quantitative structural analyses to assess whether the results of the PFM analyses of the RPV beltline (Activity "A") bound the other forged components	Quantitative deterministic structural analyses to assess whether the beltline PFM analyses bound design stresses and transients for the RPV heads, pressurizer dome region, and SG channel heads
D. Assess impact of carbon macrosegregation for SG tubesheets, based on expert judgment and experience with fabrication of the tubesheets as large forgings	Qualitative analysis to determine whether tubesheet design is tolerant of the effects of carbon macrosegregation
Estimated completion date for B - D	**October 2017 (Report – November 2017)**

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