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ASME and NRC Discussion on Code Case N-766 Weld Inlay/Onlay Mitigation or Repair

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Goals of the Meeting

- Review the NRC Comments received on the Code Case, which is now published
- Present new information on the service experience of Alloy 690 and Alloy 52/152
- Come to agreement as to how to resolve the staff comments

Why we like N-766 as it stands

- Carefully developed and reviewed in the ASME code process
- Inlay/onlay material is highly resistant to crack initiation (at least 16 years service with no cracks in SG applications)
- Service experience of inlays/onlays has been very good (ten years service with no cracks)
- Inspection capability is more than sufficient to find degradation
- The code case as it stands encourages mitigation

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Topics of Presentation

- NRC Comments – status, summary of comments and ASME responses
- Operating history and PWSCC resistance of Alloy 690 and Alloy 52
- Inspection capabilities
- Sample inlay/onlay fatigue crack growth calculation
- Status of inlays/onlays in operation

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Summary of Remaining NRC Comments

- The NRC staff disagrees with the proposed rules for embedding pre-existing flaws using an inlay, based on their PWSCC concerns (NRC Report ML101260548)
  - The NRC staff believes that Code Case N-766 should require PWSCC crack growth analysis
  - The NRC staff believes that the minimum required inlay thickness should be increased based on PWSCC concerns (NRC Report ML101260548)

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ASME Responses

- PWSCC is not a concern for Alloy 52/152 because it is a highly resistant material (*presentations to follow*)
- N-766 requires volumetric and surface examination prior to and after inlay (including excavated cavity)
  - DMW flaws will be removed or seal welded prior to inlay
  - Indications greater than 1.5mm (1/16 inch) are not permitted in the inlay surface
- Welds with embedded flaws require volumetric and surface examination once during the next two refueling cycles to ensure that the flaws are not growing and new flaws have not initiated (N-770-1, Table 1, Footnotes 16 and 17
- The 1/8 inch minimum thickness provides adequate margin for fatigue crack growth (*presentation to follow*)
- The treatment of embedded flaws is consistent with Section XI and Code Case N-770-1

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PWSCC Resistance of Alloy 690 and Alloy 52

- Operating experience and current data indicate that Alloy 690 and associated weld metal Alloy 52, are highly resistant materials
  - Extremely PWSCC initiation resistant
  - Very slow PWSCC growth from starter indications

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Operating Experience with Alloy 690 and Alloy 52/152 Weld Metal

- PWSCC and Secondary side SCC of Alloy 690 TT steam generator tubing is excellent
- Alloy 690TT SG tubes perform well in PWR water because of the Cr carbide microstructure and the Cr chemistry
- Alloy 52/152 welds perform well in primary water mostly because of the Cr chemistry. Additional opportunity for carbide precipitation occurs during PWHT and during multi-pass welding

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PWSCC Issues Related to an Inlay Repair

- If a high quality, indication-free weld is deposited on the inlay surface, do we anticipate a remaining service life without PWSCC initiation?
- If minor indications (<1.5 mm) and micro-indications such as ductility dip cracking flaws exist in the inlay weld metal, will these indications grow to un-acceptable levels during the remaining service life?

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Where is there the most operating experience with Alloy 52/152 welds?

- Inlay Experience
  - Ringhals 3 and 4
  - More details later; no PWSCC after **10 – 11 EDY** with multiple volumetric inspections
- Replacement SG Welds (~**25 EDY**)
- PZR Heater Sleeve Repairs (>**100 EDY**)
- Replacement RV Heads (~**19 EDY**)
- Embedded Flaw Repairs to Head Penetrations (no PWSCC after >**10 EDY**)

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Replacement SG Experience with Alloy 52/152 Welds

- Steam Generators (divider plates / stub runner welds / SG inlet/outlet dissimilar metal welds)
- Between the first Alloy 690 Replacement SG (DC Cook in March 1989) and the end of 2008, over 79 other PWRs have replaced SGs with Alloy 690 tubed generators
- Over 227 SGs have been replaced; Most have 52/152 welds
- Listing of Alloy 690 steam generators on following slide
- Earliest US steam generator with Alloy 52 welds installed in 1994, VC Summer, over 16 years experience
- Lead hot leg weld exposure is > 25 EDYs
- No service problems identified with 52/152 welds;
- There have been welding difficulties
- Limited inspections performed, no indications found

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Alloy 690/52/152 Steam Generators

majority of SG made since 1994 use 52/152

Installation	PWRs with Alloy 690 Steam Generators (USA, Europe, Asia)
1989	D.C. Cook-2, Indian Point-3, Ringhals-2
1990	Dampierre-1
1991	Ohi-3
1992	Penly-2
1993	Millstone-2, North Anna-1, Beznau-1, Ohi-4
1994	VC Summer, Gravelines-1, Golfech-2, Mihama-2, Takahama-2, Genkai-1, Daya Bay-1, Daya Bay-2, Genkai-3, Ikata-3
1995	North Anna-2, Tihange-1, Ringhals-3, Dampierre-3, St. Laurent-B1, Sizewell-B, Ohi-1
1996	Catawba-1, Ginna, Doel-4, Gravelines-2, Mihama-1, Takahama-1,
1997	McGuire-1, McGuire-2, Point Beach-2, Tricastin-2, Mihama-3, Ohi-2, Genkai-4
1998	Byron-1, St. Lucie-1, Braidwood-1, Tihange-3, Tricastin-1, Kori-1, Ikata-1
1999	Beznau-2
2000	Farley-1, DC. Cook-1, S. Texas Project-1, Arkansas Nuclear-2, Chooz-B1, Civaux-1, Civaux-2, Gravelines-4, Krsko
2001	Kewaunee, Shearon Harris, Farley-2, Tihange-2, Tricastin-3, Genkai-2, Ikata-2
2002	Calvert Cliffs-1, South Texas Project-2, Fessenheim-1, Chooz-B2, Ikata-2
2003	Calvert Cliffs-2, Palo Verde-2, Sequoyah-1, Oconee-1, St.-Laurent Des Eaux B
2004	Oconee-2, Prairie Island-1, Oconee-3, Tricastin-4, Dampierre-2, Doel-2, Ulchin-5
2005	Callaway, ANO-1, Palo Verde-1, Ulchin-6
2006	Beaver Valley-1, Fort Calhoun, Watts Bar-1
2007	Commanche Peak-1, St. Lucie-2, Palo Verde-3
2008	Diablo Canyon-2, Salem-2
2009	Crystal River-3, Diablo Canyon-1, TMI-1, Angra-1
2010	San Onofre-2, San Onofre-3

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Other Components
Alloy 690/52 Pressurizer History

- Alloy 690 and its weld metals were also used to repair pressurizer components in 17 plants between 1994 and 2006
- The high service temperature in the pressurizer, (typically 653^{0}F) is particularly aggressive regarding PWSCC initiation and growth
- Many of these pressurizer components that have been repaired with Alloy 690 and its weld metals, have the equivalent of more than 100 EDYs of time-temperature exposure since installation without cracking.
  - Service history follows
- Good service performance; inspections performed have shown no evidence of indications

PWR Pressurizer Repairs with Alloy 690/52

- Service history estimated using repair times
- Visual inspections performed for boric acid indications
- High temperature (653^{o}F) pressurizer leads to high EDY
  - No PWSCC experienced to date

Prz Repair with 690/52	Plant EFPY 1/1/2011	Approximate Repair Date	Plant MWHe at Pzr Repair	Avg. MWe 2002-2010	~ EFPY at Pzr Repair	Operation EFPY with 690/52	Arreh. T factor	~ EDYs vs. 600^{o}F
Palo Verde-3	18.81	Jul-94	5.577E+07	1377	4.62	14.19	7.67	109
St. Lucie-2	22.76	Jul-94	7.039E+07	882	9.11	13.65	7.67	105
San Onofre-3	21.70	Jul-95	8.455E+07	1127	8.56	13.14	7.67	101
St. Lucie-1	27.30	Jul-95	1.067E+08	872	13.97	13.33	7.67	102
San Onofre-2	21.92	Jul-97	1.048E+08	1127	10.62	11.30	7.67	87
Calvert Cliffs-2	27.07	Jul-98	1.157E+08	880	15.01	12.06	7.67	93
Waterford-3	21.45	Jul-01	1.291E+08	1188	12.41	9.04	7.67	69
Millstone-2	22.91	Jul-06	1.496E+08	910	18.77	4.14	7.67	32
ANO-2	23.66	Jul-06	1.608E+08	1030	17.82	5.84	7.67	45
Fort Calhoun	27.83	Jul-06	9.469E+07	507	21.32	6.51	7.67	50

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Other Components: RV Head Replacement

- Between 1992 and 2001, at least 34 reactor pressure vessel heads have been replaced with wrought Alloy 690 tubes and Alloy 52/152 weld metal (early replacements in France)
- These replacement heads have operated for 10 to 19 years with no inspection findings, and all have been inspected at least once, with no findings
- Maximum service time to date is ~19 EDY
- In both France and the USA, detailed inspections required at 10 year intervals
- Replacement history shown on following slide
- Since 2002, over 40 additional heads have been replaced in the US with these materials and the service performance has been excellent
- Limited inspections have been performed to date but additional inspections are scheduled as mandated ISI inspections become due

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Reactor Vessel Head Replacement with Alloy 690/52/152 Materials through 2007

In-Service	PWRs with Alloy 690/52/152 Replacement Reactor Vessel Heads
1992	Bugey-3
1994	Bugey-5, Blaiyais-1, Gravelines-4, Bugey-2
1995	Blayais-2, St. Alban-1, Flamanville-1, Gravelines-3, Blaiyais-3, Tricastin-1
1996	Tricastin-4, Paluel-4, St. Laurent-B2, Blaiyais-4, Dampierre-1, Fessenheim-1, St. Alban-2
1997	Bugey-4, Dampierre-2, Dampierre-4, Belleville-2, Cruas-4, Gravelines-5
1998	Flamanville-2, Dampierre-3, Paluel-3, Cattenom-2, Fessenheim-2, Cruas-2
1999	Chooz-B1, Chooz-B2
2000	Civaux-1, Civaux-2
2002	North Anna-2
2003	North Anna-2, Crystal River-3, Ginna, Oconee-1, Oconee-3, Surry-1, Surry-2, TMI-1
2004	Farley 1, Kewaunee 1, Oconee 2, Turkey Point 3
2005	ANO-1, Farley 2, Millstone-2, Point Beach-1, Point Beach-2, Prairie Island-2, Robinson-2,
2005	Salem-1, Salem-2, St. Lucie-1, Turkey Point-4
2006	Beaver Valley-1, Calvert Cliffs-1, D.C. Cook-1, Fort Calhoun, Prairie Island-1,
2007	Calvert Cliffs-2, Commanche Peak-1, D.C. Cook-2, St. Lucie-2,

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Summary of Operating Experience with Alloy 52/152 materials

- Alloy 52/152 has been used extensively for repairs and replacement parts in PWRs since 1994
- No significant service problems identified
- Current inspection results favorable
- More detailed and frequent inspections scheduled for future years

Suitability of using a 30% Cr material, Alloy 690 Material

- Regarding the long-term suitability of a weld material containing 30% Cr to withstand long term PWR service, a case can be made based on the present performance of Alloy 690 steam generator tubing
- Most steam generator tubes walls are ~ 1 mm thick;
  - thinner than the weld zone we are considering
- It is a very demanding application

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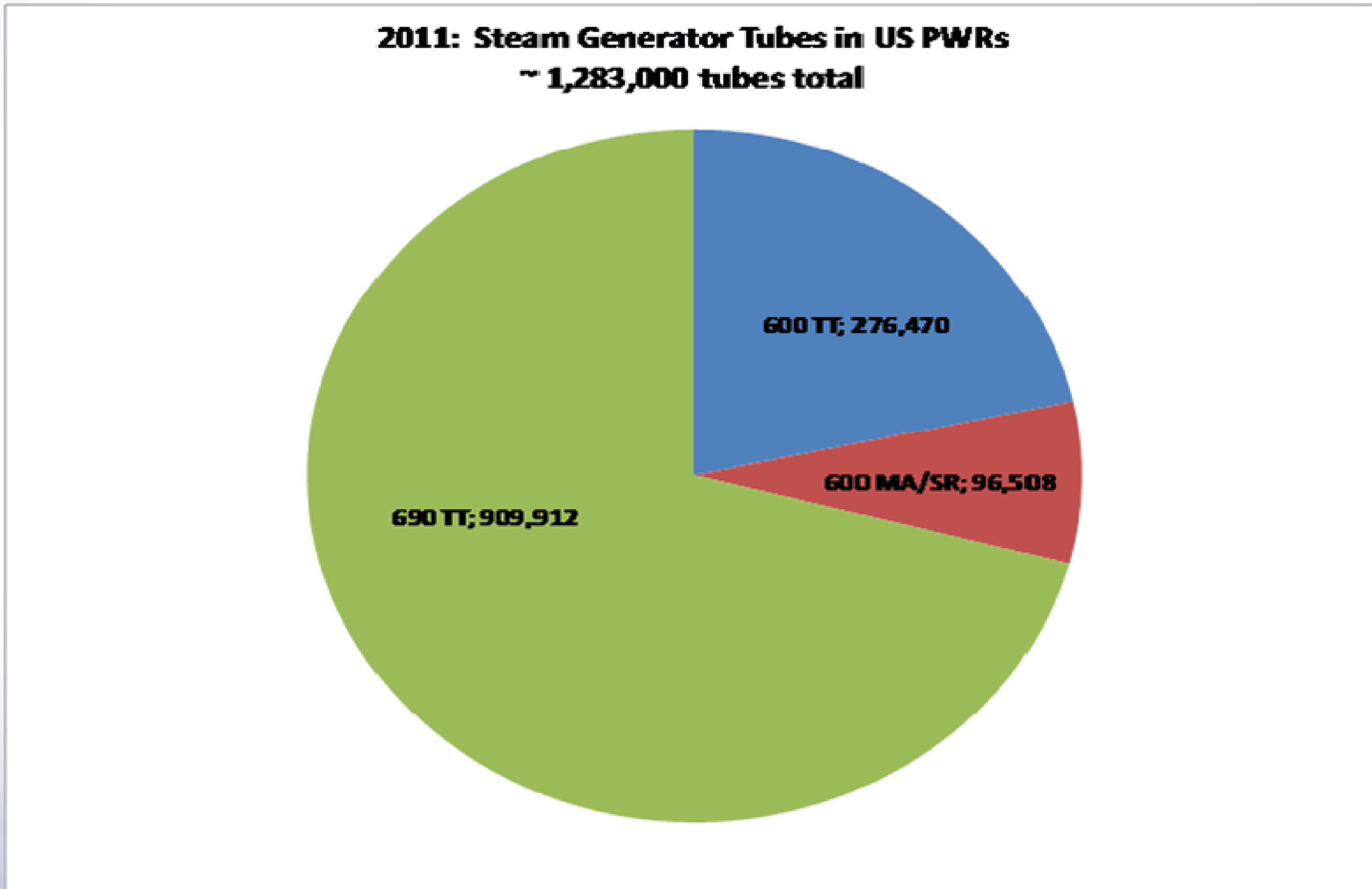
Alloy 690 tubing in Steam Generators

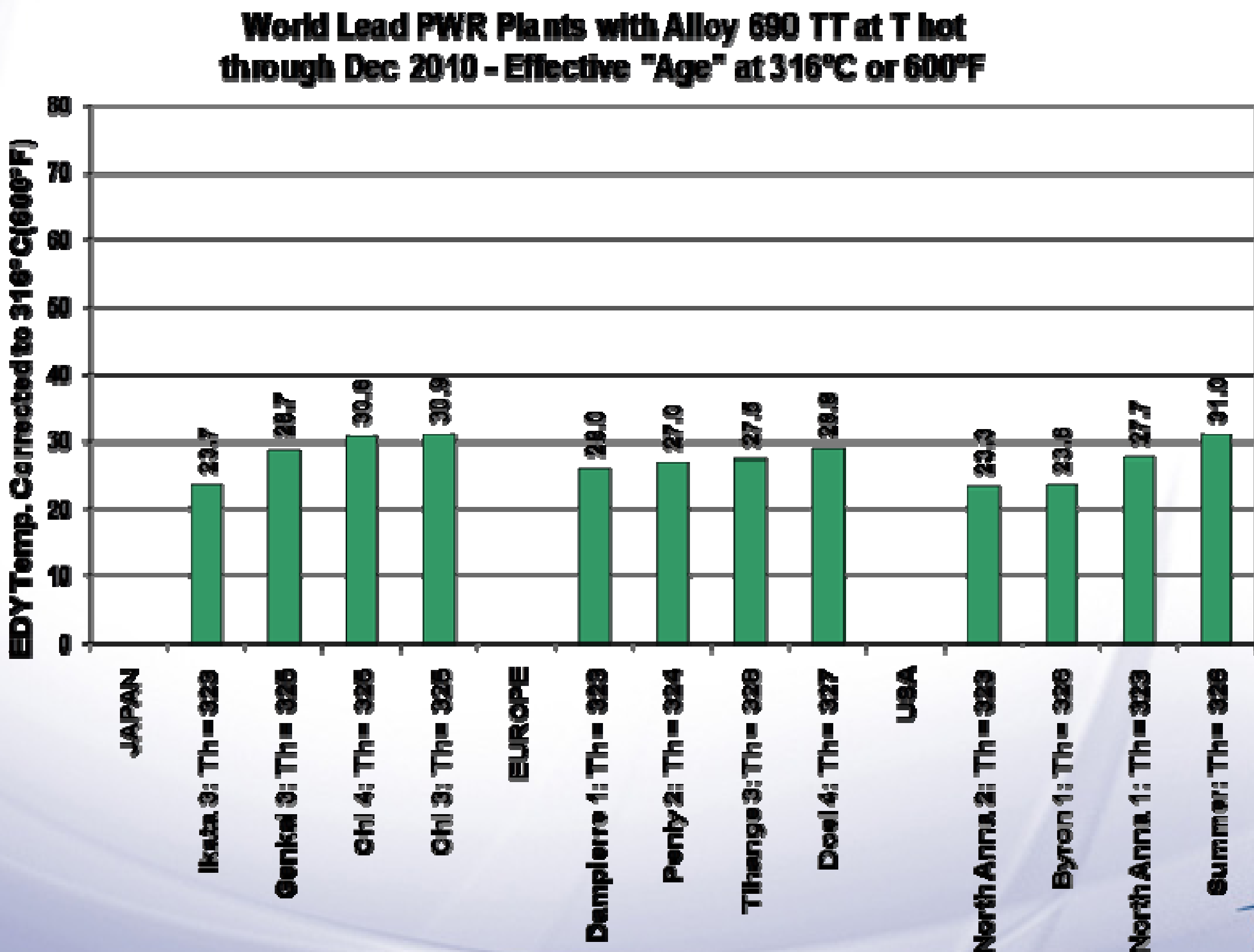
- Large number of tubes (over 900,000 tubes in service in the US for up to 22 years of operation)
- Soon there will be 2 million Alloy 690 tubes in service in the Americas, Europe and Asia
- Tubes are under moderate active stresses
- For steam generator tubes, corrosion and SCC is possible on both inside and outside surfaces
- Several regions on the tubes with moderate residual stress
- Majority of the tubes are bent (moderate cold work)
- High temperature exposure on hot leg (600º to 622ºF)
- Periodically inspected with sophisticated NDE techniques
- Two seal welds on every tube (690/52)
- Recall that median Alloy 600 MA steam generator replaced after ~17 EDY of hot leg exposure
- ***ZERO tubes plugged to date for PWSCC / ODSCC / other corrosion issues***

US usage of A690 in SGs
excellent performance, large database



Time-Temperature History Significant

Lead SGs have >127,000 tubes with over 27 EDY time-temperature exposure and NO PWSCC



PWSCC Initiation in Alloy 690TT

- Initiation of PWSCC from a smooth surface in these 30% Cr materials in primary water appears to be almost impossible, both under service conditions and in the laboratory
- Review of the SCC literature on Alloy 690 shows that no cracking has been observed in long term, constant load or constant deformation tests in heats with good intergranular carbide morphology
- Some laboratory tests approaching 100,000 hours
- In some rare cases, cracking has been observed in Alloy 690 with microstructures exhibiting very fine grain size or poor carbide morphology during constant deformation or slow strain rate testing. Situation of limited applicability to service conditions

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Comments related to ML101260548

- PWSCC growth rates used in ML101260548 are appropriate given the low magnitude of PWSCC rates that has been observed in the Alloy 690 material and weld metals
- Using the Alloy 82/182 rates divided by 100 or ~3.0E-9 mm/s (~100 um/year, or 1 to 2 grains per year)
- That CGR is the median rate listed in ML101750347
- Note these rates are very low and by their nature extremely precise experiments and long test durations (e.g. > 6 months) under constant K conditions are required to obtain the data
- Nevertheless, when these low rates are compared to recent, actual constant K crack growth rates, these low measurements may still be conservative
- As more crack growth rate data for Alloy 52/152 becomes available, it is anticipated that the Alloy 52/152 CGR will be in the range equal to the Alloy 182 rates/400

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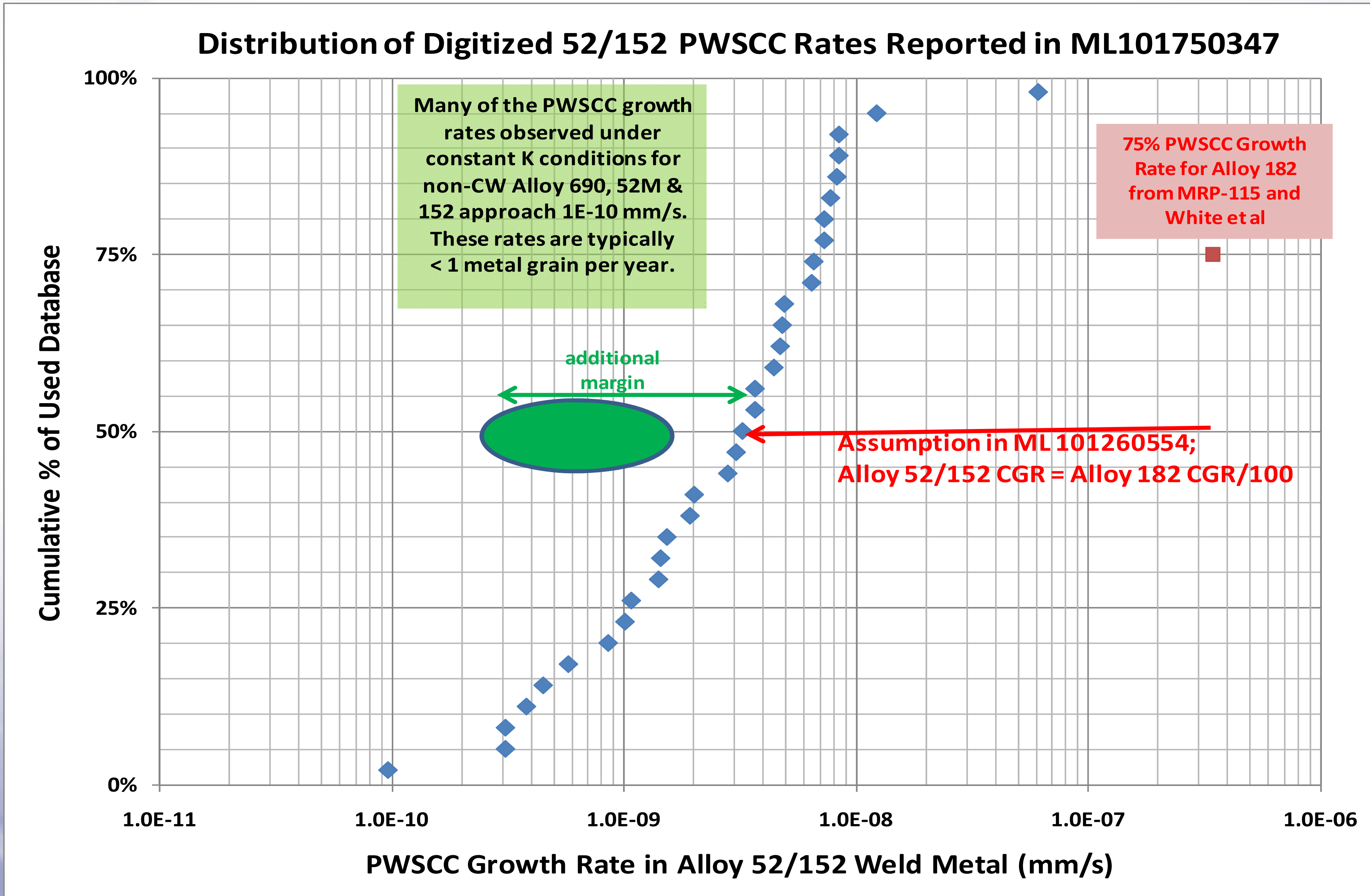
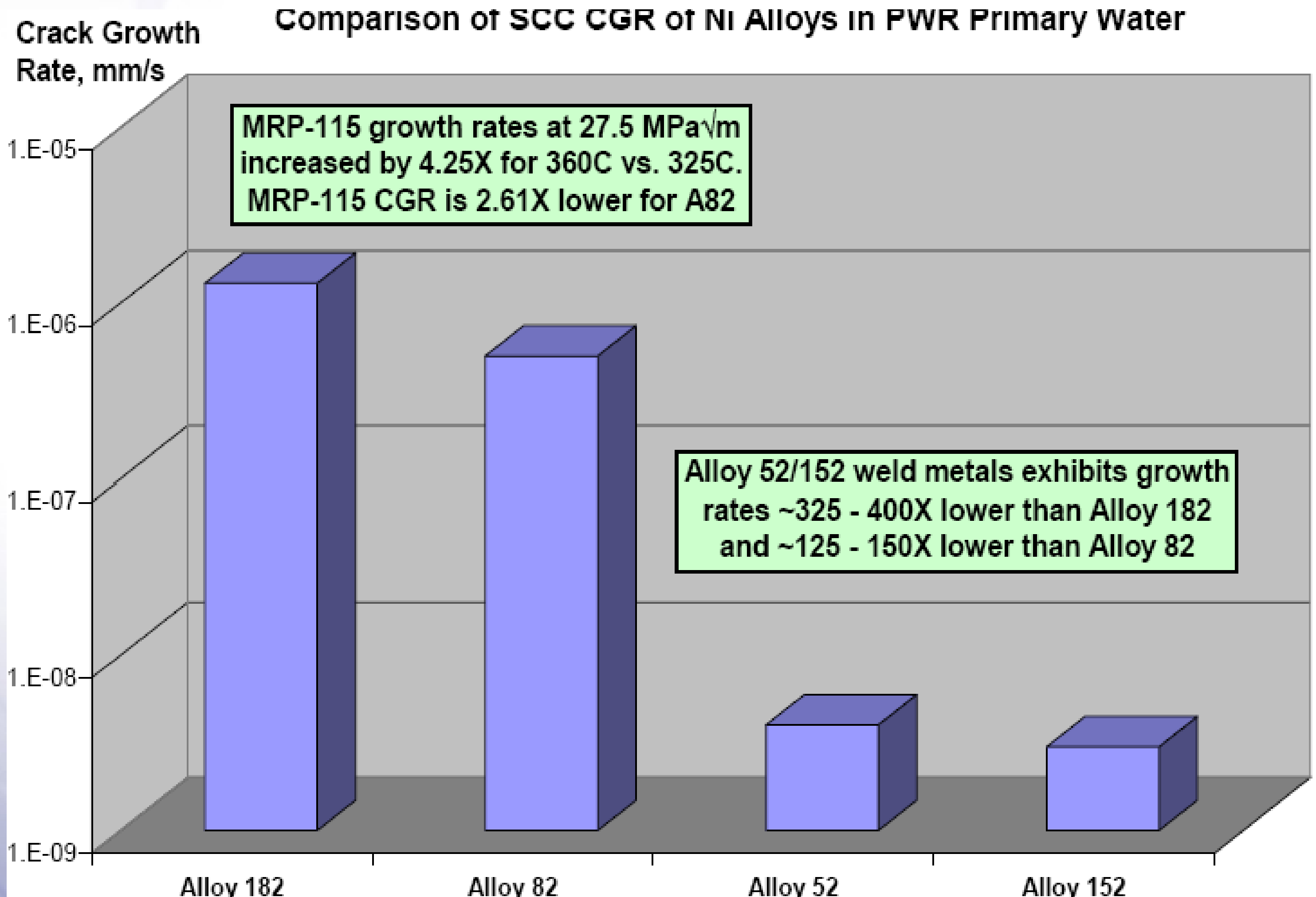
PWSCC Rates used in NRC Analysis Alloy 182 CGRs/100

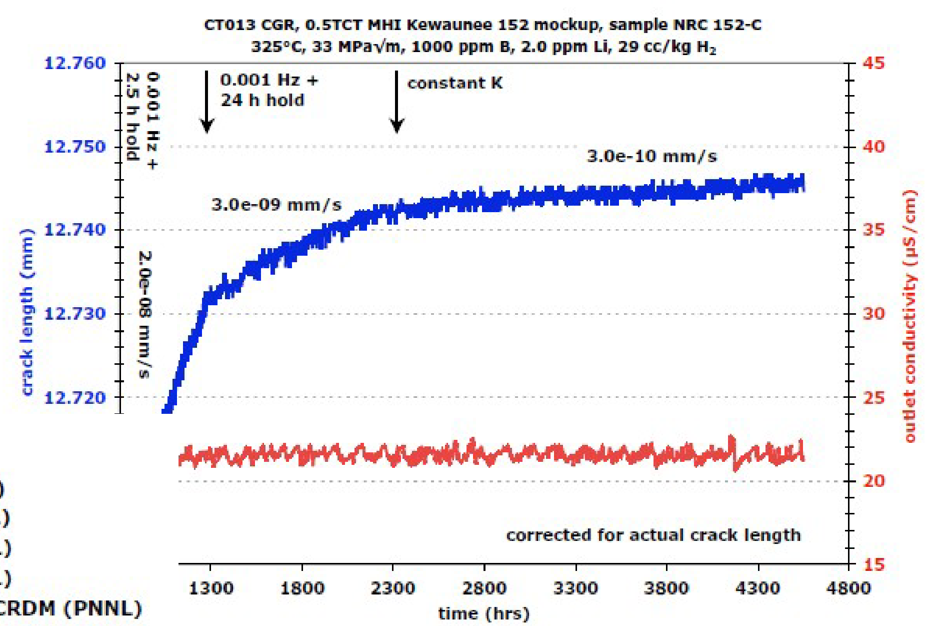


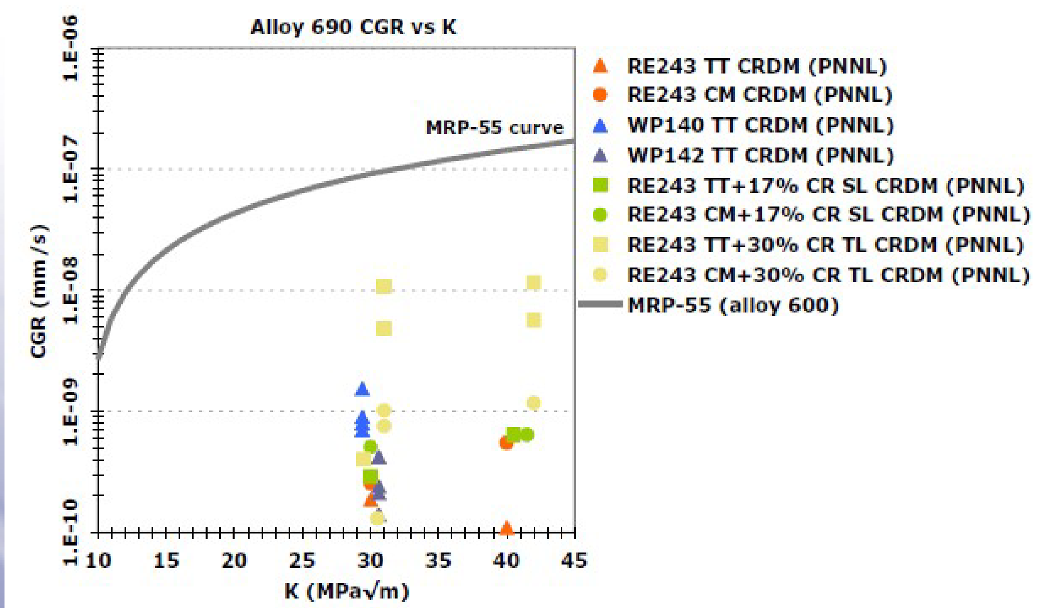
Recent GE/MRP Data suggests PWSCC rates are lower than used in NRC analysis



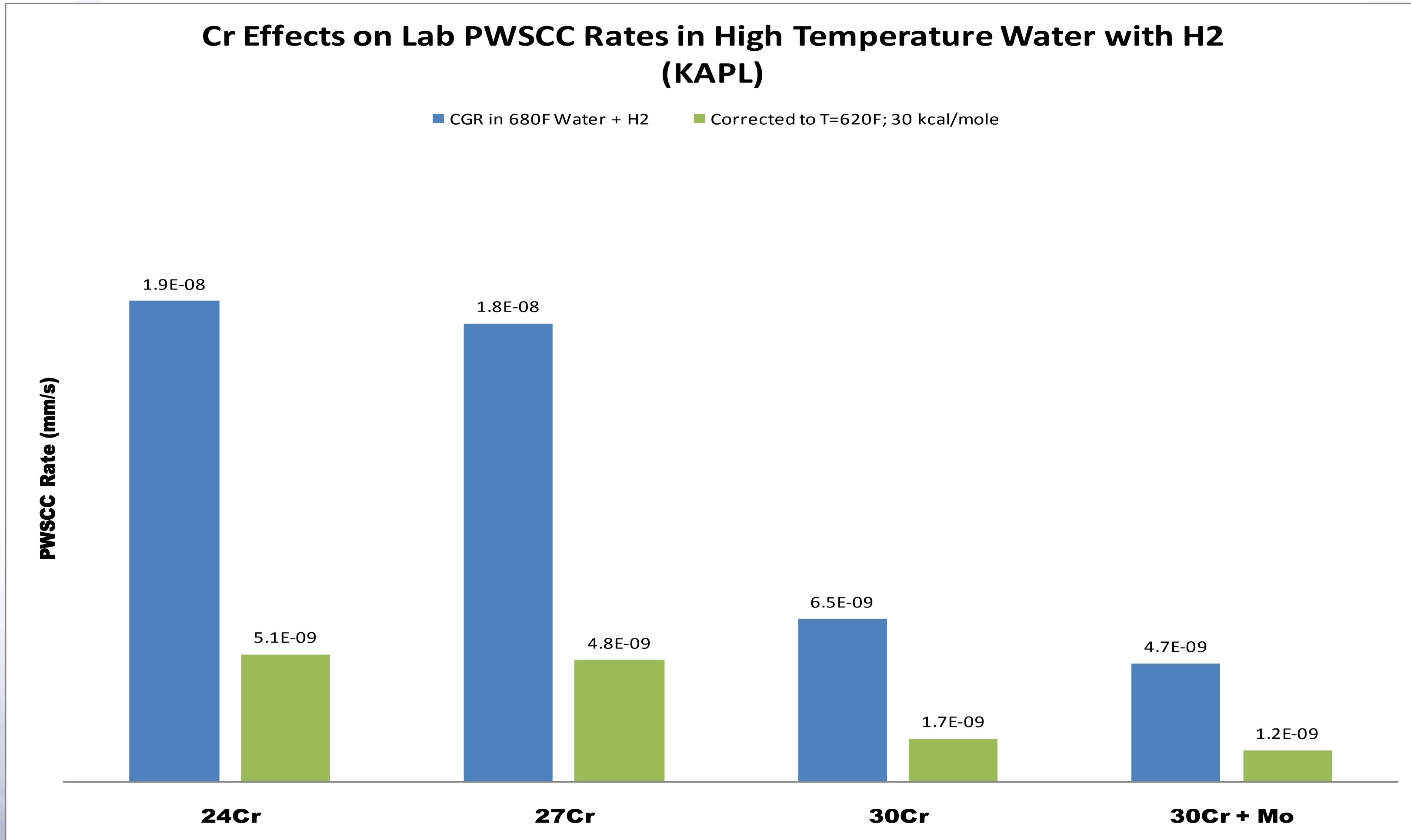
MRP/GE Data

Recent PNNL Data suggests PWSCC rates are lower than used in NRC analysis





PWSCC Rates in the KAPL Cr Study



Alloy 52/152 is Highly Resistant, but Not Assumed to be Immune from PWSCC

- Over the last 6 years, many Alloy 690/52/152 crack growth rate tests have been performed by many organizations
- The vast majority of those tests have shown that these materials can undergo slow PWSCC growth
- An immunity statement to crack growth from an initiated crack cannot be supported
- From inspections completed to date on these weld materials, we have >100 EDY exposure with no indications
- Continual decrease in PWSCC rates and response can be shown with increasing Cr concentration in these materials;
  - Decrease continues beyond 24% Cr

Capabilities for Inlay Examination

- Volumetric (UT) and surface (ET and PT) examinations insure that surface and subsurface flaws are detected prior to inlay
- Volumetric and surface examination of the excavation so that unacceptable flaws are detected and removed or seal welded
- Eddy current has been demonstrated to reliably detect flaws smaller than 1/16 inch in size (0.060” long, up to 0.014” deep, and 0.002” wide)

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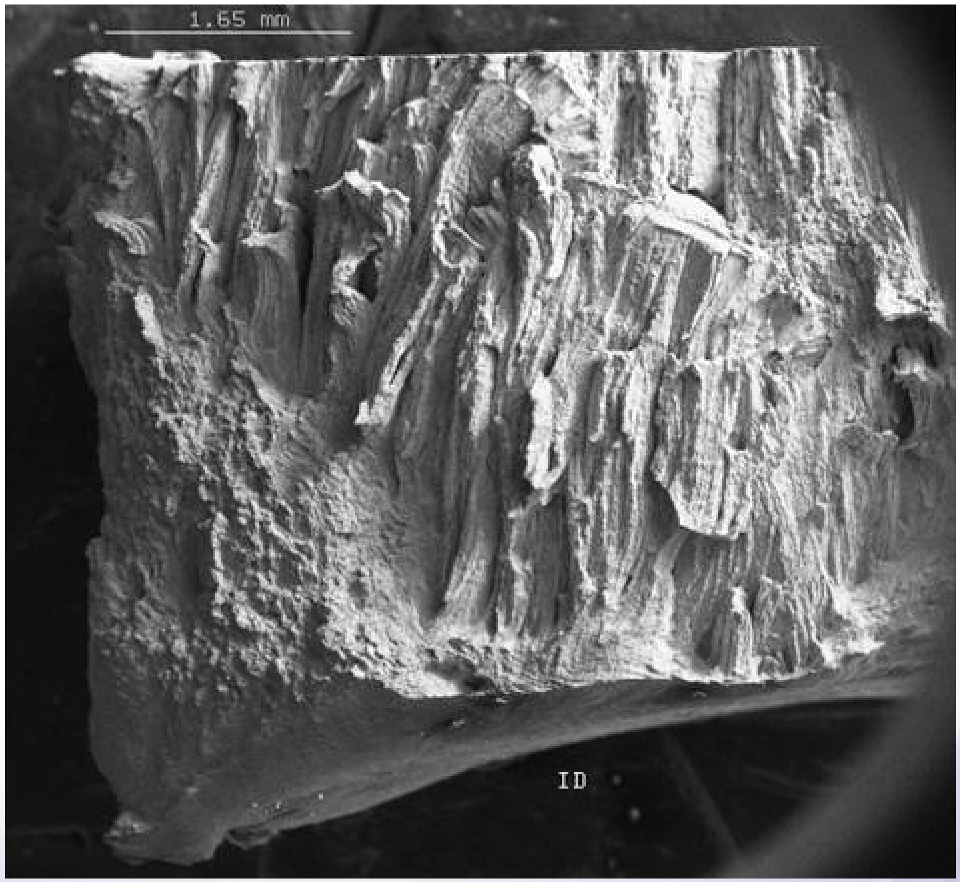
Surface and Subsurface PWSCC detected by Eddy Current Testing



Capabilities for Inlay Examination (Cont)

- Successful field inspection confirmed with destructive metalography on VC Summer nozzle (Alloy 600 class materials). Detected axial and circumferential cracks in initiation and developed stages, including surface and subsurface ligaments.
- NUREG/CR6996, conclusions from this report have confirmed that the eddy current testing was the most useful technique for finding PWSCC on the J-groove weld (Alloy 600) and showed much higher sensitivity than any of the other techniques.
- Extensive laboratory testing on authentic samples representing fusion zones along DMW, excavated inlay cavities, and welded inlays have confirmed adequate signal-to-noise ratios when detecting short surface indications (1/16” long)

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Sample Fatigue Crack Growth Analysis

- Sample analysis demonstrates that the minimum inlay/onlay thickness provides a conservative margin for fatigue crack growth, which is the only operable mechanism of growth here

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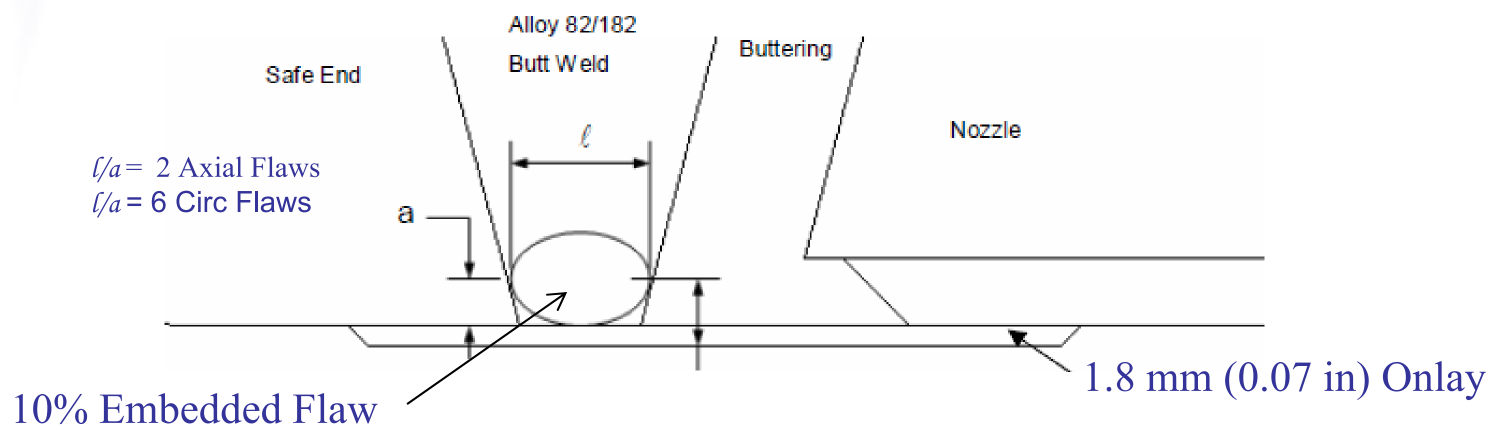
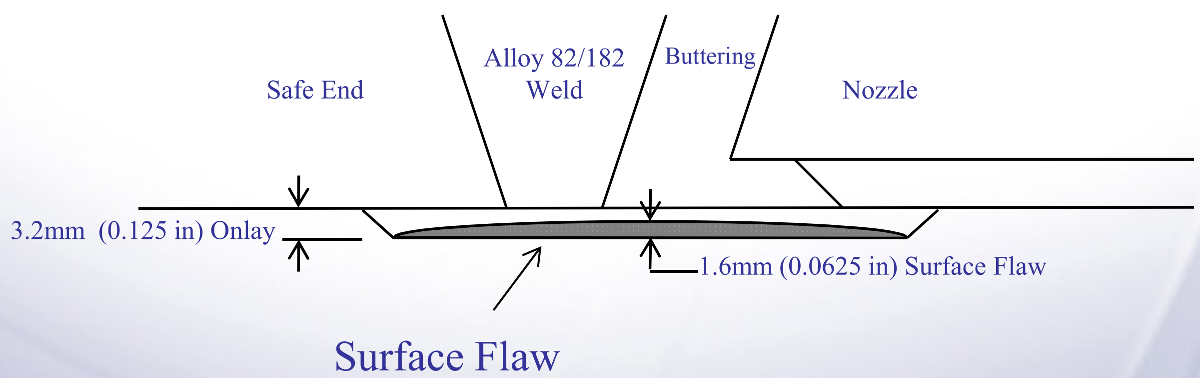
Onlay Fatigue Crack Growth (FCG) Analysis

- Based on early draft of CC N-766
- Representative 4 loop PWR geometry
- Representative operating design transients and loading
- Outlet nozzle evaluated as limiting case
- Residual weld stresses with ID weld repair from MRP-106

Embedded and Surface Flaw Evaluated for Onlay Geometry





FCG Analysis Curves

- Alloy 182 crack growth rates were used for both DMW and Onlay
  - Alloy 600 air curve, with a factor of 2, used for embedded flaw growth calculation in both directions (NUREG/CR-6721)
  - Alloy 600 air curve with a factor of 5 was used for surface flaw growth calculation (NUREG/CR-6907 & PVP 2006-93594)

FCG Results for 40 Year Life

Embedded Flaw Case (1.8mm Onlay)	
Axial Flaw Growth	Circumferential Flaw Growth
0.030mm (0.0012in) *~2.0% of 1.8 mm Onlay thickness*	0.015mm (0.0006in) *~1.0% of 1.8 mm Onlay thickness*

Surface Flaw Case (3mm Onlay)	
Axial Flaw Growth	Circumferential Flaw Growth
0.701mm (0.0276in) *~22% of Total Onlay thickness*	0.160mm (0.0063in) *~5% of Total Onlay thickness*

Both Cases Show Onlay Design Life of > 40 Years

Experience with Inlays in Operation

- Weld inlays installed at Ringhals 3 an 4 in Sweden
- Ringhals 4 – inlay applied in 2002
  - Inspected with UT and ECT in 2005 – no indications
  - Inspected: UT and ECT in 2010– no ind. after 11.7 EDY
  - Now on a 10 year re-inspection frequency
- Ringhals 3 – inlay applied in 2003
  - Inspected with UT and ECT in 2006 – no indications
  - Inspected: UT and ECT in 2010– no ind. After 10.4 EDY
  - Now on a 10 year re-inspection frequency

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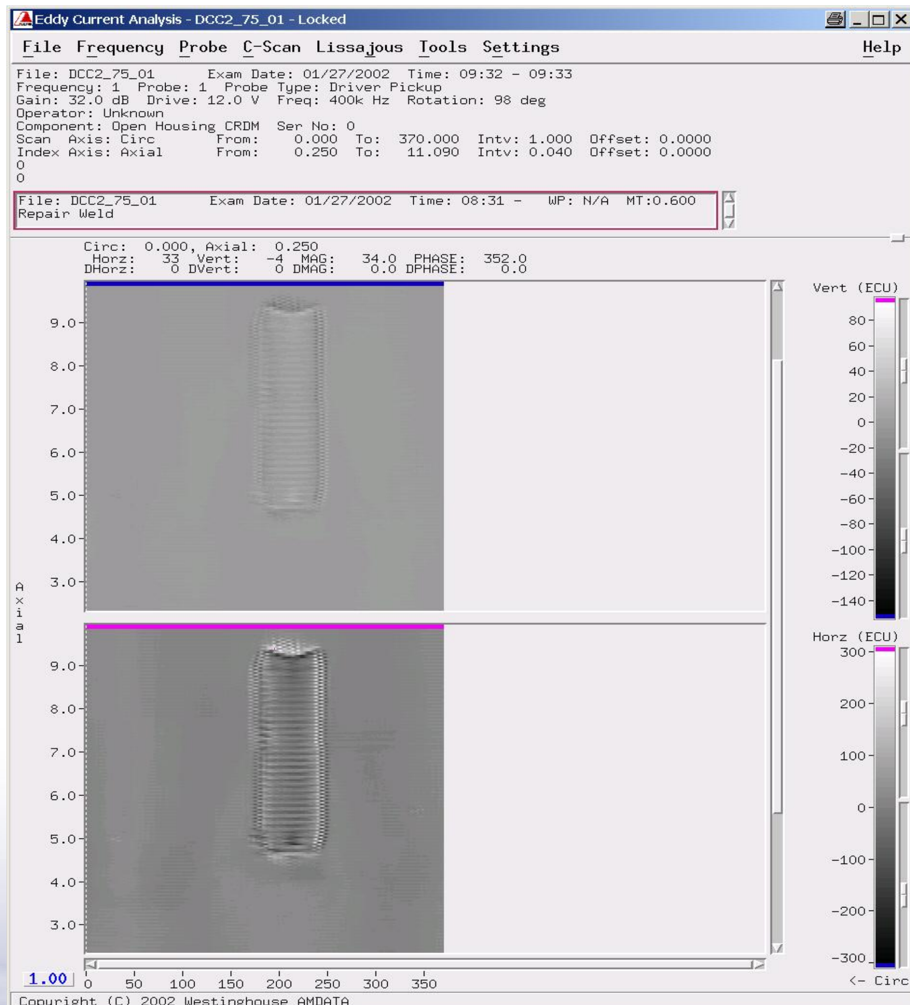
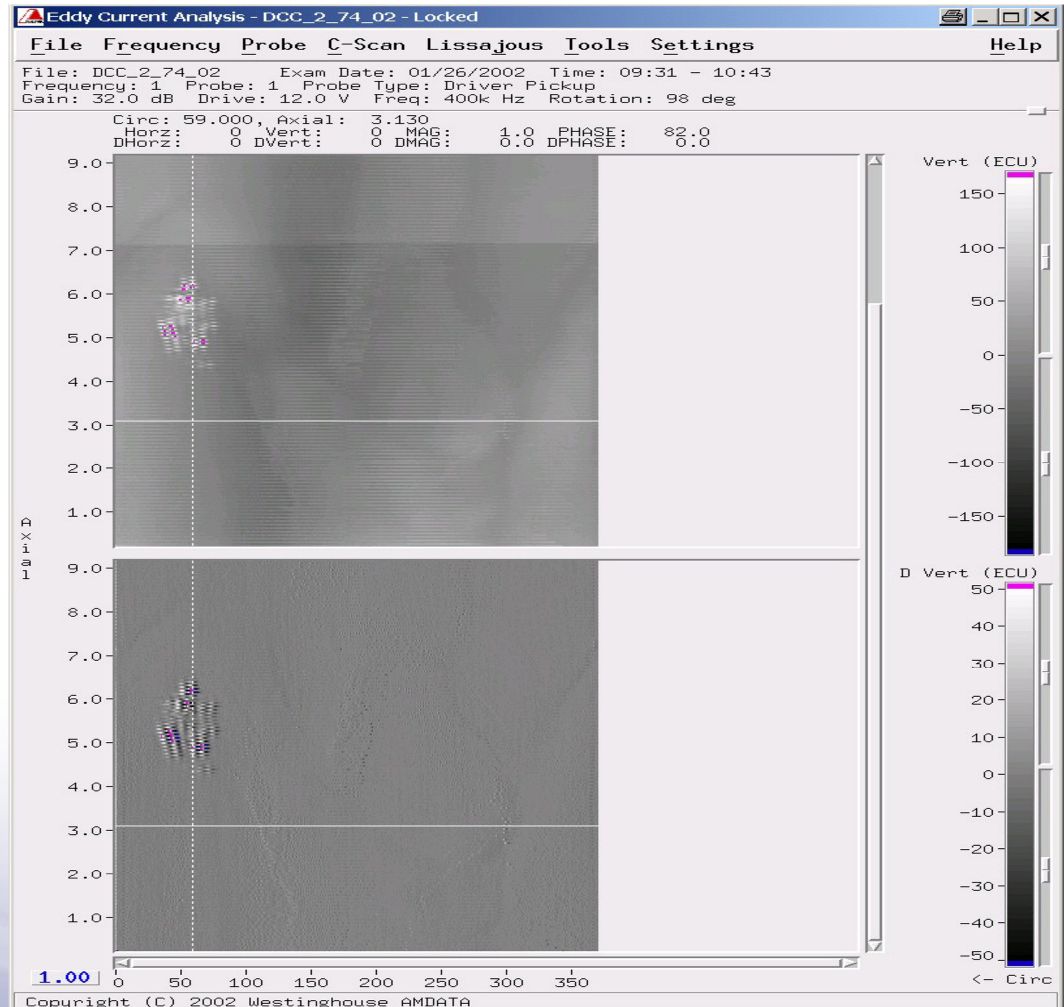
Embedded Flaw Repairs of CRDM Nozzle ID Regions

Plant	# Tubes Repaired	Year
DC Cook 2	1	1996
Doel 1	3	2005

ECT View of 1996 Repair, taken in 2002



Sample ECT View: Craze Cracking



Embedded Flaw Repairs of CRDM OD Regions and J-welds

Plant	# Tubes Repaired	Year
North Anna 2	3	2001
ANO-1	2	2002
Beaver Valley 1	4	2003
San Onofre 3	4	2004
D C Cook 2	2	2004
Beaver Valley 2	3	2006
Byron 2	1	2007
Beaver Valley 2	1	2008
Byron 1	4	2011

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Why we like N-766 as it stands

- Carefully developed and reviewed in the ASME code process
- Inlay/onlay material is highly resistant to crack initiation (at least 16 years service with no cracks in SG applications)
- Service experience of inlays/onlays has been very good (ten years service with no cracks)
- Inspection capability is more than sufficient to find degradation
- The code case as it stands encourages mitigation

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