WESTINGHOUSE 17X17 RFA FUEL PERFORMANCE

M.B. O'CAIN[1], F. TABORDA[2], R. MCKENZIE[3], B. HELMERSSON[4], K. RYTTERSSON[4],
S. CHOITHRAMANI BECERRA[5]

[1]Westinghouse Electric Company LLC, Hopkins, South Carolina, United States 29061
+1-803-647-3627 and ocainmb@westinghouse.com
[2]Westinghouse Electric Company LLC, Orsay, France, 91400
[3]Westinghouse Electric Company LLC, Springfields, United Kingdom PR4 0XJ
[4]Westinghouse Electric Company LLC, Västerås, Sweden 72136
[5]ENUSA LLC, Madrid, Spain 28040

ABSTRACT

This paper provides an update on the fuel performance of the 17x17 Robust Fuel Assembly (RFA) design since introduction in fall 1997. The RFA design has operated in 60+ reactors around the world (25,000+ assemblies), with overall excellent performance past 60,000 MWD/MTU burnup. This experience includes operation in both 3 and 4-loop plants with 12-18 month cycles, mixed vendor cores, residence times in excess of five years and over a range of coolant temperatures, chemistries, flow rates and inlet flow distributions.

Enhanced debris resistance is maintained via design features at the bottom of the assembly, while bow resistance is ensured using stiffer guide thimbles and optimized holddown forces. The RFA mid grid design prevents grid-to-rod fretting by ensuring uniform grid interaction with the core flow to eliminate assembly vibration.

The 17x17 RFA design has performed well in a host of operating environments and is an exceptionally reliable design.

1. Introduction

Westinghouse's Fuel Reliability Improvement (FRI) process is used to drive excellence in fuel reliability. Reliability in this context includes all fuel issues that potentially degrade the performance of Westinghouse fuel products in the customers' reactors. As Westinghouse has continued to grow globally, the FRI process is likewise globalizing. This allows the company and its partners to leverage operating and manufacturing experience from across the globe.

The ongoing efforts of the FRI programs have brought about a Westinghouse pressurize water reactor (PWR) leaker-free indicator nearing 100% of plants for the last five years. This paper presents the 17x17 Robust Fuel Assembly (RFA) fuel performance and, by extension, its contribution to overall nuclear fuel reliability in a global environment.

2. Prevention of Grid-to-Rod Fretting Leakers

As the nuclear industry moved to a dedicated focus on eliminating fuel leakers in the 1990's, with the primary leak mechanism for PWR plants then being grid-to-rod fretting (GTRF) wear, significant fuel development projects were put in place [1]. As one of those advancements in fuel performance, Westinghouse introduced the 17x17 Robust Fuel Assembly (RFA) fuel design in fall 1997 in a United States-based four loop plant with eight lead use assemblies (LUAs). The design was developed to provide additional GTRF margin relative to the previous Westinghouse design (17x17 Vantage 5 Hybrid (V5H)) then in-core. The primary changes made to the RFA mid grid design compared to the 17x17 V5H mid grid were the vane pattern, vane geometry and the spring and dimple rod support geometry. The RFA grid has a symmetrically balanced vane pattern that provides for a more uniform grid interaction with the core flow and eliminates fuel assembly self-excitation. The RFA mid grid also incorporates "closed" spring and dimple windows to reduce cross-communication flow between grid cells. Additional GTRF performance margin is also added at the bottom of the fuel assembly by optimizing span lengths between grids and the use of the Protective grid feature.

To further improve the GTRF performance of the RFA mid grid, a slightly modified grid design noted as "RFA-2" was introduced in 2002 at the same United States-based plant with four LUAs. The main change moving to the RFA-2 design was an increase in the grid's rod support contact area as compared to the RFA mid grid. This change provided additional margin to GTRF wear. Since its introduction, other minor enhancements have been made in the RFA-2 mid grid design to improve strap manufacturability. As background, a comparison of the V5H, RFA and RFA-2 mid grids' dimples and springs is shown in Figure 1.

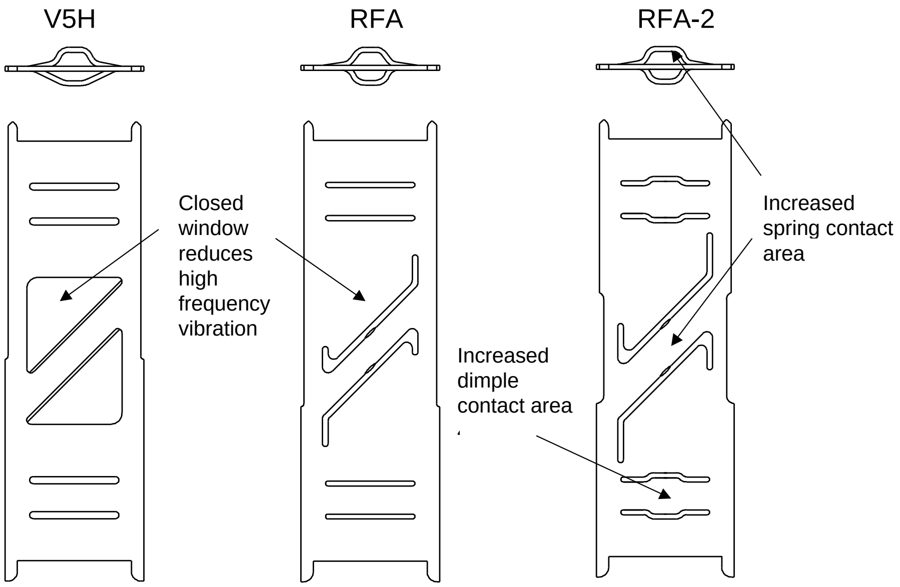


Figure 1: Comparison of 17x17 V5H, RFA and RFA-2 Mid Grid Strap Cell Profiles

In addition to the mid grid changes, the more recent RFA/RFA-2 designs can include the following key features (Figure 2).

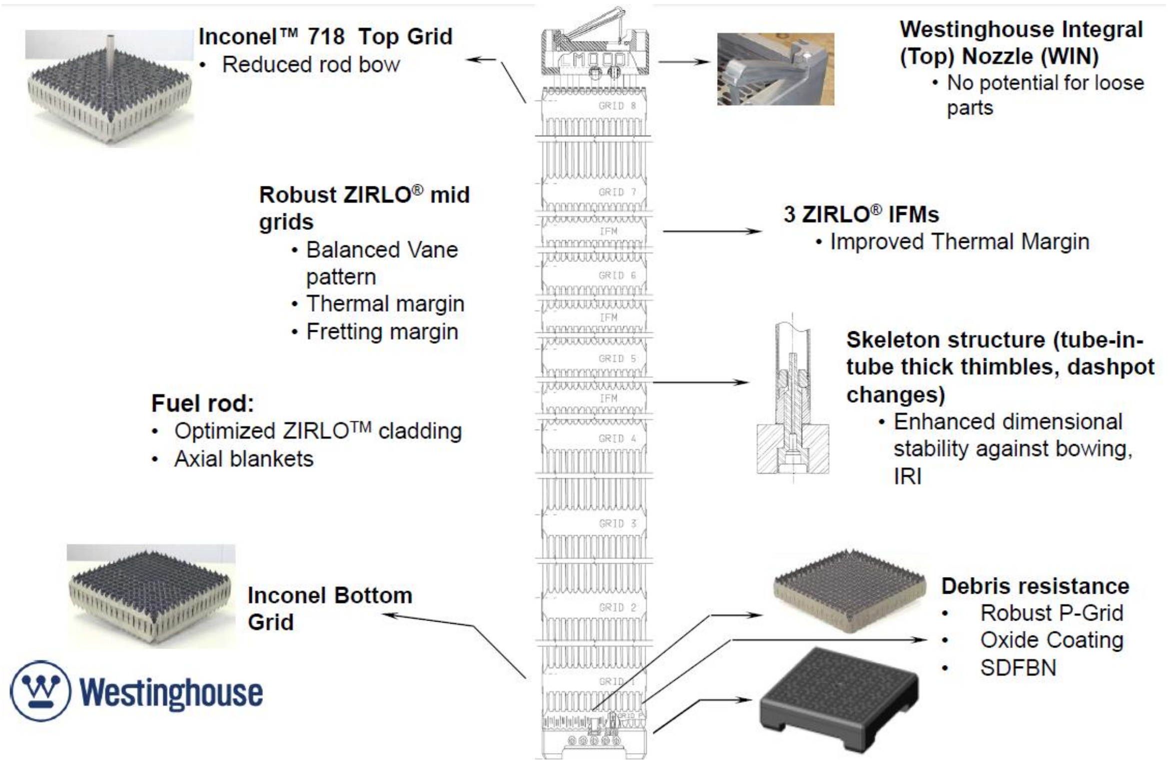


Figure 2: 17x17 RFA and RFA-2 Designs

3. Prevention of Debris-Related Leakers

The latest RFA/RFA-2 debris resistant features are shown in more detail in Figure 3. The debris filter bottom nozzle (DFBN) and its successor the Standardized DFBN (SDFBN), plus the Robust Protective grid (RPG), long solid fuel rod bottom end plugs and oxide coated cladding provide an excellent barrier to possible debris-related leakers. Larger debris is typically trapped under or in the DBFN/SDFBN, while smaller debris is captured by the RPG where it can only vibrate harmlessly against the solid bottom end plug or the protective oxide layer thickness at the bottom of the rods.

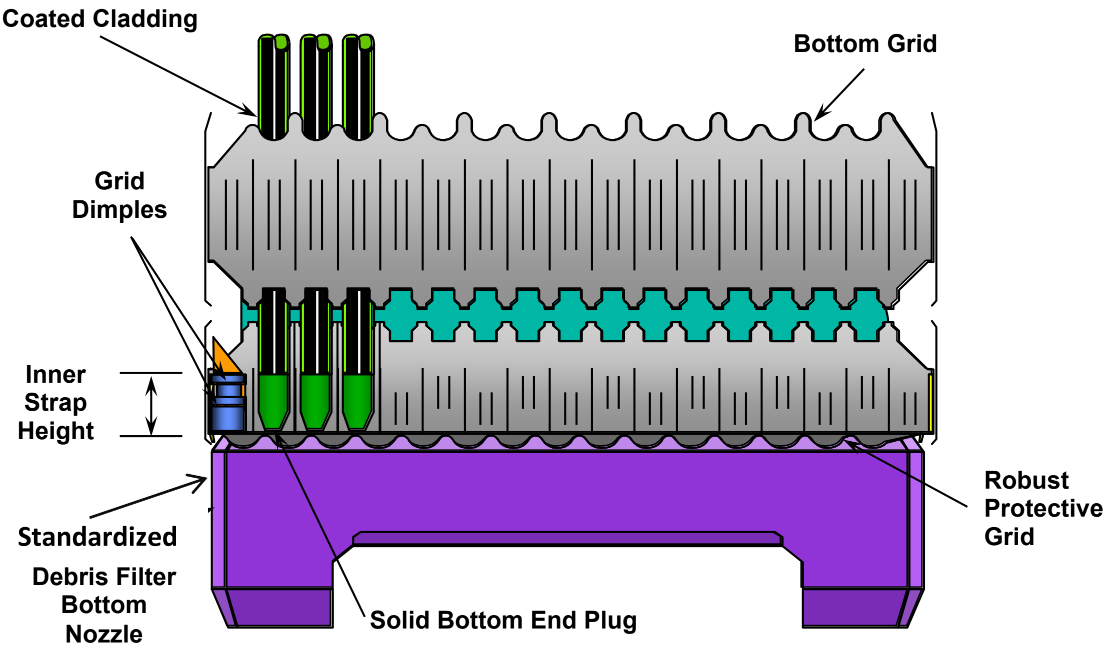


Figure 3: Debris Resistant Features

4. Operating Experience

The RFA and RFA-2 fuel design has operated in plants in the United States, Spain, Belgium, France, Sweden and South Africa. As previously noted, eight LUAs were inserted in a four loop plant in fall of 1997, with the first RFA reload regions beginning operation in 1998 at another US-based plant (with RFA XL 14-foot fuel). ZIRLO® material is used for fuel rod cladding, guide tubes and grids for RFA in all plants since 2008. As of 2012, all plants which had initially used RFA had transitioned to RFA-2. RFA plants began using the advanced Optimized ZIRLO™ fuel rod cladding in region quantities starting in 2011 in pursuit of reduced oxidation and hydrogen pick-up of the rods. Approximately one-fifth of the RFA/RFA-2 plants are using that cladding now, with more planning to make a similar move in the future.

The following observations can be made on the RFA/RFA-2 experience through December 2017:

- Either RFA or RFA-2 fuel (12 and 14-foot versions) has been used in 62 plants with 620+ reload regions and ~28,000 assemblies with 7.3+ million fuel rods
  - RFA fuel (12 and 14 foot versions) was used in 20 of the 62 plants with ~7,000 assemblies delivered
  - RFA-2 fuel (12 and 14 foot versions) has been used in all 62 plants with 21,000+ assemblies delivered
- All plants have transitioned to RFA-2 as of 2012

- All RFA or RFA-2 plants have transitioned from Zircaloy-4 to ZIRLO fuel rod cladding as of 2008 for better oxidation resistance
- Most of the RFA or RFA-2 operating experience is with 18 month cycle lengths, although several plants in Europe are on 12 month cycles. Typical operation is for three 18 month cycles (~4.5 years). Assemblies have also operated for four 18 months cycles with in-core residence time of approximately six years and for five 12 month cycles with in-core residence time of about five years.

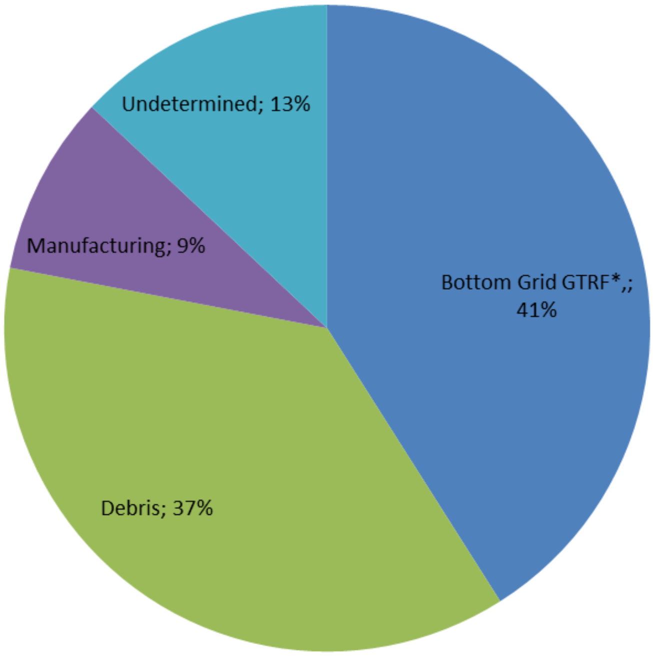
RFA and RFA-2 fuel has been used in both 3-loop and 4-loop 17x17 plants with 12-foot fuel designs with and without Intermediate Flow Mixer (IFM) grids and 14-foot fuel designs without IFM grids over a range of coolant temperatures, flow rates and inlet flow distributions.

The RFA-2 fuel design is currently manufactured at four locations:

- Westinghouse's Columbia Fuel Fabrication Facility (CFFF) in the United States,
- Westinghouse's Springfield Plant in the United Kingdom,
- Westinghouse's Västerås Plant in Sweden, and
- ENUSA's Juzbado Plant in Spain.

3. Fuel Reliability

Approximately 28,000 RFA and RFA-2 fuel assemblies have shipped/operated through 2017. The overall performance of this fuel has been very good for fuel using the Protective Grid and its successor debris filter, the RPG. Since 1997, a total of 76 fuel assemblies containing 91 leaking fuel rods have been identified as leaking out of ~28,000 delivered RFA or RFA-2 assemblies. A summary of these leakers is given in Figure 4.



* Either Root Cause Analysis (RCA) exam confirmed bottom grid GTRF or visual/ultrasonic testing (UT) indicated the leaking rod's signature was consistent with bottom grid GTRF.

Figure 4: Summary of RFA and RFA-2 Leaking Fuel Assemblies by Leakage Mechanisms through December 2017

Of the 76 leakers, more than 40% are due to GTRF wear at the bottom grid in a sub-set of plants that experience high cross flow anomalies in the bottom of the core. These leaking assemblies were all RFA-2 without the Protective grid. The Protective grid's primary focus is on preventing debris from entering the bottom of the assembly, but it also provides additional restraint on the fuel rod bottom ends and thereby limiting localized flow-induced vibration.

Overall, approximately one-half of all RFA/RFA-2 leakers have occurred in fuel without the Protective grid or RPG. The performance of fuel with the Protective grid or its success the RPG has been very good overall. The RFA fuel design without the Protective grid has been phased out, with the last deliveries in 2008 and almost all susceptible (i.e., non-Protective grid) assemblies discharged by 2012. RPG implementation for the RFA/RFA-2 design is complete within the U.S. since 2016, while several European plants continue to use the Protective grid.

Per Figure 4, slightly over a third of the leakers have been identified as having been caused by debris. The debris-related leakers have occurred on first, second, and third-burned assemblies. Except for two instances, all the debris wear scars were near the Alloy 718 Protective grid or bottom grid. Some of these leaking assemblies have only had a visual exam that showed evidence of debris. Root cause examinations may be performed in the future on some of these more recent leakers to definitively confirm or refute that debris is the leakage mechanism. In support of minimizing debris leakers, Westinghouse and its manufacturing plants continue to focus on maintenance of strong foreign material exclusion (FME) programs, along with the reactor sites.

The cause of the remaining identified leakers is likely manufacturing-related due to internal hydrogen contamination, cladding flaw or end plug weld anomaly. However, these types of leakage mechanisms are difficult to definitively confirm, given the typical level of secondary hydriding found and without the forensics necessary from a costly hot cell exam. Manufacturing improvements put in place since their possible occurrence further reduce the likelihood of a similar issue in the future.

None of the leaking RFA or RFA-2 rods have been due to GTRF wear of the zirconium-based mid or IFM grids. This is in comparison to the previous fuel design (V5H) that experienced mid grid GTRF leakers in multiple assemblies while in-core. Based on the twenty years of operational experience, the RFA/RFA-2 design has proven to have effectively eliminated GTRF of the mid grid as a leakage mechanism. GTRF wear exams that have been performed on discharged RFA or RFA-2 fuel have shown low wear, less than 10% of the wall thickness generally, with residence times of up to six years in-core.

The RFA/RFA-2 leaking fuel assembly rate per fuel shipments is higher for the designs without the Protective grid (~2%) because of the previously noted bottom grid GTRF leakers, plus the fuel's overall debris resistance is lower without the Protective grid feature in place. The assembly leakage rate for designs with the Protective grid/RPG (~0.02%) is lower by ~100X+ because of the enhanced debris resistance and reduced susceptibility to bottom grid GTRF wear. Note that there has been only one confirmed debris leaker in more than 10,000 assemblies that used oxide coated cladding and the Protective grid or the RPG. This lone instance was due to reactor baffle bolt debris above the protected bottom portion of the fuel assembly.

In conclusion, the RFA/RFA-2 leakage rate has declined throughout the years with manufacturing quality improvements and the introduction of enhanced features such as the SDFBN, RPG and oxide coating. Based on available information (e.g., INPO data in the US), the RFA and RFA-2 leaker rate is well below the overall market levels both in the US and Europe.

4. Fuel Performance Inspections

To confirm the excellent in-reactor performance of the RFA and RFA-2 fuel designs, Westinghouse has performed Healthy Fuel Post-Irradiation Exams (PIEs) on 380+ irradiated fuel rods in 40+ assemblies within 11 units. Exam results indicate no wear or minimal GTRF wear on the fuel rods.

In addition to the GTRF-related fuel rod exams, other typical performance parameters, such as fuel assembly and fuel rod oxide and growth have all been within acceptable values and consistent with the Westinghouse databases. Control rod insertion behavior with RFA and RFA-2 fuel has also been as expected with low drag forces and no occurrences of incomplete rod insertion (IRI). Measurements of fuel assembly bow have shown low bow within the range of the assembly bow database. Finally, measurements of grid width on RFA and RFA-2 assemblies after two, three, and four cycles of irradiation show that the grid growth behavior is consistent with the Westinghouse grid growth database and as expected.

5. Discharge Burnups

The discharge burnup experience with RFA/RFA-2 fuel is extensive via fuel permanently discharged or still in service. Figure 5 shows burnup achieved for discharged RFA/RFA-2 assemblies through the end of 2016. Through 2016, more than 12,900 RFA/RFA-2 assemblies had reached burnup of 40 GWD/MTU or higher, with 2,100+ assemblies achieving burnups greater than 52 GWD/MTU. Several LUAs have operated to approximately 68 GWD/MTU burnup with very good performance. Detailed PIEs of four RFA assemblies that operated in a European plant to a burnup of 68 GWD/MTU have confirmed the good performance at high burnup, including GTRF wear inspections on high burnup assemblies. The RFA/RFA-2 burnup experience will continue to increase in the future years due to the large number of plants that are operating with this fuel design.

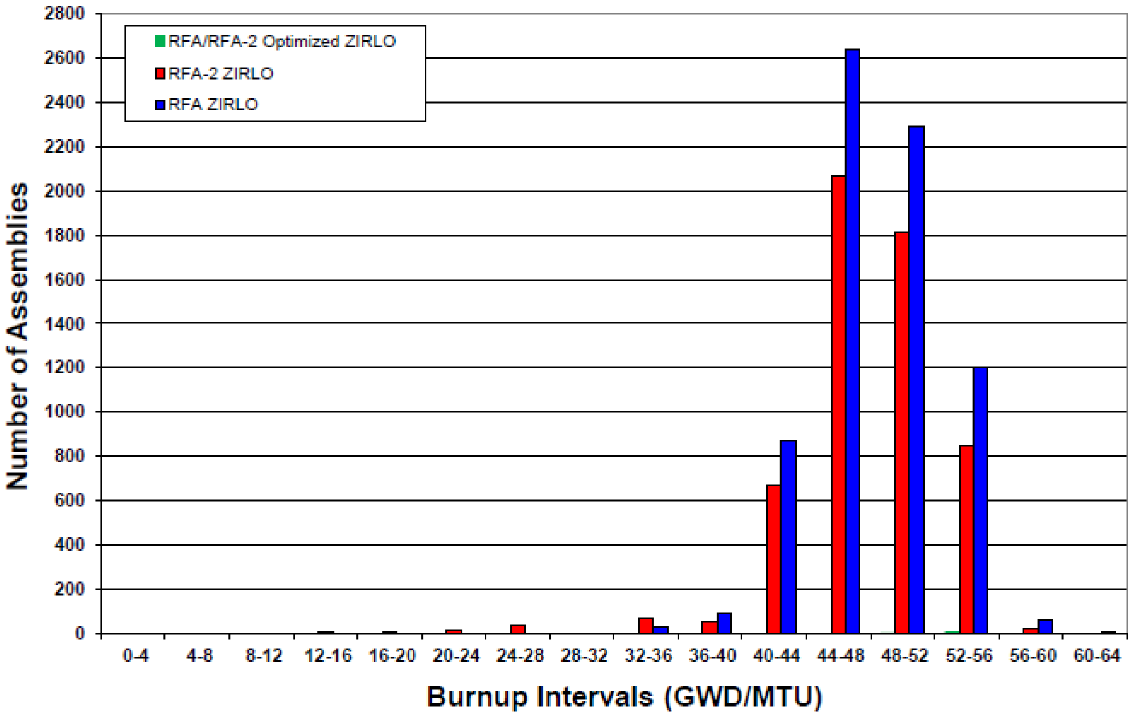


Figure 5: Number of Discharged RFA/RFA-2 ZIRLO® and Optimized ZIRLO Assemblies through December 31, 2016
(only a small number of Optimized ZIRLO assemblies discharged to-date)

6. Summary

A large amount of successful operating experience has been achieved with the RFA and RFA-2 fuel designs since introduction in 1997 [2]. Through December 2017, the RFA and RFA-2 fuel has operated in 62 plants worldwide with ~28,000 assemblies and over 7.3 million fuel rods. The RFA and RFA-2 designs have demonstrated excellent behavior in operation with:

- Minimal fretting wear of the rods up to four 18 months cycles operation
- Good corrosion behavior of ZIRLO and Optimized ZIRLO cladding up to a discharge burnup greater than 52 GWD/MTU
- No incomplete rod insertion issues and good fuel assembly bow behavior
- Minimal incidents of grid damage during fuel handling
- Very good fuel reliability for fuel with the Protective grid/RPG and oxide coated cladding

7. References

[1.] “Fretting Performance of the RFA Fuel”, Top Fuel 2009, Paris, France, September 6-11, 2009.

[2.] “17x17 Robust Fuel Assembly: A Decade of Excellent Fuel Reliability and Competitive Fuel Cycle Economics”, Top Fuel 2008, Seoul, Korea, October 19-23, 2008.

Approval Information
Author Approval OCain Max May-15-2018 16:45:28

Files approved on May-15-2018