Trans Indian Inst Met (2016) 69(2):561–566
DOI 10.1007/s12666-015-0746-y

TECHNICAL PAPER

High Temperature Performance of Creep Strength Enhanced Ferritic Steels Under Steady and Cyclic Operating Conditions

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Received: 13 October 2015 / Accepted: 2 November 2015 / Published online: 6 January 2016

Abstract High energy components must exhibit reliable long-term performance under cyclic operating conditions. Historically assessment of the performance of these components focused on defining the transients related to hot, warm and cold starts and stops. The complexity and range of cycles in many plants now includes rapid changes in generating output to operating levels of 30 % of rated capacity. In many cases, the desirable levels of low load operation are below the values considered in the original design. EPRI programs have thus been working with utilities to implement monitoring campaigns which record the changes in local pressure, temperature and flow with time at different locations within a system and to undertake analysis to assess the influence of these effects on performance. The present review summarizes EPRI achievements linked to transient effects in modern generating plant, with particular emphasis on the behavior of creep strength enhanced steels. These steels, typically based on 9–12 % Cr, offer significant benefits to the design and fabrication of components in high efficiency fossil fueled plants because, when properly processed, tempered martensitic steels offer an excellent combination of strength and toughness. However, assessment of in-service experience demonstrates that cracking in creep strength enhanced ferritic steel components has occurred relatively early in life. Solutions to prevent cracking are presented.

Keywords Creep · Fatigue · Advanced steels · Flexible operation

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1 Introduction

The steam pressure and temperature in fossil-fired power plants have been raised to improve thermal efficiency [1, 2]. In general, these operating changes have been made in new power plants in response to the demand for environmental protection as well as addressing concerns for energy conservation.

In 2010, coal provided 48 % of the electric generation in the United States [3] and over 40 % of the electric generation in the world [4]. Despite its use as major source of electricity, coal faces strong regulatory and economic challenges as the world adopts policies for reducing carbon consumption. As world-wide demand for electricity grows, it is clear that a robust portfolio of power generation options is needed to ensure the availability of reliable and environmentally responsible electricity at a reasonable cost. To meet these challenges, advances in design and technology are needed. For example, The Coal Utilization Research Council/EPRI developed Coal Technology Combustion roadmap, identifies key technologies needed for coal to be considered as an option for future power generation. A key aspect of this roadmap is the continued deployment of higher efficiency pulverized coal combustion boilers using Advanced Ultra supercritical (A-USC) technology.

The High Efficiency, Low Emission plan for coal technology proposed by the International Energy Agency (IEA) indicates that coal generation from older inefficient subcritical plants should be replaced by new high efficiency USC and A-USC plants. This switch would significantly reduce carbon emissions. Further carbon reductions would then be achieved by commercial deployment of Carbon Capture and Storage technologies [5].

2 Boiler Components

The key boiler components in high efficiency or ultra-supercritical plants are high-energy steam piping, headers and tubing. In advanced plant, all of these pressure boundary parts have to meet creep performance design requirements. However, these components cannot simply be 'over designed' since unnecessary increases in thickness significantly raise cost, increase the challenges with fabrication and reduce the expected life under cyclic operating conditions. These issues raise particular problems for the dimensions and design of thick sections components, particularly at local regions of constraint and at stress concentrations. These features are all present in high temperature headers, Fig. 1. These particular issues are highlighted when comparing the relatively simple Design by Rule approaches, which have traditionally been advocated by Construction Codes, to the modern methods involved in Design by Analysis. It is currently the accepted *best practice* to apply the reasonably simple methods to overall design but to compliment these methods using detailed analysis where this is necessary.

Main steam lines and superheater headers, are normally considered as 'heavy section', and can thus be particularly subject to thermal fatigue damage. This damage mechanism occurs when the thermal stresses which result from cyclic operation exceed a given threshold. Creep strength enhanced ferritic (CSEF) steels are of significant benefit in applications involving cyclic operation because of the lower coefficient of thermal expansion and higher thermal conductivity compared to austenitic steels [7]. Early problems in USC plants were often linked to the use of austenitic steels which were prone to thermal fatigue. Recent research has focused on developing cost-effective, high-strength ferritic steels that are resistant to damage.

Fig. 1 Photograph of a typical high temperature boiler header [6]. Using creep strength enhanced ferritic steel reduces the thickness compared to a part made from low alloy steel

Material selection decisions should balance performance, e.g. high temperature strength, with overall cost (fabrication and through life maintenance costs should be considered). In general, higher cost materials have greater high temperature strength, Fig. 2. Thus, for example Nickel based alloys have the potential to operate at temperatures of 700 °C but will have a base cost around 20 times that of CSEF steels. However, this simple analysis does not reveal the full picture. Components manufactured from high strength alloys have reduced section thickness compared to the thickness needed for less expensive alloys. Application of advanced alloys, in combination with Design by Analysis and necessary Quality Assurance, should lead to greater reliability so that savings in operational and maintenance costs are realized.

Consideration of component service performance should consider both *strength* and *ductility*. Creep ductility influences the tendency for fast fracture and thus is important for assessing the risk of catastrophic failure. The tendency for low ductility can be assessed from uniaxial creep tests under the appropriate conditions. For example, the true rupture strain of plain and notched bar creep tests on Grade 92 steel at 600, 625 and 650 °C are plotted as a function of rupture time in Fig. 3 [9]. It is apparent that the true rupture strain decreases as the rupture time increases. At the same rupture duration, the values of true rupture strain of notched specimens are lower than those of plain specimens, Fig. 3. Thus, the constraint introduced by the notch geometry reduces the creep strain to fracture at a given life.

3 Factors Affecting High Temperature Performance

In Fig. 2, the performance of the steel alloy known as Grade 91 is shown in the group of 9–12 % Cr steels. These steels have higher cost than carbon and low alloy steels but are significantly lower cost than austenitic steels and nickel based alloys. This excellent cost: performance advantage has resulted in this steel achieving broad acceptance within the modern power industry for use in fabricating a variety of critical pressure part components. Manufacturers and designers favor Grade 91 and 92 steels because, within a specific temperature range, and when properly processed, they provide superior elevated temperature strength at substantially lower cost than the austenitic stainless steels. The benefits include the fact that components made from higher strength steel are significantly thinner than those made from traditional steels. The significant reductions in wall thickness offer significant weight savings and advantages to flexible operation. Thus, use of CSEF steels should provide benefits over low alloy steels in the fabrication of components for advanced power plants.

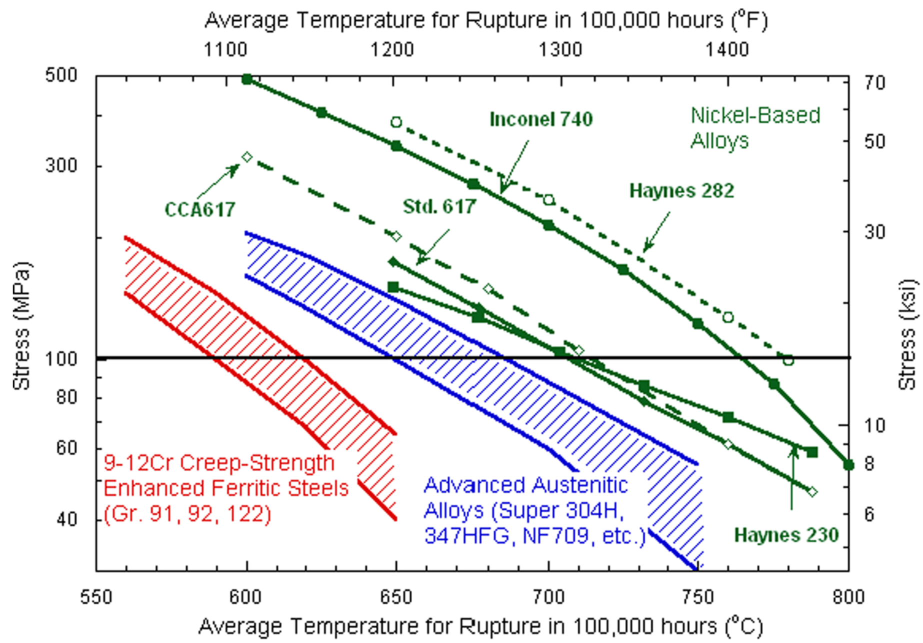

Fig. 2 10^5 h creep-rupture strength as a function of temperature for alloy classes [8]

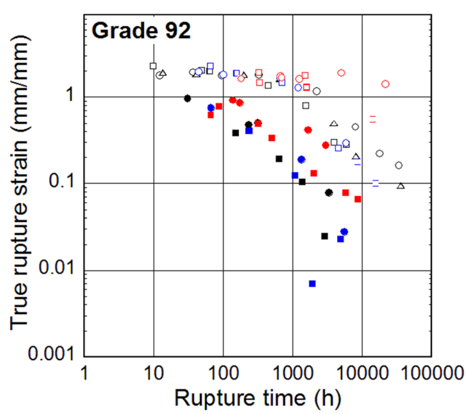

Fig. 3 Comparison of the true creep rupture strain for plain bar (*open symbols*) and notch bar (*closed symbols*) tests on Grade 92 steel base metal [9]

Service experience with CSEF steels [10, 11] has reported examples of component cracking and failure. In many cases, these failures were linked to design or fabrication irregularities. One particular concern was the fact that lack of control of heat treatment resulted in components entering service with deficient elevated temperature properties. An EPRI Guideline document [12] provides recommendations and information to overcome these problems. This guide provides details of how the material should be ordered, how it should be processed, how quality control should be maintained during processing, and how the material should be inspected in the shop and the field to determine its condition before or soon after installation. This Guideline, produced by synthesis of more than 30 years of experience, is provided to the Electricity Supply Industry to ensure that deficient Grade 91 material is never installed in plant.

Very low creep ductilities have been reported in Grade 92 steel base metal samples using test conditions near typical operation of advanced boilers, Fig. 3. An alternative approach to assessment of creep fracture behaviour using the variation of Reduction of Area (ROA) with rupture life is shown in Fig. 4. This iso-ductility compilation shows the measured creep fracture strain for different combinations of test temperature and duration. Samples with a ROA >50 % are represented with a cross, with data for a ROA of below 50 % shown as a circles. For tests at 650 °C and for durations near to, or above 10,000 h the measured ductility is invariably <50 %. In contrast, for tests at 550 °C even with durations approaching 100,000 h the reported ductilities are >50 %. Interestingly, the results reported for tests at 600 °C, i.e. near to the design temperature for many Grade 92 steel components, tests with durations above 10,000 h show a mixed behaviour. At this temperature it appears that, some steel casts show relatively low ductility at lives around 10,000 h; yet others show high creep ductilities. Detailed assessment to establish the reasons for these differences in behaviour are clearly necessary.

The tendency for brittle behaviour in tempered martensitic steels is in all cases due to the formation of creep voids on prior austenite grain boundaries and at other microstructural features such as lath boundaries. The detail of the number of voids formed, and the tendency for reductions in strain to fracture, is different for the different

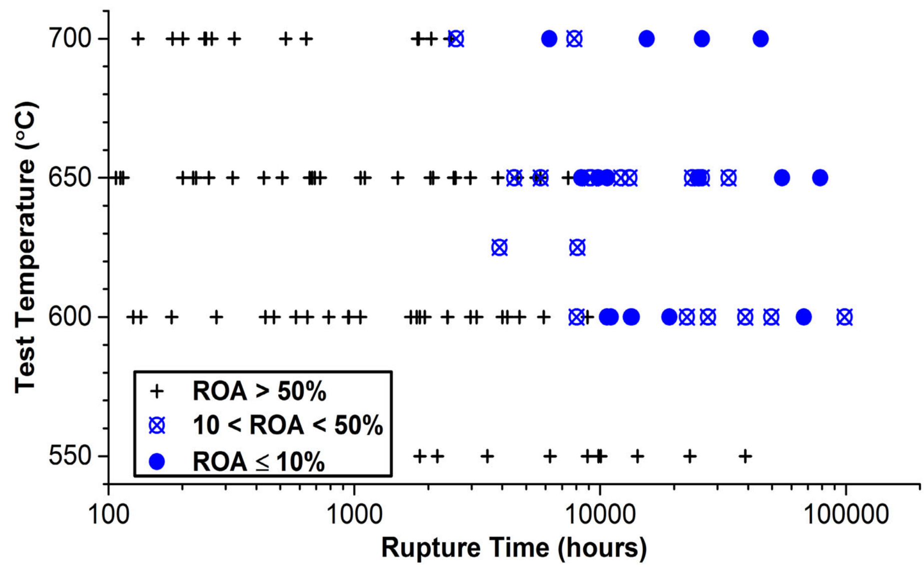

Fig. 4 Creep iso-ductility changes with temperature and time for Grade 92 steel

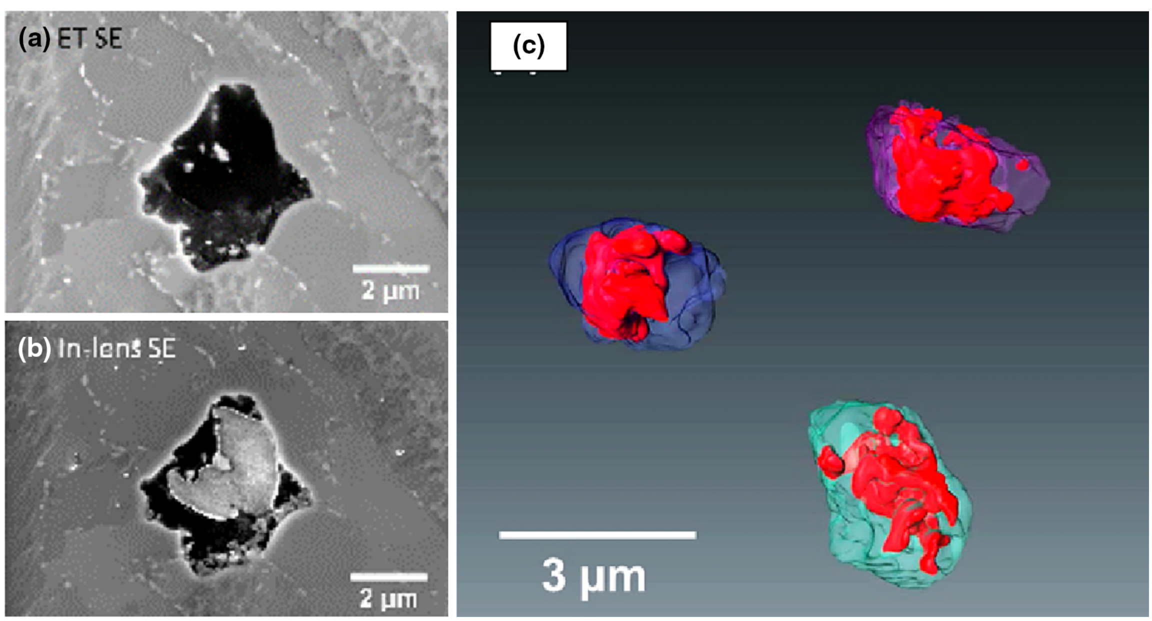

Fig. 5 SEM micrographs collected using the standard SE detector (**a**) the in-lens SE detector (**b**). Reconstruction of data recorded from serial sectioning showing the 3-D shape of cavities (shown in *blue*, *purple* and *green*) and associated particles (shown in *red*) (**c**) (color figure online)

steels [13]. Analysis of the creep cavities formed in P92 steel after long term creep exposure revealed that the majority of the voids present were associated with hard ceramic particles [14]. This behaviour is illustrated with reference to the images shown in Fig. 5 [14]. Electron micrographs of creep voids were collected using a secondary electron (SE) detector in backscatter mode, Fig. 3a. Imaging of the inclusions present was then performed using in-lens SE techniques at short working distances. This approach clearly showed that inclusions were present which were not imaged using standard secondary electron methods, see Fig. 5b [14].

Selected locations containing creep voids were also investigated using serial sectioning [14]. The data collected were reconstructed into a 3 dimensional image using Avizo v6 software and typical 3-D image reconstructions are shown in Fig. 5c. The angular shape of the creep voids and the association with inclusions are clearly shown. Chemical analysis revealed that most of the particles present at creep voids were boron nitrides which appeared to be associated with MnS or Al_2O_3 [14]. It appears that the boron nitride inclusions developed on the alumina or magnesia particles which were formed during de-oxidation or originated from the refractory of the steel-making furnace.

4 Influence of Flexible Operation

EPRI's on-going strategy to establishing solutions to design and performance assessment of the flexible operation of high energy components has involved:

- Facilitating annual expert workshops,
- Preparation of critical reports and publications'
- Establishing a knowledge base of materials behavior, and
- Preparation of new ASTM standards for creep fatigue testing and data analysis.

Achievements in increasing understanding of the factors affecting creep fatigue behaviour are directly linked to engagement and international collaboration. In workshops and annual meetings invited participants bring expertise together to establish key goals and schedules. Discussions focus on emerging issues with future work leading to improvements to component design and assessment. The community benefits of these efforts are illustrated below with consideration of acceptance of two ASTM standards associated with testing.

Many countries had established national guidelines and procedures for creep fatigue testing. However, there were differences in detail between many of the recommendations. A key activity facilitated by EPRI was development of specific ASTM Creep Fatigue Standards. Currently efforts have resulted in two standards:

- *ASTM Standard* Test Method for Creep Fatigue Testing, E2714-13 [15]. This method covers the determination of mechanical properties pertaining to creep-fatigue crack formation in nominally homogeneous materials. It is primarily aimed at providing the material properties required for assessment of defect-free engineering structures containing features that are subject to cyclic loading at temperatures that are sufficiently high to cause creep deformation.
- *ASTM Standard* Test Method for Creep-Fatigue Crack Growth Testing, E2760-10. This test method is concerned with developing creep-fatigue crack growth data under cyclic conditions which is used in some more sophisticated assessments of in-service materials when large flaws may be present.

As part of the review and acceptance process, the provisional Standards were evaluated through round robin test programs. The round robin testing program is complete for ASTM E2714-13 [15] and precision and bias statements were added. For ASTM E2760-10 the round robin testing and data analysis will be completed by the end of 2015.

The round robin test program for ASTM E2714-09 involved participation of 16 laboratories from different parts of the world. The results of 13 participants were reported to EPRI and reviewed by the ASTM Task Group on Creep-fatigue Crack Formation (E08.05.08). In all cases, strain controlled creep-fatigue tests were conducted at 625 °C at three strain amplitudes. Each laboratory followed guidelines of the provisional standard, but variations in specimen geometry, heating methods, and numbers of tests were acceptable. Statistical analysis of the results was conducted. Assessment of the data required development of an improved analytical method, not originally prescribed in the standard, to determine the cycles to crack formation. The analysis of the data found the variability factor for the 95 % CI bands increased at longer hold times and lower strains. One significant finding was that post-test inspection of specimens was necessary to determine if a test was valid (or not). Uneven heating due to the use of induction heating methods or failures due to bending were not identified by the testing laboratory, but post-test inspection and metallography resulted in some tests being rejected. EPRI recommends metallographic assessment as part of the post-test evaluation to see if damage was intergranular or transgranular.

5 Benefits of Advanced Fabrication Methods

Many complex shape components are manufactured by casting. However, it is well known that casting can exhibit problems with quality. It is not unusual for large cast bodies to have more than 30 major defects found during non-destructive testing. Remedial action typically involves excavation followed by weld repair. Obviously this process is relatively inefficient. Moreover, because of the risk that small pore type defects may not be identified and repaired, in many cases even the final wall thickness of a cast component must be significantly greater than the minimum.

It should also be noted that when using these fabrication methods with some of the more metallurgically complex alloys, it is particularly difficult to achieve a fully homogeneous structure throughout the component. This is even more difficult when seeking to optimize microstructure. Indeed, the heterogeneity involved with the cast and repair approach, in combination with the need for good control of final heat treatment steps, means that even when care is taken during the casting process, the performance may not be of the expected level. To overcome the problems associated with casting an alternative approach to fabrication of some geometrically difficult components has been developed. These approaches are based on recent improvements to power metallurgy, see for example Fig. 6.

These advances have the potential to realize the benefits of near net shape manufacture; these benefits include the following:

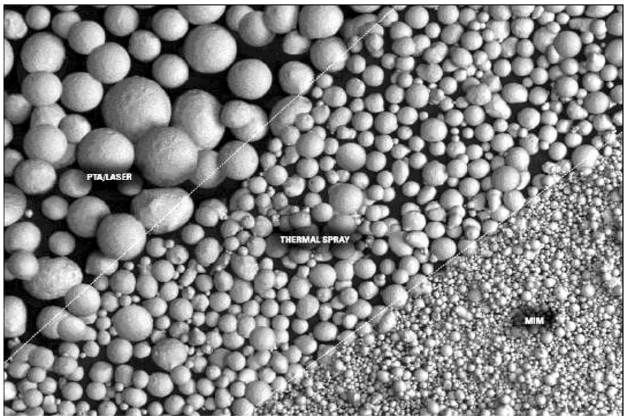

Fig. 6 Examples of alloy powders produced using different methods [16]

- Eliminating problems associated quality assurance in general and the application of non-destructive testing in particular,
- Enabling the manufacture of large, complex "Near-Net Shape" components which require less machining than is the case with castings,
- Production of high quality products with improved confidence in performance. A product made using modern powder metallurgy should have:
  - Predictable production schedule, and
  - Significantly reduced (or even eliminated) the need for repairs.
- The ability to make parts with compositions which could not be achieved by casting, and
- Providing an alternate supply route for long-lead time components. This offers benefits through having increased diversity in sourcing components.

These developments have been researched by key groups, including EPRI, for some time and are now at a stage where components have received acceptance by standards and specifications [16]. This development illustrates that new technologies can be established.

6 Concluding Remarks

Research and development is ongoing to improve the economic benefits of building advanced, highly reliable power plants which will operate in flexible mode. It is increasingly recognized that improved Design and Life Management strategies require consideration of Damage Tolerance. Since the ability to limit the risk of fast fracture from very small defects is critical to safe, reliable performance, efforts must continue to assess the factors affecting both strength and ductility. The creep strengthening mechanisms of tempered martensite ferritic steels has been referred to as carbide stabilized, substructure hardening. Thus, the excellent strength of these steels is due to the fact that high densities of fine carbo-nitrides retain a dislocation substructure during operation at elevated temperature and stress. However, it is now well established that detailed changes in composition, steel making and heat treatment can have a marked effect on creep performance. For example, long term creep and creep fatigue ductility is influenced by metallurgical processing factors that change the susceptibility to the nucleation and growth of creep voids. It is clear that to ensure safe and reliable power generation research and development must integrate design, manufacture, and operation with performance assessment.

References

1. Viswanathan R, and Bakker W T, *Materials for Ultra Supercritical Fossil Power Plants*, Report TR-114750, EPRI, Palo Alto (2000).
2. Masuyama F, *ISIJ Int*, **41** (2001).
3. The CURC-EPRI Coal Technology Roadmap. August 2012: Update. www.coal.org.
4. International Energy Agency © OECD/IEA, (2012) www.iea.org.
5. Diczfalusy B, in IEA Clean Coal Centre Workshop: On Advanced ultrasupercritical Coal-Fired Power Plants, Vienna, Austria (2012).
6. Hamart O, Vallourec, Private communication.
7. DiStefano J R, and Sikka V K, in Summary of Modified 9Cr-1Mo Steel Development Program, 1975–1985. ORNL-6303, Oak Ridge National Laboratory (1986).
8. Shingledecker J, Purgert R, and Rawls P, in Seventh Int Conf on Advances in materials Technology for Fossil Power Plants, EPRI/ASM (2013).
9. Shigeyama H, Takahashi Y, and Parker J D, in Proceedings of the ASME 2015 Pressure Vessels and Piping Conference, PVP2015—45252, Boston, USA (2015).
10. Parker J, *Int J Pressure Vessels Pip*, **101** (2013).
11. Parker J D, *Int J Pressure Vessels Pip*, **114–115** (2014).
12. *Guidelines and Specifications for High-Reliability Fossil Power Plants: Best Practice Guideline for Manufacturing and Construction of Grade 91 Steel Components*. EPRI, Palo Alto, CA.1023199 (2011) updated as EPRI 3002006390 (2015).
13. Parker J D, *Advances in Materials Technology for Fossil Power Plant*, EPRI/ASM (2014), p 714.
14. Gu Y, West G D, Thomson R C, and Parker J D, *Advances in Materials Technology for Fossil Power Plant*, EPRI/ASM (2014), p 596.
15. Standard Test Method for Creep-Fatigue Testing, ASTM, Designation: E 2714—13.
16. Gandy D W, Shingledecker J, Lherbier L, and Novotnak D, *Powder Metallurgy Methods for Producing Large Components*, Nuclear Exchange (2011).