THE PERFORMANCE OF COMBUSTION ENGINEERING FUEL IN OPERATING PWRs

INTRODUCTION AND SUMMARY

Combustion Engineering (C-E) currently has seven PWRs in full scale commercial operation. Six of these reactors use fuel assemblies of a 14 x 14 array. The exception is Palisades which utilizes a 15 x 15 array. An eighth reactor, Arkansas Nuclear One-Unit II (ANO-II), currently is in the power ascension phase of its initial startup. ANO-II is the first C-E reactor to feature fuel assemblies of a 16 x 16 array, the precursor to C-E's standardized System 80™ design.

This paper reviews the performance record of C-E fuel and other components of the fuel assemblies of, basically, the 14 x 14 design. Some of the 14 x 14 fuel assemblies loaded for the first cycle include from 8 to 12 burnable poison rods to control excess core reactivity. The need for burnable poison decreases as the equilibrium cycle approaches, thus reload fuel batches generally do not contain burnable poison. Each of the five control element assembly (CEA) guide tubes in the 14 x 14 fuel assemblies displaces four fuel rod lattice positions, leaving a total of 176 fuel rods in an assembly with no burnable poison rods. The guide tubes and the spacer grids have always been fabricated from Zircaloy-4, the exception being the bottom spacer grid which is Inconel-625.

The performance of C-E supplied fuel rods has been excellent over the past four years. Following the experience with early-design fuel in Maine Yankee Core I, pellet clad interaction (PCI), assisted by stress corrosion cracking (SCC), essentially has been eliminated through design changes as a cause of fuel rod perforations in C-E fuel. The perforation of burnable poison rods due to a primary hydriding mechanism in reactor also has been eliminated in current C-E fuel by decreasing the moisture content within the rod. Guide tube wear caused by vibration of the CEA has been corrected without significant consequence to reactor performance by utilizing wear sleeves which can be retrofit into worn guide tubes of irradiated assemblies at poolside. Data obtained from lead assemblies through four cycles at Fort Calhoun demonstrate that the C-E all-Zircaloy grid is a proven design. The status of each of these four areas of fuel assembly performance in particular are described in detail in the paper.

A discussion also is provided in this paper of C-E's involvement in the verification of fuel performance at extended burnups, in light of the significant conservation benefits to be obtained through improved uranium utilization. Major areas of concern to fuel rod performance at high burnup are addressed, including: enhanced fission gas release; PCI/SCC; assembly dimensional stability; and external corrosion of cladding.

GUIDE TUBE WEAR

During visual inspection of fuel assemblies following the first scheduled refueling shutdown of the Millstone II reactor in December 1977, it was discovered that wear had developed in some of the CEA guide tubes at an elevation approximately 17 inches from the top of the fuel assemblies. This position corresponds to both the top of the active core and the lower end of the fully withdrawn CEAs. The total time of operation for the first cycle was about 15,000 hours.

Subsequent closer examinations of the fuel assemblies revealed that the wear had been produced by lateral motion of the tips of the Inconel-625 CEA fingers against the inner surface of the Zircaloy-4 guide tubes.

Following the initial discovery of this wear phenomenon, C-E developed eddy current examination methods for remotely measuring the extent of wear, including the capability to measure axial and circumferential guide tube wall thicknesses. As combinations of these examination techniques were employed in the fuel inspections during the normal refueling shutdowns of other C-E operating reactors, it became apparent that guide tube wear, to some magnitude, was occurring in all other (then-operating) C-E reactors except Palisades (which uses cruciform control rods and has no guide tubes) and Fort Calhoun. The Fort Calhoun guide tubes had very slight wear which may be related to the smaller size and lower flow rates of this core relative to those cores having greater guide tube wear.

Hot Cell Evaluation

In order to examine the nature of the wear patterns and to determine the extent of hydrogen pickup and redistribution which may have resulted from the wear, the upper section of a Millstone II fuel assembly was cut off and sent to a hot cell. The measurements taken of remaining wall thicknesses served to confirm the eddy-current measurements, and the patterns observed were typical of nearly all wear indications examined to date. These patterns are summarized below:

1. The wear area begins abruptly at an elevation corresponding to the hemispherical lower end of a fully withdrawn CEA and tapers gradually to an essentially unworn condition several inches above the start of the wear. All significant indications of wear were found at elevations in the guide tubes either at or within a few inches of the position of the fully withdrawn CEAs. The few wear indications encountered at positions corresponding to greater CEA insertion were all insignificantly small.
2. The cross section of the worn area is nearly always highly asymmetric, including many cases where the material 180° away from the location of maximum wear exhibits little or no wear.
3. The hydrogen concentration in the wear areas is greater than elsewhere in the tube, with the maximum values located where the guide tube is thinnest. However, there was no indication of zirconium hydride being a dominant phase, and hydrides that are present are essentially uniformly distributed through the tube wall thickness.

Impact of Worn Tubes

The principle concern associated with guide tube wear is the reduced capability of the fuel assembly to carry various operating and calculated accident loads. As regards this concern, two conclusions can be made:

1. There have been no instances of failures of even the most severely worn guide tubes.
2. The observed guide tube wear was never found to affect CEA scram performance.

Analysis did show, however, that a small number of guide tubes had sustained wear to a degree such that guide tube reinforcements should be installed as a precaution for fuel handling operations.

Immediate Corrective Action

The overall occurrence of guide tube wear has been viewed as arising because of a combination of circumstances wherein (1) flow forces give rise to vibrations of the CEA which cause relative motion between the CEA and the fuel assembly, and (2) the inner surface of an annealed Zircaloy-4 guide tube provides a comparatively poor wear surface. Understanding and controlling the forces which give rise to the vibration appeared to necessitate a long range program. Immediate efforts, therefore, were concentrated on developing the best way to protect the inner surface of the guide tube at those elevations where long term CEA operation could be expected (*i.e.*, at or near the fully withdrawn position). Major design criteria included maintaining feasibility of remote installation while assuring that subsequent reactor operation with repaired fuel assemblies would produce no undesirable effects on either fuel assembly or CEA performance. A thin-walled wear sleeve of stainless steel, chrome plated on the inner surface, was designed to meet all of these requirements. The upper end of the sleeve is flared slightly to match up with a corresponding flare in the top of the CEA guide path, and the overall length of the sleeve ensures that the guide tube is protected when CEAs are fully withdrawn (no evidence of significant wear has been found where CEAs were partially inserted).

The wear resistance of this sleeve design was demonstrated in C-E's hot flow test facility. Wear sleeves have since been installed in approximately 600 fuel assemblies in the five operating reactors having a 14 x 14 array. Wear sleeves have also been installed in the initial core assemblies of ANO-II.

Long Term Control of Wear

The stainless steel wear sleeves discussed in the preceding section appear to be an effective means of preventing guide tube wear without adversely affecting other aspects of reactor performance. In-service evidence of the acceptability of the sleeve design, however, must await the results of the first interim irradiation examination of sleeved guide tubes at Millstone II.

C-E is also exploring long term solutions to control the CEA vibration that produces guide tube wear. The almost complete absence of wear at Fort Calhoun is regarded as a demonstration that a reduction of CEA vibration to acceptable levels need not necessarily involve extensive modifications to component designs.

Accordingly, in parallel with the efforts to develop the wear sleeve concept, C-E has been conducting a test program aimed at increasing the understanding of factors which produce CEA vibration. It is possible that appropriate design modifications could differ among operating reactors and reactors not yet in operation. An overall goal of all program efforts, however, is to reduce vibration sufficiently so as to eliminate the need for wear sleeves in future reloads or first core loadings.

BURNABLE POISON RODS

Observed reactivity anomalies during the first 800 Mwd/MTU core-average burnup at St. Lucie I in 1976 have been attributed to perforated rods containing Al_2O_3-B_4C pellets as a burnable poison material. Poolside and hot cell examinations of the Zircaloy-4 cladding of these rods revealed the cause of perforation to be primary hydriding of the cladding. The hydriding has been attributed to moisture retention of the Al_2O_3-B_4C during rod fabrication. Specifications were revised, and the rod fabrication procedure was altered accordingly, to produce burnable poison rods with lower moisture levels. Subsequently, all burnable poison rods in the initial core of St. Lucie I were replaced at poolside, and all burnable poison rods already fabricated for the initial core of Calvert Cliffs II were reworked to comply with the new poison rod specification. Recent visual examinations of the fuel assemblies from both of these plants after their first full cycle of operation have verified the integrity of the burnable poison rods made to the revised specifications. The occurrence of perforated burnable poison rods, therefore, has been resolved for the current generation fuel assemblies through elimination of the direct cause of the perforations.

Perforated burnable poison rods also have been observed during routine refueling outages at other C-E operating plants which, like St. Lucie I, contained rods fabricated to the earlier specification. The presence of perforated poison rods, however, has not been a cause of premature fuel assembly discharge, nor has it significantly limited core availability at any of these plants.

ALL-ZIRCALOY SPACER GRIDS

The performance status of the C-E all-Zircaloy spacer grids requires only a brief update following the last report of trouble-free operation at the ANS Topical Meeting in St. Charles.[1] The cumulative experience with these grids continues to demonstrate the reliability of the current design. Table I quantifies the extent of this experience. The lead plant in operating experience is Fort Calhoun, which began its fifth reactor cycle in January 1979. All of the fuel assemblies which have been in the Fort Calhoun reactor core are of a similar C-E design. Twenty-one of these assemblies have either completed or are currently operating in their fourth cycle. The low values of coolant activity in Fort Calhoun and in all other C-E plants verifies the absence of significant fretting of fuel rods in these assemblies. Thus the grids have been operated well beyond their initially planned lifetime in reactor, thereby providing a sound basis for continued application of this proven design at higher burnups.

TABLE I
NUMBER OF FUEL ASSEMBLIES IRRADIATED WITH C-E'S STANDARD ALL-ZIRCALOY GRIDS

Plant	No. of Assemblies	Current Reactor Cycle	Peak Assembly Burnup GWd/MTU
Palisades	272	3	24.4
Maine Yankee	650	4	30.6*
Fort Calhoun	290	5	35.6*
Calvert Cliffs I	361	3	32.6
Millstone II	289	2	25.2
St. Lucie I	277	2	21.5
Calvert Cliffs II	301	2	20.7
Totals	2,440		

*Discharged assemblies.

FUEL RODS

The statistics listed in Table II represent the current status of fuel rod performance in C-E operating plants. ANO-II is included without data on coolant activity since it currently is in the initial startup phase of commercial operation. The other plants are all beyond their first reactor cycle, and the levels of iodine-131 in the coolant indicate very low levels of perforated fuel rods. These plants in general have been operating at full or stretch power without a significant change in the reliability of the fuel rods.

The use of coolant activity to deduce the number of perforated fuel rods is accomplished through an empirical escape rate coefficient, and accounts for the time at steady-state power and the flow rates through the clean-up system of each plant. Although data from leak testing of discharged fuel assemblies would be more accurate, these data currently are not available, since no utility has found it necessary to leak test C-E fuel since 1975. The use of coolant activity also provides a more up-to-date status of operating fuel performance since leak testing can be performed routinely only during planned refueling outages. Furthermore, an early batch of C-E fuel experienced PCI/SCC induced fuel rod perforations in the first core of Maine Yankee. Leak test data from that core have been reported,[2] and these date have served to benchmark the escape rate coefficient used in converting coolant activity to numbers of perforated rods. As discussed in Reference 2, the UO_2 fuel in that initial core was subject to in-reactor densification. When combined with the lack of prepressurization, the fuel operated at higher temperatures than does modern fuel at equivalent power. Since 1974, all of C-E's fuel has been prepressurized and has incorporated other design changes. The pellet shape was changed to add chamfers and to reduce the length-to-diameter ratio from 1.7 to 1.2. The pellet density was increased to 95.0% T.D., and the fuel fabrication process was changed to reduce in-reactor densification. The wall thickness of the cladding was increased from 0.026 to 0.028 in. for added conservatism.

The result of the above design changes can be evaluated by examining Fig. 1. Each of the operating plants are monitored frequently to estimate current defect levels. The sum of the highest defect levels for each plant has been plotted by year in Fig. 1 in terms of the number of defective fuel rods per each 10,000 rods in operation. The improvement shown in the reliability level begins with the changeover to the current C-E standard design following the Maine Yankee experience. Some carryover of earlier fuel is evident from fuel fabricated before 1972 and operating beyond that point. The continuous improvement over the last five years from 3 defects in 10,000 rods to less than 1 defect in 10,000 rods is evidence of excellent fuel performance. C-E's irradiation test programs are dedicated to maintaining this high level of reliability

TABLE II
STATUS OF OPERATING C-E PLANTS
(Feb. 1, 1979)

Plant	Current Reactor Cycle	Core Ave GWd/MTU	Peak Assy GWd/MTU	Steady-State Power, %	I-131 μc/mℓ‡	Estimated Number of Leaking Rods
Palisades*	3	15.2	24.4	100	2×10^{-2}	1
Maine Yankee	4	14.1	27.1	104†	1×10^{-2}	1
Fort Calhoun	5	10.5	29.1	100	1×10^{-2}	2
Calvert Cliffs I	3	16.3	32.6	100	1×10^{-2}	3
Millstone II	2	17.8	25.2	100	1×10^{-1}	1
St. Lucie I	2	15.4	21.5	100	4×10^{-2}	6
Calvert Cliffs II	2	11.8	~20.7	103†	2×10^{-2}	4
Arkansas Nuclear One, Unit II	1	Startup	< 1.0			

*One-third of the core is C-E fuel and includes the peak burnup assemblies.

†At stretch power.

‡Based on plant specific calculations which take into account primary coolant volume and purification system flow rate.

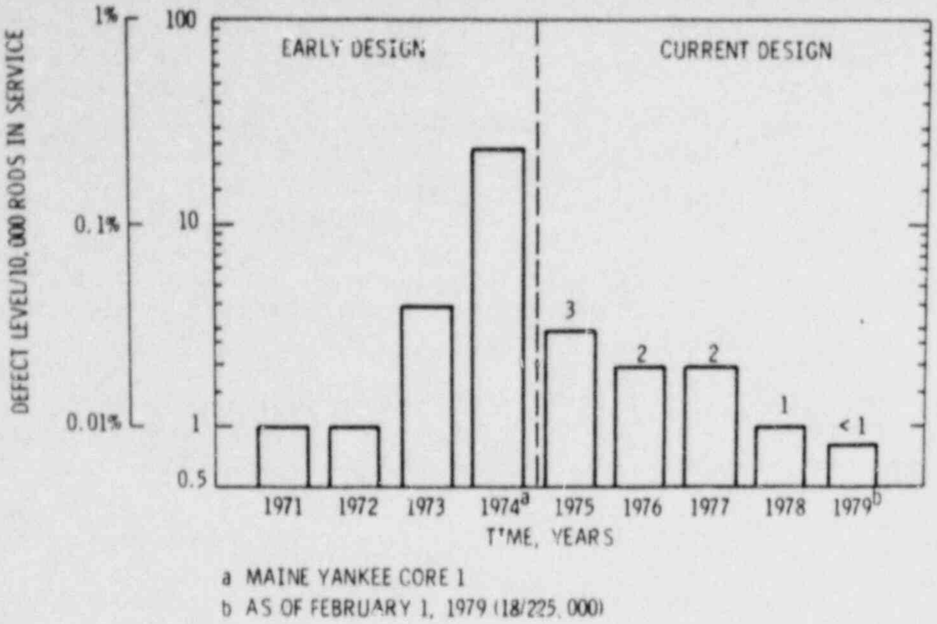

Fig. 1: History of C-E fuel performance

in light of the utilities' desires to increase: fuel maneuverability; reload fuel design flexibility; and batch-average discharge burnups.

HIGH BURNUP R&D

C-E has an extensive commitment to fuel irradiation tests and demonstration programs with major goals that impact high burnup fuel assembly performance. The programs address four major performance concerns at high burnup: PCI/SCC in fuel rods; possible enhanced fission gas release (and high end-of-life rod internal pressures); fuel assembly dimensional stability; and external corrosion of cladding. Various programs are being conducted in test reactors and power reactors and will provide the type of data needed to resolve open questions about fuel performance at high burnup relative to these four concerns.

Potential for PCI/SCC

Evidence exists from test reactor ramp experiments of a burnup dependency for fuel rod perforations caused by PCI/SCC. Contributing factors may be related to: fuel-to-clad gap closure mechanisms (*e.g.*, fuel swelling and cladding creepdown); increased availability of volatile fission product species; increased fuel handling events; and increased number of fuel reconditioning events. Test-reactor power ramp experiments ongoing at Petten and Studsvik (OVER-RAMP Program) on short rods will aid in establishing failure boundaries for PCI/SCC in prepressurized PWR rods with varied fuel and cladding designs. Failure thresholds as a function of burnup and ramp operating variables (such as rate of power change) are also being explored in these ramp tests. Programs are underway in C-E commercial reactors to provide irradiated strings of short rodlets which eventually can be ramp tested as in the Petten and Studsvik programs.

Fission Gas Release

C-E is developing a data base to benchmark fission gas release at high burnups in prepressurized PWR rods. Data are already available at burnups close to 30 GWd/MTU from the C-E/EPRI joint program at Calvert Cliffs I.[3] Measurements were obtained on fuel rods containing three different UO_2 pellet microstructures after one and two reactor cycles of irradiation. The densification behavior of the fuel markedly affected the cold internal pressures measured after irradiation. Gas release fractions were less than 1% in all rods, and no burnup enhancement was evident at 29.1 GWd/MTU. Significant new data, at burnups up to 45 GWd/MTU, will be obtained in 1980.

Dimensional Stability

Irradiation causes both stress-free and stress-induced permanent dimensional changes in the components of fuel assemblies, including axial growth and bowing of fuel rods and CEA guide tubes. Stress relaxation of spacer grid spring tabs also is caused by irradiation. Lead assembly irradiations of 14 x 14 fuel assemblies in Fort Calhoun and Calvert Cliffs I should provide significant data on C-E's standard fuel assembly designs to at least 40 GWd/MTU by early 1982.

External Corrosion

C-E, KWU and EPRI have entered into a long term joint program to obtain corrosion data and develop a correlation for in-reactor Zircaloy-4 corrosion in a PWR environment. High burnup data to about 50 GWd/MTU will be obtained by 1980 from KWU commercial reactor fuel rods of standard design as a part of this program. C-E test assemblies should produce additional corrosion data on fuel rod clad corrosion at high burnup in the near future.

CONCLUSIONS

The reliability of C-E supplied fuel continues to be excellent. The C-E all-Zircaloy spacer grid has been proven to current discharge burnups and are being qualified for higher burnups in a large number of lead assemblies. Current design burnable poison rods have eliminated the primary hydriding of the Zircaloy-4 cladding experienced with rods of early design. The occurrence of significant guide tube wear appears to be corrected by sleeving, although efforts are continuing at C-E to eliminate vibration of CEAs and, therefore, the cause of wear. The major emphasis of C-E's fuel-related R&D programs has shifted to demonstrating high burnup capabilities of standard and advanced fuel designs.

REFERENCES

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