ADVANCED PWR FUEL DESIGN CONCEPTS

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INTRODUCTION

For nearly 15 years, Combustion Engineering has provided pressurized water reactor fuel with the features most suppliers are now introducing in their advanced fuel designs. Zircaloy grids, removable upper end fittings, large fission gas plenum, high burnup, integral burnable poisons and sophisticated analytical methods are all features of C-E standard fuel which have been well proven by reactor performance.

C-E's next generation fuel for pressurized water reactors features 24-month operating cycles, optimal lattice burnable poisons, increased resistance to common industry fuel rod failure mechanisms, and hardware and methodology for operating margin improvements. Application of these various improvements offer continued improvement in fuel cycle economics, plant operation and maintenance.

EXTENDED CYCLE LENGTH CAPABILITY

U.S. utility experience has shown that extending fuel cycle length from 12 to 18 months or more can provide a significant reduction in total power generation cost as a result of higher plant availability and reduced replacement power cost. An essential factor in the economic implementation of longer cycles is the use of advanced fuel design features, such as high burnup, optimum burnable poisons and low leakage fuel loading patterns which compensate for the fuel cycle cost penalty which would otherwise be associated with longer cycles.[1,2] C-E's leadership in the use of such features combined with advanced reactor engineering methods has enabled a smooth transition to extended cycles for many C-E customers. From 1983-1985, C-E fueled plants operating with extended cycles had an overall capacity factor of 75%. This compares very favorably to the U.S. industry average of 59% over the same period.[3]

Responding to customer interest in the potential benefit of further increases in cycle length, C-E completed two studies of 24-month fuel cycles in 1985.[4]

As a consequence of these studies, Southern California Edison (SCE) and Baltimore Gas & Electric Co. (BG&E) are implementing 24-month cycles. Cycle 8 of Calvert Cliffs Unit 2, which began early this year, will mark the first 24-month cycle in a U.S. PWR. Unit 1 is scheduled to begin 24-month cycle operation in spring, 1988. The two Calvert Cliffs units will refuel during

Table 1

24-Month Cycle-By-Cycle Summary

CYCLE TYPE	CYCLE NO.	#OF ASSEMBLIES	ENRICHMENT	FRESH SHIMS	LENGTH (EFPD)	BOC HFP MTC	1-PIN POWER PEAK	MAX 1-PIN BURNUP	BATCH AVERAGE DISCHARGE
18-EQUILIBRIUM	7	60	4.05/3.40	0	400	-0.1	1.48	49.4	41.4
24-TRANSITION	8	88	4.05	576	602	0.0	1.53	52.8	40.0
24-TRANSITION	9	96	4.25	576	613	0.0	1.56	54.6	43.7
24-EQUILIBRIUM	10	92	4.25	544	610	0.0	1.58	54.3	45.6
24-EQUILIBRIUM	11	92	4.25	544	603	0.0	1.59	55.0	46.5

the spring of alternate years; and the low cost replacement power available to BG&E during the spring season should produce savings of 1-2 percent of annual energy costs compared to present operations with 18-month cycles.[4]

The fuel cycle characteristics for successive transitional and equilibrium 24-month cycles in Calvert Cliffs Unit 2 are indicated in Table 1. The 24-month cycles are designed to optimize fuel cost by limiting the number of fuel assemblies to 92 in the equilibrium cycles (core-to-batch size ratio of 217/92), and by using low-leakage fuel loading patterns as illustrated in Figure 1. The fuel management employed in 24-month cycles places increased demands on the nuclear design and fuel performance analyses relative to 18-month cycles as a result of higher fuel enrichment, fuel discharge burnup, local power peaking, and reactivity control using integral burnable poisons.

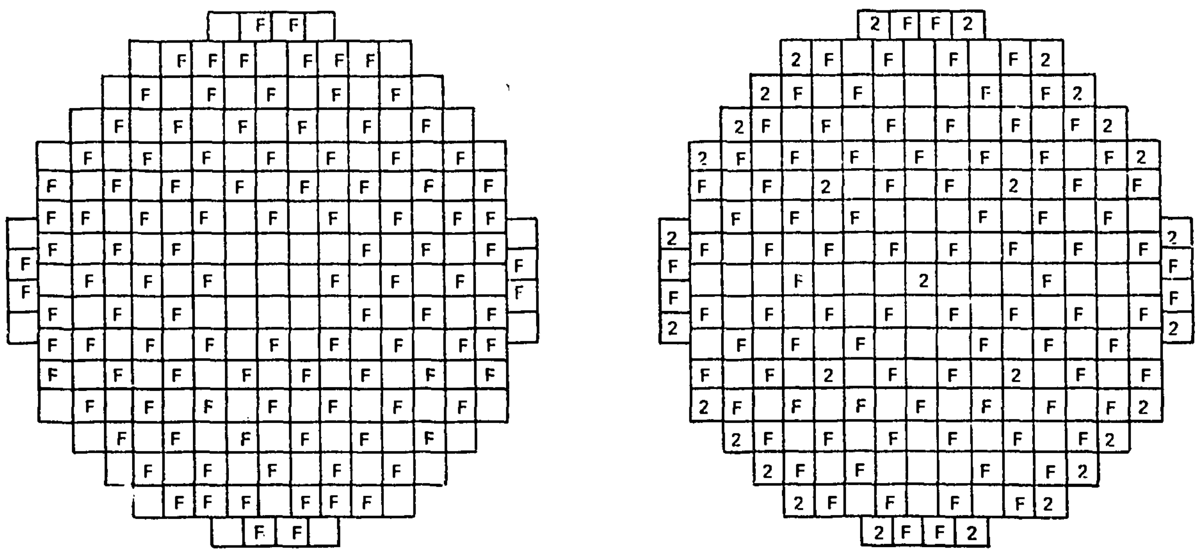
The principal bases for accommodating these requirements are the outcome of C-E programs begun in the late 1970's to develop and implement advanced fuel management and high burnup in operating PWRs.[5] A series of generic analyses have been performed along with modifications to technical specifications in order to facilitate the licensing and operation of successive transitional 24-month cycles in accordance with 10CFR50.59. Among these activities are the qualification of fuel handling and storage facilities for fuel enrichments up to 5 wt% U-235, implementation of proven margin gain features in the fixed in-core detector monitoring system, licensing approval of enhanced C-E methodologies including use of the FATES3B fuel performance code,[6] and extension of the C-E data base for high fuel discharge burnups.

HIGH BURNUP

Increasing discharge burnup has long been recognized - and has been widely reported - to be a beneficial means of reducing fuel costs.[7] The average discharge burnup of C-E supplied fuel has increased steadily from a range of 30-33 MWD/kg in the late 1970's to a present range of 42-45 MWD/kg.

C-E has implemented high burnup capability through a long term research and development program which has produced an extensive base of fuel irradiation test data and has resulted in the validation of advanced methodologies for predicting fuel rod and assembly phenomena with extended burnup. Through this program C-E became, in 1984, the first fuel vendor to receive generic licensing approval of design methodology for extended fuel burnups, covering batch average discharge burnups to 45 MWD/kg, and maximum fuel rod discharge burnups to 52 MWD/kg.[8] Further increases in discharge burnup for C-E fuel are progressing in pace with the implementation of longer cycle lengths.

Specifically, to support the requirements of 24-month cycles, C-E is currently licensing higher average assembly and maximum rod limits of 50 MWD/kg and 60 MWD/kg, respectively.



24- MONTH LOADING MAP* (SONGS) | 24- MONTH LOADING MAP* (CALVERT CLIFFS)

*NOTES: "F" DENOTES FRESH FUEL LOCATION
"2" DENOTES TWICE-BURNED FUEL LOCATION
ALL OTHER LOCATIONS CONTAIN ONCE-BURNED FUEL

Fig. 1 Low Leakage Fuel Management Patterns

OPTIMIZED BURNABLE POISON

Modern reload core designs involving high burnup, extended-cycle-length, and low-leakage fuel management require the use of burnable poison rods to control the global power distribution and to maintain a negative moderator temperature coefficient of reactivity (MTC). C-E utilizes two basic burnable poison designs in order to optimize a fuel cycle. The first is a $B_4C-Al_2O_3$ design, with the burnable poison in the form of homogeneous pellets contained in Zircaloy-4 clad rods that displace fuel rods in the lattice.[9] These poison rods remain in the assembly after they are depleted, thus eliminating the handling of separate radioactive waste. The magnitude and duration of reactivity control with this design are controllable by varying the concentration of B_4C in the pellets and the number of poison rods per assembly. The relatively slow release of reactivity by the boron in this lumped poison geometry makes this burnable poison design most suitable for longer cycle lengths, such as first cycles or 24-month reload cycles. C-E has used the $B_4C-Al_2O_3$ design in all first cycle designs, and in reload cores transitioning to longer cycles and low-leakage fuel managements. To date, C-E has successfully irradiated more than 20,000 burnable poison rods of this design.

The second option is a gadolinium burnable poison design in the form of Gd_2O_3 admixed homogenously with natural UO_2 (0.71 wt%).[10] The $Gd_2O_3-UO_2$ poison rods replace normal fuel rods in the lattice. The very high neutron absorption cross section of gadolinia gives this lumped poison design a relatively "black" initial absorption characteristic relative to the $B_4C-Al_2O_3$ design. Therefore, the initial reactivity control using $Gd_2O_3-UO_2$ is basically determined by the number of poison rods, while the duration of control with burnup is determined by the concentration of Gd_2O_3 in the pellets.[11] The ability of gadolinia to provide strong reactivity control with relatively low loadings of burnable poison in the core and to deplete to a low residual reactivity worth after only several months irradiation makes this design best suited for shorter cycle lengths and for MTC control near beginning of cycle.[12] For longer cycle lengths, the higher core loadings of gadolinia result in increased residual reactivity worth (as shown on Figure 2) making it somewhat less desirable for such application.

Detailed design analyses confirm that one or both of C-E's burnable poison designs meet shim requirements of all anticipated, advanced fuel management schemes;

- Both designs provide adequate core reactivity and power distribution control for 12-, 18-, and 24-month low leakage cycles (see Figure 3).

- Both maintain a negative MTC at full power.

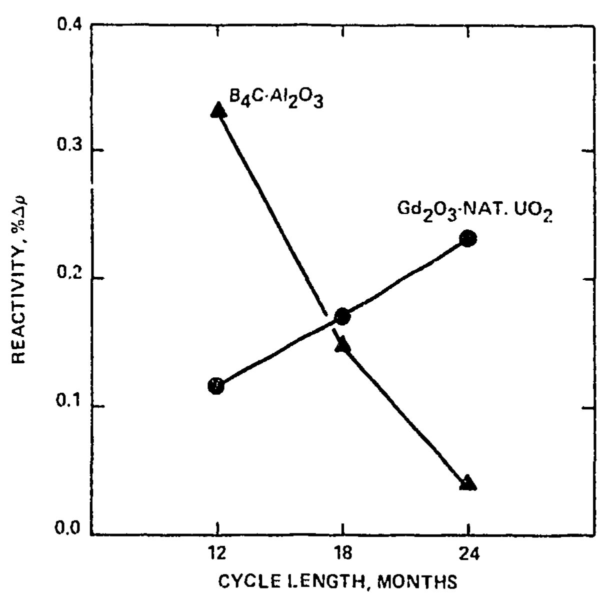


Fig. 2 Residual Core Reactivity Worth of Burnable Poisons in Equilibrium Fuel Cycles

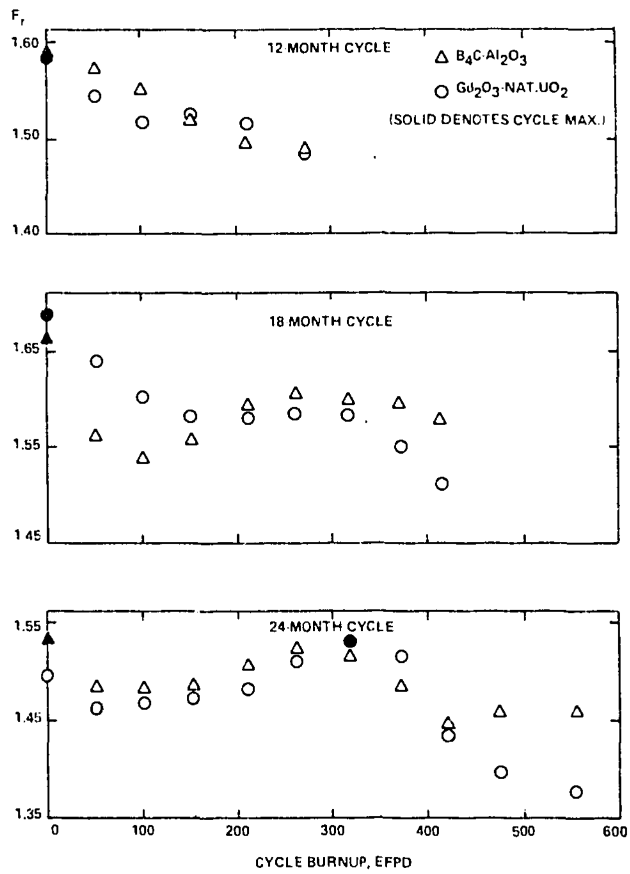


Fig. 3 Core Radial Peaking Factor (F_r) vs Cycle Burnup

- While the gadolinia design has lower uranium resource requirements (ore and SWU cost) for 12-month cycles, the $B_4C-Al_2O_3$ design has lower uranium resource requirements for 24-month cycle. The resource requirements are essentially the same for 18-month cycles. (Figure 4)

Both poison designs occupy fuel lattice positions, rather than water holes, so that fresh fuel assemblies can be placed directly under control rods. This provides design flexibility to minimize core power peaking and enhance net control rod worth.

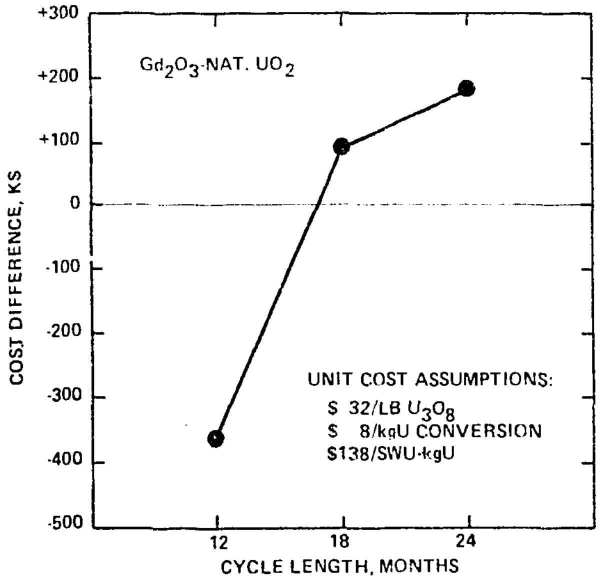


Fig. 4 Difference in Total Uranium Resource Costs (Ore, Conversion, Enrichment) Per Equilibrium Fuel Batch Relative to Reference Fuel Management Using $B_4C-Al_2O_3$

OTHER FUEL MANAGEMENT FEATURES

A number of other fuel cycle economy features have been routinely implemented with C-E supplied fuel including low-leakage fuel loading patterns, reinsertion of previously discharged fuel, end-of-cycle stretchout by means of planned power coastdown, and the use of natural UO_2 axial blankets.[10,13] These options have been used individually and in combination to provide fuel cost savings and to help achieve other operational objectives (e.g., timing of refueling outages, reduced spent fuel storage requirements, etc.). C-E has also supported specialized core design analyses for the purpose of reducing neutron irradiation to PWR reactor vessels.[14]

C-E has investigated various fuel rod mechanical design modifications for their effect on both economics and fuel performance. Specific concepts include annular fuel pellets and reduced rod diameter. Annular fuel provides the capability to lower fuel temperatures and to enable higher fuel burnup before internal rod pressure limits are reached. Although not required at present to support extended fuel cycle capabilities, this concept is under demonstration by C-E to support its development as a potential, future offering.[15] Investigation of reduced rod diameter designs have not shown significant economic benefit to offset the adverse thermal margin effects caused by higher heat flux.[16]

MARGIN IMPROVEMENTS

In general, most of the fuel cycle economy improvements discussed above adversely impact thermal margins and consequently transient performance.[7] The degree to which this proves a constraint depends on plant design and the inherent margins available for compensation. When a problem arises, C-E can often obtain additional margin, through improved analysis techniques such as statistical treatment of uncertainties, three dimensional modeling, and space-time calculations.[9] Also hardware solutions such as C-E's improved power distribution monitoring systems based upon fixed in-core detectors have been employed.[17, 18, 19, 20] Such margin improvements are generally preferred to placing margin related constraints on the plant operation. Margin improvements may also be used to minimize the cycle-by-cycle reload design costs.

C-E has developed considerable experience in the improvement of all forms of thermal margin. Some programs yield gains in all areas, while others are more specific. Improved analytical techniques which are useable on all PWRs, include:

- o Statistical combination of uncertainties[9]
- o Three dimensional modeling[9]
- o Space-Time Analyses[9]
- o Revised LOCA Modeling

Advanced core monitoring systems which require the presence of a fixed-incore detector system include:

- o BASSS
- o Mini-CECOR
- o COLSS[9]

Typical margin improvements in C-E plants using one or more of these techniques have ranged from 5% to 25%. Such margin improvements are also available on non-CE PWR designs.

MIXING GRIDS

Fuel rod thermal margin and DNB performance can also be improved by modifications to the fuel assembly including the addition of mixing vanes to spacer grids. Even though C-E's standard fuel design does not require the use of spacer grid mixing vanes to achieve adequate fuel rod thermal performance, C-E has been evaluating the performance of spacer grid mixing features since the mid-1970's especially in conjunction with its program to develop fuel for non-CE PWR's.

The effectiveness of preliminary designs on thermal hydraulic behavior was first determined using various testing methods including flow visualization, pressure drop experiments, and laser doppler anemometry to evaluate changes in fluid velocity and direction as a function of vane design. The most promising designs were then subjected to DNB tests to measure critical heat flux under DNB conditions. The most promising, innovative concepts are being further developed for use on spacer grids fabricated from either wavy or straight Zircaloy-4 grid strips.

As a result of this program, C-E has the design, manufacturing, and analytical expertise to offer spacer grid designs with integral mixing features if needed to satisfy specific customer thermal margin requirements. This mixing vane technology has also been incorporated into C-E reload fuel designs that are available for non-CE cores where the co-resident fuel already uses mixing vanes.

IMPROVED FAILURE RESISTANCE

Another aspect of C-E's advanced fuel program supports U.S. utilities' objective of reducing the primary coolant activity through the design and manufacture of nuclear fuel with improved resistance to potential fuel rod failure mechanisms commonly experienced in LWRs.

Also to this point, C-E continues to upgrade the fuel manufacturing process. Recent improvements were made to the UO_2 pellet processing and fuel rod fabrication operations to preclude the introduction of harmful impurities, such as moisture, into the fuel rod. Since the completion of these process modifications, fuel has been operated with no significant activity releases to the coolant indicating the elimination of primary hydriding as a cause of fuel failure.

CORROSION RESISTANCE

Oxide film thickness measurements performed on discharged fuel from C-E's older PWRs show excellent performance to high burnup. For example, a maximum circumferential averaged oxide thickness of 75 µm was measured at a local burnup of 55 GWD/MTU without adverse effect on fuel performance. However, the lifetime of fuel in newer PWRs that operate at higher coolant temperature and/or higher heat flux may be limited by the waterside corrosion behavior of the Zr-4 cladding.

Accordingly, C-E has been investigating a number of different Zr-4 cladding types which provide more corrosion resistance margin. Several promising types representing different thermal-mechanical processing during tubing manufacture and variations in chemical composition within the Zr-4 specification limits have been identified. These are included in a power reactor irradiation program to demonstrate the improved corrosion resistance relative to standard cladding. C-E is also considering more advanced zirconium alloys (outside the allowable Zr-4 compositional ranges) to improve corrosion resistance.

DEBRIS RESISTANCE

One of the possible plant-related causes of fuel failure is debris in the primary system which can become lodged in the fuel assembly spacer grids. In most cases, debris is captured by the lower spacer grid of the fuel assembly, and vibration of this debris resulting from coolant flow through the fuel assembly can produce wear against the cladding resulting in fuel failure. A number of possible assembly design modifications can render the assembly more resistant to such debris-induced failures. The C-E design provides a strainer grid attached to the flow plate of the lower end fitting. The strainer grid is in close proximity to the fuel rod lower end caps and screens out debris in that region. Wear due to captured debris then occurs in the solid, end-cap region of the fuel rod and cannot produce fuel failure.

The advantage of this design is that, except for the strainer grid itself, C-E's proven fuel assembly design features are unchanged. The lower end fitting is not modified, fuel rod end caps are the same and standard spacer grids are used. While the strainer grid increases pressure drop slightly, the increase is not significant compared to the overall pressure drop through the fuel assembly. Fuel rod reconstitution features are not affected since the strainer grid does not actually contact the fuel rod end caps and the rods are guided by the spacer grid just above the strainer grid during rod insertion or removal.

C-E offers the design to utilities who are interested in improving resistance to debris induced failures.

DIMENSIONAL STABILITY

As the duty and the lifetime of fuel is extended, potential fuel failure mechanisms relating to the dimensional stability of fuel rods must be reconsidered. These include: (1) fuel rod bow to contact adjacent fuel rods, (2) fretting of fuel rods in the spacer grids, and (3) fuel rod axial growth leading to interference with the upper end fitting. These potential problems have been avoided in the standard C-E all-Zircaloy assembly design because of the inclusion of design margins utilizing empirical growth correlations for fuel rods and guide tubes based on extensive data covering rod average burnups as high as 56 GWD/MTU. Sufficient margin is provided in the design to allow flexibility in fuel management by the reactor operators.

RESISTANCE TO PRIMARY HYDRIDING

In addition to the aforementioned manufacturing process improvements made to eliminate sources of hydrogen in the fuel rod, there are further design precautions available to increase resistance to primary hydriding. If one desires additional assurance against this failure mechanism, C-E can supply hydrogen getters installed in the plenum region of the fuel rod. Tests have indicated that the getter materials are effective in removing hydrogen and moisture from the UO_2 pellets and the fill gas. While getters provide more margin against primary hydriding failure, they do not appear to be needed with improved manufacturing process controls and procedures discussed above.

HIGH STRENGTH ZIRCALOY GRIDS

A final feature of C-E's advanced fuel assembly is the flexibility to meet a wide variety of seismic conditions with proven All-Zircaloy grids. During the development of the fuel assembly design for San Onofre Units 2 and 3, C-E addressed a wide range of seismic conditions and special site characteristics. The San Onofre design basis included a 0.67g ground motion, with site and building amplification in the low frequency range coincident with the fuel assembly natural frequency. To meet these severe requirements, several high strength Zircaloy spacer grid designs were developed and tested. As a result, C-E can offer a choice of All-Zircaloy configurations (not only using a single grid design, but also with axial distributions using more than one design) in which standard "off the shelf" components are arranged in a custom fashion depending on the particular site characteristics.

SUMMARY

By virtue of its decision to incorporate many advanced features in its earlier designs, C-E fuel development programs can concentrate on providing the fuel technology for the 1990's and beyond. Advanced fuel management, margin improvement and reduced fuel failures are the features of C-E's advanced fuel supply. All of these can be achieved without significant departure from the designs used to establish C-E's broad base of research, manufacturing and excellent operating experience.

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