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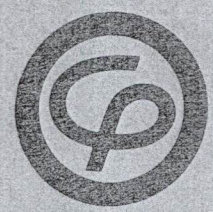
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Fuel Performance Improvement Program



Assessment
of Fuel Concepts



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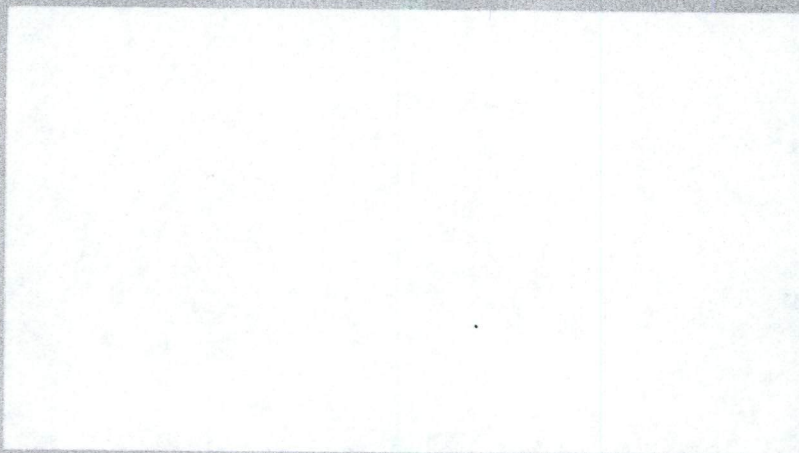
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FUEL PERFORMANCE IMPROVEMENT PROGRAM

**Assessment
of Fuel Concepts**

**W. J. Bailey
J. O. Barner**

January 1978

This report was prepared for the
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CONTENTS

1.0	SUMMARY	1
2.0	INTRODUCTION	3
3.0	CONCLUSIONS AND RECOMMENDATIONS	5
4.0	CRITERIA FOR EVALUATING CANDIDATE FUEL CONCEPTS	9
4.1	Criteria Addressing the Fuel-Cladding-Interaction (FCI) Mechanism	10
4.2	Criteria Addressing Development and Licensability	13
5.0	SELECTION OF IMPROVED FUEL CONCEPTS	15
5.1	Annular Pellet Fuel	15
5.1.1	Comparison of Annular Pellet Fuel with the Criteria Addressing the FCI Mechanism	16
5.1.2	Comparison of Annular Pellet Fuel with the Criteria Addressing Development and Licensability	18
5.1.3	Experience Summary for Annular Fuel	20
5.2	Graphite-Coated Cladding	22
5.2.1	Comparison of Graphite-Coated Cladding with Criteria Addressing the FCI Mechanism	23
5.2.2	Comparison of Graphite-Coated Cladding with Criteria Addressing, Development and Licensability	24
5.2.3	Experience Summary for Graphite-Coated Cladding	27
5.3	Packed-Particle Fuel	30
5.3.1	Comparison of Packed-Particle Fuel with Criteria Addressing the FCI Mechanism	30
5.3.2	Comparison of Packed-Particle Fuel with Criteria Addressing Development and Licensability	32
5.3.3	Experience Summary for Packed-Particle Fuel	34
5.4	Consideration of Other Possible Improved Concepts	41
5.4.1	Other Fuel-Related Concepts	42
5.4.2	Other Cladding-Related Concepts	50
5.4.3	Other Fuel Rod Concepts	55
5.4.4	Summary Discussion of Other Possible Improved Concepts	61
6.0	REFERENCES	65

CONVERSION TABLE FOR SI UNITS^(a)

	To convert from	to	Use equation or multiply by
Temperature	degree Fahrenheit (°F)	degree Celsius (°C)	$^{\circ}\text{C} = (^{\circ}\text{F} - 32)/1.8$
	degree Fahrenheit (°F)	kelvin (K)	$\text{K} = (^{\circ}\text{F} + 459.67)/1.8$
	degree Celsius (°C)	kelvin (K)	$\text{K} = ^{\circ}\text{C} + 273.15$
Time	hour (hr)	second (s)	3.600×10^3
	day (d or day)	second (s)	8.640×10^4
Length	inch (in.)	metre (m)	2.540×10^{-2}
Area	inch ² (in. ²)	metre ² (m ²)	6.452×10^{-4}
Volume	inch ³ (in. ³)	metre ³ (m ³)	1.639×10^{-5}
Pound-Mass	lbm	kilogram (kg)	4.536×10^{-1}
Pound-Force	lbf	newton (N)	4.448
Pressure or stress	psi (lbf/in. ²)	pascal (Pa)	6.895×10^3
Energy ^(b)	British thermal unit (Btu)	joule (J)	1.055×10^3
	calorie (cal)	joule (J)	4.187
	watt-second (W-s)	joule (J)	1.000
Linear Heat Rating	kilowatts/ft (kW/ft)	kilowatts/metre (kW/m)	3.281
Burnup	megawatt-day/metric ton of heavy metal ^(c) (Mwd/MTM)	gigajoule/kg of heavy metal ^(c) (GJ/kgM)	8.640×10^{-2}

(a) Conversions are based on ASTM Metric Practice Guide E380-74. Four of the prefixes (*) are to be avoided where possible.

Prefix	SI Symbol	Multiplication Factors
tera	T	1 000 000 000 000 = 10^{12}
giga	G	1 000 000 000 = 10^9
mega	M	1 000 000 = 10^6
kilo	k	1 000 = 10^3
hecto*	h	100 = 10^2
deka*	da	10 = 10^1
deci*	d	0.1 = 10^{-1}
centi*	c	0.01 = 10^{-2}
milli	m	0.001 = 10^{-3}
micro	μ	0.000 001 = 10^{-6}
nano	n	0.000 000 001 = 10^{-9}
pico	p	0.000 000 000 001 = 10^{-12}
femto	f	0.000 000 000 000 001 = 10^{-15}
atto	a	0.000 000 000 000 000 001 = 10^{-18}

(b) 10^6 Btu = 1.055 GJ = 0.17 barrels of oil = 100 kW-hr, assuming one barrel of oil = 42 gallons and the conversion efficiency from heat to electricity is 0.33.

(c) M is normally the SI symbol for mega; an exception in this report is the additional use of M in burnup units to denote heavy metal.

LIST OF PREVIOUSLY PUBLISHED REPORTS

- C00-4066-1 Quarterly Progress Report, April-June 1977, July 1977.
- C00-4066-2/PNL-2488 State-of-the-Technology Review of Fuel-Cladding Interaction, December 1977.
- C00-4066-4 Quarterly/Annual Progress Report, April-September 1977, November 1977.

1.0 SUMMARY

The Fuel Performance Improvement Program was initiated by the Energy Research and Development Administration, and subsequently sponsored by the Department of Energy, to address remedies to the constraints imposed on commercial power reactors caused by the restricted power maneuvering capabilities of current light water reactor (LWR) fuel rod designs. The purpose of the program is to establish the technical bases for design of improved fuel concepts which can be operated consistent with the maneuvering capability of nuclear steam supply systems. Consumers Power Company, Exxon Nuclear Company, and Battelle, Pacific Northwest Laboratories are the three participants in the program.

Task 1, "Assess Fuel-Cladding Interaction State-of-the-Technology and Potential Improved Concepts," of the program addressed the qualitative assessment of the relative merits of candidate fuel concepts with the potential for improved power ramp behavior and selected several concepts for further evaluation. It was deemed important that the main concepts selected be low-risk types, be representative of the current state of the technology, and have a substantial experience base. Of those concepts considered presently to have an adequately developed data base, annular pellets, graphite coatings on the inside cladding surface, and packed-particle fuel^(a) were selected for evaluation. Actually, graphite-coated cladding is being evaluated in combination with annular pellet fuel in order to combine the potential improvements associated with each design change (graphite-coated cladding is also being used in combination with some of the "reference" solid pellet fuel to evaluate separate effects). Prepressurization, in combination with these improved fuel designs, is being considered for evaluation as a fuel-cladding-interaction remedy.

(a) Two types of packed-particle fuel are being considered in this program: vipac fuel (vibrationally compacted angular fuel particles) and sphere-pac fuel (vibrationally compacted fuel microspheres).

A number of other fuel concepts were identified and appeared worthy of further development as part of this program. Several of those concepts are being investigated by other laboratories. Results from these other programs will be monitored for possible incorporation of those concepts into this program.

2.0 INTRODUCTION

Experience has shown that fuel rod performance, specifically the integrity of the cladding, in light water reactors may be adversely affected by power increases and the rate at which the linear heat rating is increased. In order to compensate for these limitations associated with current fuel rod designs, fuel-related constraints have been imposed upon the magnitude of power increases and the rates at which these increases may be made. While restrictions on power maneuvering may improve fuel rod reliability, they are costly from the standpoint of decreased power production. As a result, the remedy-oriented Fuel Performance Improvement Program was initiated to develop and demonstrate selected fuel concepts that have potential for improved power-ramping capability.

The three principal participants in the Fuel Performance Improvement Program are Consumers Power Company (CPC), Exxon Nuclear Company (ENC), and Battelle Pacific Northwest Laboratories (PNL). This program is directed by Consumers Power Company under prime contract to the Department of Energy. The program is managed by ENC under subcontract from CPC and involves task assignments at PNL and ENC.

Portions of the program involve out-of-reactor studies, in-reactor experiments, and in-reactor demonstrations of the selected fuel concepts. An activity was performed to provide the basis for the selection of the candidate fuel concepts with potential for improved power-ramping capability to be evaluated. One part of this activity involved the evaluation of postulated fuel-cladding-interaction mechanisms and the associated supportive data and the results of that part were described in a separate report.^(a) The second part of the activity addresses the qualitative assessment of the relative merits of those fuel concepts with the potential for improved power-ramping capability to be evaluated

(a) W. J. Bailey, C. L. Wilson, L. J. MacGowan, and P. J. Pankaskie, State-of-the-Technology Review of Fuel-Cladding Interaction. COO-4066-2/PNL-2488, 1977.

as part of this program, and the rationale is presented in this report. Several fuel concepts appear to exhibit potential for improved power-ramping capability; however, from a practical point of view, only selected fuel concepts can be evaluated or developed within the scope of this program. The following discussion includes: the criteria used to evaluate the candidate fuel concepts; a comparison of the concepts selected for irradiation with the criteria, including a general description of their experience bases; and a general discussion of other candidate concepts, including identifying those which may be considered for out-of-reactor evaluation as part of this program, those for which the results of other programs will be monitored, and those which have been deleted from further consideration at this time.

3.0 CONCLUSIONS AND RECOMMENDATIONS

The relative merits of various LWR UO_2 fuel concepts with the potential for improved power-ramping capability were qualitatively assessed. In the evaluation, it was determined that of the various concepts being considered, those that presently possess an adequately developed experience base include annular pellets, cladding coated with graphite on the inner surface, and packed-particle fuel. Therefore, these were selected for initial evaluation as part of the Fuel Performance Improvement Program. For this program, graphite-coated cladding is being used in conjunction with annular pellet fuel as one of the concepts with the anticipation of gaining the advantage of the combined improvements.

Annular pellet fuel was selected because, under comparable heat ratings, it will operate at lower fuel temperatures than solid pellet fuel. Hence, the driving force (fuel temperature) for thermal-mechanical interaction and chemical reaction in annular pellet fuel is expected to be lower than for solid pellet fuel because annular pellet fuel is expected to produce lower general cladding stresses; lower localized stresses at pellet-pellet interfaces; lower releases of fission products, hence a decrease in the likelihood of stress-corrosion cracking; and improved safety margins in comparison to solid pellet fuel. The existing experience base indicates that annular pellet fuel has performed entirely satisfactorily. Efforts to develop, fabricate, and license annular pellet fuel should be minimal because of the extent to which this has already been done.

Coated cladding was selected because of the favorable experience with fuel rods that had a graphite coating on the inside surface of the cladding. In power-ramping tests in support of the Canada Deuterium Uranium (CANDU) reactor system, such fuel rods exhibited improved behavior in comparison to fuel rods with uncoated cladding. Though the mechanisms for behavioral improvement are not fully understood, it is suspected that the graphite acts either as a lubricant, an adsorber or absorber of

active fission products, or a barrier to certain fission products or, most likely, a combination of these effects. Commercial fuel rod designs with graphite-coated cladding are currently in use in Canadian power reactors (e.g., Bruce and Pickering). Graphite-coated cladding should represent a minor deviation from current practice; however, application, outgassing, and handling technology will need to be developed. Licensing efforts should be minimal. The effect of high burnup on fuel rods with coated cladding in BWR and PWR environments needs to be studied.

Packed-particle fuel was selected because localized cladding deformation is virtually absent for this fuel type. The performance of a significant amount of packed-particle fuel has generally been demonstrated to be satisfactory. No inherent performance limitations are evident. Packed-particle fuel has been shown to perform equally well as or, in some cases, superior to pellet fuel. Most behavioral problems that have occurred with Zircaloy-clad, packed-particle fuel can be attributed to the entrapment of excessive quantities of hydrogenous impurities (e.g., moisture) within the fuel rods. However, this fabrication-technology-related problem is not unique to this fuel type. By implementing sound fuel fabrication methods and procedures, it has been demonstrated in the past that the problem can be alleviated. It will be important to convincingly demonstrate that contaminants in the packed-particle fuel can indeed be kept at an acceptably low level under manufacturing conditions. The development of commercial fabrication capabilities for vipac and sphere-pac fuel may be expected to be significant. The effort to license vipac and sphere-pac fuel may be expected to be significant; however, packed-particle fuel has been licensed previously for use in two United States commercial BWRs (Big Rock Point and Dresden-1). Safety-related considerations [e.g., loss of cooling accident (LOCA)] associated with packed-particle fuel are to be evaluated in this program.

Prepressurization with helium has been reported to have a beneficial effect by reducing fuel-cladding interaction in both BWR and PWR fuel designs. Because it is not considered to be a major departure from

current technology, prepressurization in combination with the annular, coated-cladding, and packed-particle fuel designs is being considered for evaluation in this program as a fuel-cladding-interaction remedy.

Several other fuel concepts had attributes which were considered to have significant potential for improving the power-ramping behavior. However, it was judged that those concepts require further analytical evaluation of their effect on power-ramp behavior or further out-of-reactor testing before performing in-reactor evaluations as part of this program. Selected concepts are being considered for further evaluation as part of this program. Other concepts with potential for improving fuel-cladding-interaction behavior are being evaluated in other programs. Among those concepts are: chamfered pellets, variable (radially) enrichment fuel, barriers, cladding with a noncylindrical inside surface, pellet spacers, getters and other means for control of fission products, and several concepts involving fuel and cladding property variations. Results from these other programs will be monitored. Some of those concepts may be included in this program for evaluation at a later date. Several possible concepts were deleted from further consideration because they had a low probability of being developed, and/or they represented a major deviation from current technology, and/or the degree of anticipated behavioral improvement was minor.

4.0 CRITERIA FOR EVALUATING CANDIDATE FUEL CONCEPTS

The presumed cause of the fuel rod failures in commercial LWRs by a pellet-cladding-interaction (PCI) mechanism^(a) is localized cladding strain coupled with fission product chemical attack. The cladding strain is the result of differential expansion between the fuel pellets and the cladding and thermal distortion of the pellets. Stress-corrosion cracking (SCC) is the commonly accepted mechanism for the cladding failure mode. The failure usually occurs during a general or localized power increase in fuel rods that are operating at high linear powers. Power maneuvering schemes intended to prevent PCI failures have been imposed upon current reactor operations as an expedient. These restrictions have been fairly successful in minimizing fuel rod failures. However, the result has been costly from the standpoint of decreased power production.

There are three general power-ramping conditions to be considered in contemporary light water reactors: 1) fuel-imposed ramp rate guidelines, 2) ramp rates imposed by the nuclear steam supply system technical specification limits, and 3) local ramp rates due to control rod movements (primarily in BWR). The criteria described below provide the basis for selection of improved concepts that have the potential for eliminating the first constraint, i.e., the fuel-imposed ramp rates, within the limits of the second constraint, i.e., the technical specifications. The third constraint, i.e., the control-rod-initiated rates, will not be directly addressed as part of this program. However, positive results from in-reactor testing would be expected to at least partially ameliorate this problem.

The preferred long-term approach to minimizing PCI fuel failures is to develop a fuel design that is less susceptible to the mechanical and/or

(a) The term PCI (pellet-cladding interaction) is used in some parts of this report. The more general term, FCI (fuel-cladding interaction) is used in most of the report because some candidate fuel concepts (e.g., packed-particle fuel) do not employ pellets.

chemical aspects of PCI/SCC. Such a remedial fuel rod design could allow a return to unrestricted power maneuvering and a higher reactor duty factor.

The criteria used for evaluating and selecting candidate improved fuel rod designs are listed in Table 1. The criteria are separated into two general groupings: 1) technical aspects which address the failure mechanism, and 2) technical aspects which are associated with development and licensability and nontechnical items relating to the degree of acceptability of concepts which deviate from current practice. These general criteria are expanded and discussed in the following sections.

4.1 Criteria Addressing the Fuel-Cladding-Interaction (FCI) Mechanism

The first criteria for selection of improved fuel concepts should address the anticipated degree of improvement in the behavior of the concept with respect to the PCI failure mechanism. Both the mechanical and chemical aspects of the fuel-cladding-interaction phenomenon are important.

PCI cladding failures have manifested themselves as cracks initiating from the inside surface of the fuel rod. From the mechanical standpoint, those mechanisms which result in tensile stresses, and resultant inelastic strains, on the inside cladding surface are the most important.

The majority of these stresses in pelletized fuel rods of current design are the direct result of "hard" contact between the cladding and the fuel pellets. The "hard" contact is a result of the outward movement of fuel fragments caused by differential thermal expansion between the fuel and cladding, fuel fragment relocation, and/or fuel swelling. Specific tensile cladding stresses of most importance that are caused by "hard" contact are:

TABLE 1. Criteria for Evaluating and Selecting Candidate Fuel Systems

CRITERIA ADDRESSING THE FUEL-CLADDING-INTERACTION (FCI) MECHANISMS:

•GENERAL:

- REDUCE TENSILE STRAINS AT THE INSIDE SURFACE OF THE CLADDING AND/OR REDUCE PROPENSITY FOR STRESS-CORROSION CRACKING (SCC) AND/OR FISSION-PRODUCT EMBRITTLEMENT (FPE)

•SPECIFIC:

- REDUCE GENERAL AXIAL AND CIRCUMFERENTIAL STRAINS
- REDUCE LOCALIZED AXIAL AND CIRCUMFERENTIAL STRAIN CONCENTRATIONS
- REDUCE SUSCEPTIBILITY TO SCC AND FPE

CRITERIA ADDRESSING DEVELOPMENT AND LICENSABILITY

•DEVELOPMENT AND LICENSABILITY

- DEVELOPMENT EFFORT
- FABRICATION EFFORT
- EFFORT TO LICENSE
- LICENSE MARGIN

•COMMERCIAL ACCEPTABILITY (AND PROBABILITY OF DEVELOPMENT)

- DEVIATION FROM CURRENT FABRICATION PRACTICE
- DEVIATION FROM EXISTING DESIGN BASES AND CRITERIA

- 1) the general axial and circumferential stresses caused by a) fuel swelling, which occurs during steady-state and transient operation, and b) differential thermal expansion during a power increase.
- 2) the localized axial and circumferential stress concentrations at pellet-pellet interfaces caused by pellet shape distortion (hourglassing), and
- 3) the localized circumferential stress concentrations associated with axially oriented radial fuel cracks.

The magnitude of the above stresses can be affected by the degree of fuel-cladding bonding or the effective friction between the fuel and cladding. Also of importance to the overall behavior of a given fuel rod is the operating period required to obtain "hard" contact. This period is related to cladding creepdown under the influence of the coolant pressure and to the initial fuel-cladding gap. A contributing factor to the inside surface tensile stress condition prior to a power increase is the degree of cladding ovality, and the resultant bending stress, under the influence of the external pressure of "soft" contact between misaligned fuel fragments and the cladding.

From the chemical standpoint, those mechanisms which promote corrosion and/or embrittlement of the cladding are of concern. Chemical-related considerations of importance are:

- 1) the species of the fission products released from fuel,
- 2) the amount of the fission products released from the fuel,
and
- 3) the mechanisms which concentrate harmful species at undesirable locations on or near the cladding.

For purposes of discussion, the mechanical and chemical aspects of PCI have been presented individually. However, in practice, the mechanical and chemical aspects are interrelated and the degree

to which both exist in a fuel rod will determine the propensity of that rod for failure, i.e., the actual stress and strain levels in the cladding during and after a given power increase, combined with the availability of reactive fission products at a crack in the zirconium oxide layer on the inside cladding surface, will determine the likelihood of failure. Stress and strain levels prior to a power increase, as well as previous power ramps, can also be expected to influence fuel rod behavior.

In summary, the criteria addressing the defect mechanisms are concerned with reducing the stress and strain condition in the fuel rod cladding and reducing the propensity for stress-corrosion and/or embrittlement, particularly during a power increase.

4.2 Criteria Addressing Development and Licensability

The fuel rod designs with potential for improved power-ramping capability can be expected to have advantages and disadvantages with respect to a) the degree of effort required for development, fabrication, and licensing, and b) the current licensing (safety) margins.

Any improved fuel rod concept which deviates from current practice can be expected to require various degrees of effort to develop the design and fabrication processes and to assure adequate safety margins. After the initial development efforts, production of a new concept may require more or less effort than current practice. Lacking full-scale economic and engineering studies for each concept, these technical criteria can be evaluated only relatively and must be considered subjective.

The operating characteristics (e.g., component temperatures, pressures, stored energy, and heat transfer) of the improved fuel concepts during normal and accident (e.g., LOCA) conditions are of concern.

No matter how great the technical potential for an improved fuel concept, there exists the practical consideration of commercial acceptability. Attention to the associated risks that might ensue if new concepts prove to be more, rather than less, prone to failure, must be considered. Hence, it was deemed important that the primary concepts to be selected should be low-risk types and be representative of the current state of the technology. In addition, it was considered essential that a substantial technical data base demonstrating the new concept to be commercially viable must exist prior to demonstration in commercial reactors.

5.0 SELECTION OF IMPROVED FUEL CONCEPTS

Three fuel concepts with potential for improved power-ramping capability were selected for evaluation as part of this program. These concepts are: 1) annular pellet fuel, 2) graphite-coated cladding with annular pellet fuel (also with some "reference" solid pellet fuel), and 3) packed-particle fuel. Annular pellet fuel and graphite-coated cladding have been combined to take advantage of the potential improvements of each design change. The rationale with respect to the evaluation criteria and the experience base for each selected concept are presented in Sections 5.1 through 5.3. Fuel concepts which are included in other development programs, the results of which will be monitored for relevance to this program, and those concepts which were deleted from further consideration are discussed in Section 5.4.

Comparisons of the behavior of the improved concepts to a "reference" fuel rod design will be made. The reference fuel characteristics include:

- a) dished (1% each end), nonchamfered, 93-94% TD^(a) UO₂ pellets with a length-to-diameter ratio of approximately 0.8,
- b) cold-worked and stress-relieved Zircaloy-2 cladding with an etched inside surface,
- c) helium fill gas at one atmosphere (at room temperature), and
- d) a fuel-cladding diametral gap of 0.25 mm (0.010 in.).

5.1 Annular Pellet Fuel

Annular pellet fuel, i.e., pellets with a central hole, was selected as one of the fuel concepts for evaluation because, for a given fuel rod design, linear power rating, and increase in power, annular pellets will operate at lower fuel temperatures than solid pellets. Mechanical and chemical interactions could, therefore, be expected to be lower for annular fuel, as indicated in Section 5.1.1.

(a) TD = theoretical density; for UO₂, TD = 10.96 g/cm³.

5.1.1 Comparison of Annular Pellet Fuel with the Criteria Addressing the FCI Mechanism

During most of the lifetime of a fuel rod, an NEDC report⁽¹⁾ and paper by Freshley⁽²⁾ indicate that annular fuel will operate at lower fuel temperatures with lower radial temperature gradients than standard solid pellet fuel. This general condition will also occur during power ramping. Lower fuel temperatures and radial temperature gradients in annular pellet fuel are primarily the result of shorter radial heat transfer distances, more power generation near the periphery of the fuel pellet, and, because of lower fission gas release, a reduced effect on the conductance of the gas in the fuel-cladding gap.

The lower fuel temperatures and lower radial temperature gradients would be expected to result in lower fuel swelling, particularly if the fuel was operating at powers and temperatures where fission-gas-induced grain boundary swelling did not occur. Studies by Calza-Bini et al.⁽³⁾ indicate that the lower swelling combined with lower fuel-cladding differential expansion would be expected to extend the time to significant fuel-cladding contact. General stress and, particularly, strain conditions in the cladding at any point in the irradiation would be expected to be lower for annular pellet fuel than for standard solid pellet fuel.

The general circumferential (hoop) stress levels in the cladding for the annular pellet design during a power ramp would be predicted to be lower than those in solid pellet fuel. The reduced hoop stresses would result from lower fuel-cladding, differential expansion. For an annular pellet with a core volume equivalent to 10% of the volume of a solid

pellet, general circumferential cladding stresses induced by differential fuel-cladding expansion during a power increase would be expected to be 20-30% lower than for solid pellet fuel, as indicated in a compilation by Crouthamel.⁽⁴⁾ Due to lower fuel temperatures (thus lower creep rates in the fuel) in annular pellet fuel, the stress levels that are induced in the cladding may be expected to decay at a reduced rate. Even though the gas volume in the above illustrated annular rod would be about twice that of a standard rod, cladding hoop stresses induced by internal gas pressure would be approximately equivalent for both the annular and standard designs. This would result from the higher anticipated average gas temperatures in the annular design.

The general axial stress levels in the cladding of an annular pellet design during a power ramp would depend upon whether the annular pellet ends were dished or flat. Dished annular pellets would produce axial stresses similar to dished solid pellets, while flat-ended annular pellets would produce somewhat higher axial cladding stresses.

A report by Gittus⁽⁵⁾ indicates that the reduced radial fuel temperature gradients in annular pellet fuel would be expected to produce less fuel pellet hourglassing. Therefore, localized cladding stresses, and resultant ridging, at pellet-pellet interfaces would be expected to be lower for annular pellet fuel. After fuel-cladding gap closure, this condition would be expected to persist during both steady-state operation and a power ramp.

Because annular pellets have been observed by Bishop and Bailly⁽⁶⁾ to fragment in a manner similar to standard fuel, localized circumferential stress concentrations at axially-oriented radial fuel cracks would be expected to be similar in both fuel types. Perhaps some benefit for annular fuel could be envisioned for fuel

operating at high power because the core may provide for some accommodation of the fuel swelling. Under this condition, the lower fuel temperatures and resultant reduced fission-product release from annular pellet fuel could reduce fuel-cladding bonding and permit easier readjustment of fuel fragments to reduce localized cladding stresses.

The types of fission products that are released from annular and solid pellet fuel can be expected to be similar. In addition, the mechanisms that concentrate certain species at specific locations, e.g., vapor transport down pellet-pellet interfaces and axially oriented radial fuel cracks, with deposition on the inside cladding surface, would be similar for both types of fuel. However, because of the lower fuel temperatures, the annular pellet fuel would release less fission products than solid-pellet fuel. This would be expected particularly for rods operating at high power where diffusion-controlled, fission-product release would be more significant than recoil release. A report, NEDC-10586,⁽⁷⁾ indicates that annular pellet fuel has been observed to release approximately two-thirds the fission gas released by solid pellet fuel with undished ends. In this case, the fuels were mixed oxide with equivalent fuel density.

In summary, with respect to the failure mechanism criteria, annular pellet fuel can be expected to produce lower general cladding stresses, lower localized stresses at pellet-pellet interfaces, and lower fission-product release than solid pellet fuel.

5.1.2 Comparison of Annular Pellet Fuel with the Criteria Addressing Development and Licensability

The development, fabrication, and licensability of the annular pellet fuel design should be minimal because of the extent to which this has already been done. In general, the

annular pellet fuel should provide an improvement in safety margins when compared with solid pellet fuel.

Efforts required to develop annular fuel would focus upon production methods of fuel pellets with central holes and determination of uranium enrichment values that will yield acceptable power levels and core neutronic properties.

Annular pellet fuel will require a higher-enrichment feed material to compensate for the material removed to form the central hole. However, this should be partially offset by a decrease in the weight of fuel that would be required to be fabricated; i.e., fuel costs are typically based on the weight of manufactured fuel and there would be less weight fabricated.

Because of the generally lower operating fuel temperatures, stored energy in the fuel will be lower than in solid pellet fuel. Cladding temperatures during a LOCA will also be lower for an annular pellet design. The relocation of fuel particles within the central hole during normal operation has been shown by Bishop and Baily⁽⁶⁾ to be insignificant as a safety consideration. The effects of the central hole should be similar to those in high-powered, solid-pellet rods in which a central hole has formed. No new fuel properties would have to be determined, because the operating temperatures for the annular fuel would be included within the range certified for the solid pellet fuel.

The substitution of annular pellet fuel for solid pellet fuel should be only a minor deviation from current practice. No new materials would be included in the fuel rod design. Technology is in place to produce pelletized fuels. As summarized in Section 5.1.3, the existing technical data base indicates that annular pellet fuel has performed entirely satisfactorily.

5.1.3 Experience Summary for Annular Fuel

An Edison Electric Institute-General Electric sponsored program to study plutonium utilization in boiling water reactors included the development and irradiation of annular pellet fuel in commercial reactors.^(1,6-12) The program was later sponsored by Electric Power Research Institute and General Electric.⁽¹³⁻¹⁵⁾ The reason for investigating annular fuel was to increase the water-to-fuel ratio for mixed-oxide fuel in order to compensate for the greater neutron absorption in plutonium. Irradiations were divided into three groups:

- a) the 32-rod program, in which twelve rods utilizing annular pellets with a core (i.e., central hole) volume equivalent to 5% of a solid pellet, twelve rods with a core volume equivalent to 18% of a solid pellet, four rods with dished pellets, and four rods with undished solid pellets were irradiated in the Big Rock Point (BRP) Reactor.
- b) the 3-bundle program, in which 204 rods with annular pellets with a core volume equivalent to 10% of a solid pellet were irradiated in three bundles in BRP, and
- c) the Quad Cities program, in which 48 full-length rods with annular pellets with a core volume equivalent to 9.5% of a solid pellet were dispersed in five bundles with standard fuel and irradiated in the Quad Cities reactor.

The 32-rod tests were irradiated in BRP at peak linear powers in the range 23-40 kW/m to burnups up to 2600 GJ/kgM (30 MWd/kgM). During the irradiation, two overpower transients of from 30-50% higher than the preceding steady-state operating value occurred at a burnup of approximately 700 GJ/kgM (8 MWd/kgM). The rods were not subjected to the currently

recommended PCI-preventing operating restrictions. No rod failures were reported. The irradiation performance of the annular pellets was reported by Bishop and Bailly⁽⁶⁾ to be excellent and similar to standard UO₂ fuel.

One annular rod with the 5% core volume was ramp tested in the GETR.⁽¹¹⁾ The previous steady-state power was approximately 24 kW/m and the peak burnup was 1200 GJ/kgM (14 MWD/kgM). The rod was ramped twice to 56 kW/m at a ramp rate of 0.9 kW/m-min with no evidence of failure.

The 3 bundles containing 204 annular pellet rods were irradiated in BRP at peak powers as high as 43 kW/m to burnups up to 2800 GJ/kgM (33 MWD/kgM). The fuel bundles were shuffled during refueling operations to promote abnormal power cycling. Satisfactory performance with linear power increases of up to 30% was achieved. The rods were not subjected to the currently recommended PCI-preventing operating restrictions. It was informally reported in NUREG-0002⁽¹⁶⁾ that fission product leakage tests showed evidence of rod failure in two of the bundles. Two rods in the third bundle failed during a decrudding operation. BRP operated with high copper-nickel concentrations in the feedwater during this period, with resultant high crud rates. The failures were attributed to low cladding-coolant heat transfer and high cladding temperatures caused by the crud. The behavior of the annular mixed-oxide rods was concluded to be similar to that of standard UO₂-fueled rods and no significant differences were observed.

The Quad Cities program represented the first irradiation of full length (~3.7 m) annular pellet fuel rods in a modern BWR according to Roberts et al.⁽¹⁵⁾ The irradiation provides an excellent opportunity to compare the relative performance

of annular fuel with standard solid pellet UO_2 , because rods of both types are being irradiated side by side. Four of the assemblies are currently operating near the center of the core at peak linear powers of approximately 49 kW/m. The fifth assembly is operating at lower power, about 16 kW/m, in a peripheral core position. The first interim examination of the rods was completed in early 1976 after one cycle of operation. Sipping tests, ultrasonic tests, profilometry measurements, and visual inspections showed the rods to be in excellent condition.

Stacey et al.⁽¹⁷⁾ and Skinner et al.⁽¹⁸⁾ have reported on the dimensional changes resulting from mechanical interactions between annular pellet fuel and stainless steel cladding in Windscale Advanced Gas-Cooled Reactor (WAGR) fuel pins. In comparing theory with experiment, they find that the coefficient of friction between the pellet and cladding is a crucial parameter; however, no direct in-reactor measurements of this have been made. Evans et al.⁽¹⁸⁾ indicate that more than 4300 of these 1.06-m long fuel pins have been irradiated in the WAGR (apparently seven pins failed). The highest burnup achieved by one channel (i.e., 36 fuel pins) was 2246 GJ/kgM (26,000 MWd/MTM).

Short rods (about 400 mm) with annular pellet fuel were tested as part of an irradiation program conducted in EL3 and Siloë. The tests have been described by de Contenson et al.⁽¹⁹⁾ and are associated with a study of the behavior to high burnup of LWR fuel rods with the UO_2 in the molten regime.

5.2 Graphite-Coated Cladding

Investigation of the coated-cladding fuel concept was selected because the experience with graphite coatings on the inside cladding surface has resulted in improved ramping behavior in rods tested

in support of the CANDU reactor system. The mechanisms of improvement are not fully understood, but it is suspected that the graphite acts as a lubricant, a fission product adsorber or absorber, a fission product barrier, or, most likely, as a combination of the above. For this program, the coated-cladding fuel concept is combined with the annular pellet design to evaluate the additive or, possibly, synergistic effects of combining the two potential design improvements. The experience summary for the annular fuel portion of the concept is presented in Section 5.1.3.

5.2.1 Comparison of Graphite-Coated Cladding with Criteria Addressing the FCI Mechanism

Because annular pellet fuel is being combined with coated cladding, the comparisons of annular pellet fuel to the failure criteria, Section 5.1.1, are applicable to the fuel design employing annular pellet fuel and graphite-coated cladding. Only a slight increase in fuel operating temperature, $<25^{\circ}\text{C}$ at peak power, would be expected for graphite coatings with thicknesses in the range 5 to 10 μm .

Prior to and during a power increase, the graphite coating should reduce friction between the fuel fragments and the cladding. Minor adjustment or realignment of fuel fragments should be facilitated with coated cladding resulting in a reduction of stresses compared with noncoated cladding. Fragment realignment should also reduce localized stresses that occur at pellet-pellet interfaces and axially-oriented radial fuel cracks. Reduction of the general axial and circumferential stresses in the cladding would result only if significant axial movement of the fuel fragments occurred during steady-state or transient operation.

As pointed out by Hardy et al.⁽²⁰⁾ and Robertson,⁽²¹⁾ perhaps the most significant benefit of the graphite coating

is the apparent reduction or elimination of fission product reaction with the cladding. The small graphite particles which comprise the coating have a large surface area. Fission products can be expected to be tied up on that surface within the graphite layer. Thus, the fission products which accumulate in the fuel-cladding interface region are not as readily available to react with the cladding. Concentration of the released fission products in the coating might also promote recombination of reactive species that have been generated by radiolytic decomposition, e.g., recombination of cesium and iodine to form cesium iodide, thus preventing attack of the cladding by elemental iodine.

The role of the graphite coating in improving fuel rod ramping performance is not well understood and requires further study. In particular, high burnup effects on the graphite coating in BWR and PWR environments need to be evaluated.

5.2.2 Comparison of Graphite-Coated Cladding with Criteria Addressing Development and Licensability

Efforts to develop and fabricate coated cladding will emphasize methods of application and reduction of hydrogenous impurities to acceptable levels. Although specific information concerning development of these items is not available in the open literature, obviously they have been studied to the satisfaction of those who specify CANLUB fuel for the CANDU reactors.

The licensing advantages discussed for annular pellet fuel, Section 5.1.2, will apply for the design employing annular pellet fuel and graphite-coated cladding. The coated cladding design introduces a new material, carbon, into the fuel rod system. The possible loss of adhesion of the graphite

coating to the cladding with burnup needs to be considered. Chemical reactions between the carbon and the fuel rod components must be considered. During normal operation, reactions between the carbon coating and the surface of the fuel are expected to be insignificant because the temperatures are low.

If dislodged graphite were deposited near the centerline of the fuel, the graphite can be expected to react with high-temperature UO_2 to form CO and CO_2 . Campbell⁽²²⁾ indicates that increased internal pressure within the fuel rod could be expected early in the irradiation if a large portion of the graphite coating were optimally dispersed throughout the rod; however, this is considered to be highly unlikely. The Canadian experiments described by Campbell were conducted to assure that any chemical interaction between graphite and UO_2 would result in no detrimental effect on the performance of standard CANDU fuel that includes a graphite (CANLUB) layer. These experiments with graphite and hyperstoichiometric UO_2 showed that the reaction rate is strongly temperature dependent and that the reaction becomes significant only at temperatures above about 1700K. Fortunately, the high CO and CO_2 partial pressures that can exist at equilibrium as a result of the reaction will not occur in practice. In the case of CANLUB fuel rods, the pressure will be limited to rather low values because of the small quantity of graphite included in fuel rods and the fact that it must be relocated to the high-temperature fuel region. Depending on the fuel temperature and the quantity of graphite, Campbell estimated that in a typical CANDU fuel rod where graphite and UO_2 came in contact at temperatures over 1700K the result would be a fairly rapid increase in gas pressure up to something on the order of the coolant pressure. Analyses suggested and the

experiments confirmed that a mechanism exists which limits the rate and level of gas pressurization of a fuel rod to tolerable limits. Because of decomposition and the accompanying progressive separation of reactants, the internal pressure would decrease slowly with time as carbon is transported to and deposited in the cooler regions of the fuel rod and oxygen from the fuel surface is transported to the fuel interior.

The presence of CO and CO₂ in the fuel rod would degrade fuel-cladding gap conductivity and increase the fuel temperature. The changes in fuel temperature, as well as internal pressure, in LWR fuel rods as a result of the possible reaction between graphite and high-temperature UO₂ will require further study and analysis (e.g., estimate the amount of graphite that could be relocated to the high-temperature fuel region and establish that the resultant effect is insignificant). Campbell⁽²²⁾ stated that no evidence of reaction has been observed in any test involving CANLUB fuel with a graphite interlayer.

Under the conditions existing within a fuel rod, it is reported by Campbell⁽²²⁾ that reactions between carbon and fuel to form UC or metallic uranium do not occur.

Under accident conditions, it is conceivable that the carbon could react with the Zircaloy cladding to form ZrC. However, even if all of the carbon were consumed, only approximately one percent of the zirconium would have reacted. This possible reaction will be studied further.

As discussed in Section 5.1.2, substitution of annular fuel for standard fuel is a minor deviation from current practice. The addition of graphite-coated cladding should be a minor

deviation from current practice; however, application, out-gassing, and handling technologies will need to be developed. As discussed in Section 5.2.3, graphite-coated cladding designs are the current commercial designs for all CANDU reactors. The basis for selection of the graphite coating for those power reactors was its behavior during power ramps. Licensing effort should be minimal. It is anticipated that irradiations with graphite-coated cladding under this program would be initiated with small numbers of fuel rods.

5.2.3 Experience Summary for Graphite-Coated Cladding

Page,⁽²³⁾ Hardy et al.,⁽²⁰⁾ Fanjoy et al.,⁽²⁴⁾ and Robertson⁽²⁵⁾ have reported that, based upon irradiation tests in the NRU loops, fuel utilizing graphite-coated Zircaloy cladding, the CANLUB design, was selected for commercial production for all the CANDU-PHW (CANada Deuterium Uranium-Pressurized Heavy Water) reactors. Bain et al.⁽²⁶⁾ and Fanjoy and Bain⁽²⁷⁾ indicate that the graphite-coated cladding design was one of several different design modifications that were tested. The modifications were investigated in order to improve fuel rod behavior during the power ramps associated with on-power refueling.

The CANDU-PHW reactors utilize Zircaloy-4 clad fuel rods that are 500 mm long, 15 mm diameter, and have a wall thickness of 0.4 mm. The fuel is naturally enriched, high-density UO_2 . The cladding is nonfreestanding at the reactor operating conditions of 10 MPa pressure and 275°C coolant temperature. The coolant and the moderator are heavy water. The rods are irradiated in horizontal pressure tubes.

Fifty-three fuel bundles plus 340 individual fuel rods with graphite coatings have been irradiated in the vertical NRU loops, according to Hardy et al.⁽²⁰⁾ (The number of fuel

rods in the bundles was not specified. Typical numbers of rods in commercial bundles are 19 for Douglas Point, 28 for Pickering, and 37 for Bruce.) Power-ramp tests have been conducted on 14 of these bundles plus 74 individual rods. The threshold power increase (differential power) for failure was determined to be higher for graphite-coated fuel rods than for uncoated rods. Typical differential powers to the failure threshold were 8-16 kW/m (at 350 GJ/kgM burnup) and 5 kW/m (at 850-1700 GJ/kgM burnup) higher than for uncoated rods. Similar increases in the peak ramped power threshold were also observed. Rods with graphite-coated cladding could be ramped to peak power levels which were 12-18 kW/m higher at 850-1700 GJ/kgM than those for uncoated rods.

Experience in commercial reactors has shown that uncoated rods could be ramped to higher differential powers and higher power levels before failure than in the NRU loops. It is possible that these differences are due to differences between vertical irradiation in NRU and horizontal irradiation in the commercial reactor.

Hardy et al.⁽²⁰⁾ reported that several variations in the graphite coating have been investigated. Among these have been method of application, type of graphite, type of filler material, type of volatile component, size and orientation of the graphite flakes, coating thickness, density, porosity, adhesion, abrasion, and wear resistance. Whereas undoubtedly all of the above variables are important, only the effect of coating thickness has been reported. Thicker graphite coatings have been shown to increase the tolerance to power ramps more than thin coatings. The dimensions of thick and thin were not reported. In a special ramping irradiation designed

to test the effect of coating thickness, four of six rods with thin coatings failed, while none of the twelve rods with thicker coatings failed.

The specific manner in which the graphite coating increases the tolerance of coated rods to power ramping is not presently known, according to Hardy et al.⁽²⁰⁾ However, the improvement is attributed to one or a combination of the following:

- a) The coating may decrease the friction or degree of mechanical interaction between the fuel and the cladding. Actual fuel-cladding reaction or bonding may also be reduced or prevented. Thus, minor realignment of fuel fragments can reduce general and localized stresses in the cladding.
- b) The coating may adsorb or absorb fission products, such as iodine. Thus, the availability of fission products to react with the inside cladding surface is lower and the propensity for stress-corrosion cracking is reduced.
- c) The coating may form a physical barrier between the fuel and fission products.

Other irradiations utilizing graphite-coated cladding were reported by Armijo et al.⁽²⁸⁾ and Proebstle et al.⁽²⁹⁾ of General Electric. The behavior of these coated rods was similar to uncoated rods. Discussions at the referenced topical meeting^(28,29) indicated that the lack of improved behavior for these rods could possibly be attributed to the characteristics of this particular coating.

Coatings of a siloxane material are also being developed according to three Canadian papers.^(20,26,27) No failures have occurred in developmental siloxane-coated rods during ramp testing.

5.3 Packed-Particle Fuel

Packed-particle fuel was selected as one of the concepts for evaluation because localized cladding deformation is virtually absent with this fuel type.

5.3.1 Comparison of Packed-Particle Fuel with Criteria Addressing the FCI Mechanism

Localized strain concentrations that are associated with pellet-pellet interfaces and fuel cracks in rods containing sintered pellet fuel should be eliminated by the use of vibrationally-compacted type fuel. Hence, one of the most significant performance advantages of packed-particle fuel over pellet-type fuel is considered to be reduced localized fuel-cladding mechanical interaction. Although fuel-cladding contact occurs in a packed-particle fuel rod at the start of life, the distributed void volume, point contacts between fuel particles, and higher fuel temperatures (see Section 5.3.2 for temperature estimates) probably result in a weaker fuel column, thus reducing the general cladding strain during steady-state operation and during a power ramp. Kjaerheim and Rolstad⁽³⁰⁾ reported that the elongation of a column of flat-ended fuel pellets^(a,b) is governed by the central fuel temperature while that of a column of packed-particle fuel is more dependent on the average fuel temperature. Hence, during a power ramp, a column of packed-particle fuel would be expected to elongate axially at a rate more typical of the volumetric average fuel temperature while

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- (a) The "reference" solid pellet in this program has dished ends. Elongation of a column of solid pellets with dished ends tends to be determined by the temperature of the fuel at the radius corresponding to the intersection of the dish and the pellet end surface.
- (b) Studies by Depisch et al.⁽³¹⁾ demonstrated that the amount of mechanical interaction depends strongly on whether or not the fuel column is free to expand axially.

a column of pellet fuel would elongate axially at a rate determined more by the fuel central temperature. Therefore, even though the volumetric average fuel temperature may be higher for packed-particle fuel, after fuel-cladding contact is made, the axial stress and strain may be expected to be less in packed-particle rods than in rods containing flat-ended pellets.

If the packed-particle fuel and the pellet fuel expand radially at rates typical of the average temperature increase during a ramp, the general circumferential strain would be expected to be greater and uniform ductility would be promoted in the packed-particle fuel rod. However, this potential for increased circumferential strain may be considerably reduced if minor adjustments and realignments occur between particles. Because of the angular nature of the fuel particles in vipac rods, some localized fuel-cladding interaction could manifest itself as a high friction coefficient. Compared with sintered pellets operating at the same linear heat rating, the increased fuel temperatures in vipac fuel rods would tend to cause a higher fission product release and higher stored energy. These factors may increase the susceptibility for SCC. However, it is possible that these deleterious effects may be offset by the fact that when compared with a typical irradiated fuel with cracked pellets, the packed-particle fuel provides a large number of paths by which the migrating fission product species can reach and subsequently be deposited on the cladding. Hence packed-particle type fuel may have a reduced susceptibility for SCC because the mechanism for concentrating the fission products on the cladding is reduced.

Packed-particle fuel columns consisting of microspheres in sphere-pac type fuel rods would be expected to behave in a manner similar to the angular particles used in vipac fuel

rods, except that the more regular shape of the particles may tend to reduce the friction between the fuel and cladding and between particles. In comparison with vipac fuel, sphere-pac fuel may have an improved capability for adjustment and realignment of particles during a power ramp.

5.3.2 Comparison of Packed-Particle Fuel with Criteria Addressing Development and Licensability

Efforts to develop fabrication capabilities for vipac fuel are judged to be significant. Actual fabrication efforts for vipac fuel may be expected to be less than for pelletized fuel because the fabrication process for vipac fuel may be more easily automated.

Packed-particle fuel has a much greater surface area for the adsorption of contaminants (e.g., moisture) than high-density sintered pellets. As indicated by Robertson,⁽³²⁾ it will be important to convincingly demonstrate that contaminants (e.g., moisture) in packed-particle fuel rods can be controlled at an acceptably low level under commercial fabricating conditions. This has also been a problem for pellet fuel which now appears to have been corrected. Development and fabrication efforts for sphere-pac fuel would be expected to be similar to those required for vipac fuel.

Like sintered pellet fuel, significant microstructural changes can occur in packed-particle fuels due to in-reactor sintering. However, gamma scanning results obtained on long, irradiated, packed-particle fuel rods show no evidence of significant axial gaps forming in the fuel columns. The thermally-induced microstructural changes that occur in packed-particle fuel rods during irradiation at the higher heat ratings reduce the differences between the thermal

performance of packed-particle and pellet type fuels. Restructuring in packed-particle fuel (86-88% TD) results in an increase in the value of $\int_{T_s}^{T_m} KdT^{(a)}$ from about 4.9 kW/m to a value of about 5.9 kW/m. [Note - these are not linear heat generation rates.] The lower value of the integral is associated with the startup or early-in-life condition. The higher value of the integral is associated with the restructured packed-particle fuel and compares with a value of about 6.5 kW/m for pellet fuel (95% TD).

The higher fuel-cladding gap conductance generally assumed for packed-particle fuel partially compensates for the lower thermal conductivity of the packed-particle fuel column. Hence, the linear heat rating required to produce melting in a packed-particle fuel is only approximately 10 to 15% lower than that required to produce melting in a sintered pellet fuel rod.

In-reactor data reported by Fitts and Miller^(33,34) using instrumented (cladding surface and fuel center) fuel pins indicate that the thermal conductance (effective thermal conductivity) of sphere-pac fuel is higher than that of pellet fuel. This has been attributed to improved heat transfer across the fuel-cladding interface for the sphere-pac fuel and is based on the assumption that the thermal conductivity is the same for sphere-pac and pellet fuel columns of the same smear density.

Some preliminary thermal and LOCA analyses have been made for vipac fuel which indicate that the behavior is expected

(a) This is the integral of the fuel thermal conductivity (K), which is a function of temperature (T), over the interval from fuel surface temperature (Ts) to fuel melting point (Tm).

to be acceptable from a safety/licensing point of view but that more detailed analyses are required and are an important part of the Fuel Performance Improvement Program effort. Included in such analyses, for example, would be the evaluation of the effects, if any, of variations in the density along the length of the fuel rod.

The effort to license vipac and sphere-pac fuel may be expected to be significant. However, packed-particle fuel has been licensed previously for irradiation in two commercial U.S. BWRs, i.e., Big Rock Point and Dresden-1 (see 5.3.3). The significant amount of prototype and commercially representative packed-particle oxide fuels which have been irradiated under a wide range of conditions has provided a substantial technical base to demonstrate the satisfactory performance characteristics and viability of this fuel type. Although there may be special considerations related to the application of packed-particle fuels on a commercial scale, no inherent performance limitations have become evident and some behavioral characteristics of packed-particle fuels may be superior to the more standard sintered pellet type fuel. As part of the Fuel Performance Improvement Program, it is planned that investigations will be initiated with small numbers of packed-particle fuel rods. Safety-related considerations (e.g., LOCA) associated with packed-particle fuel are to be evaluated as part of this activity.

5.3.3 Experience Summary for Packed-Particle Fuel

Since the late 1950's, a significant amount of prototypic and commercially representative packed-particle UO_2 and UO_2 - PuO_2 thermal reactor fuel has been tested in a variety of irradiation facilities as summarized in Table 2. Average maximum fuel rod burnups of over 1728 GJ/kgM (20,000 MWd/MTM) and peak fuel rod burnups of more than 2333 GJ/kgM

TABLE 2. Experience Base for Packed-Particle Fuel

<u>IRRADIATION TESTS</u>		
• <u>PEAK CONDITIONS:</u>		
BURNUP	> 2333GJ/kgM (> 27,000 MWd/MTM)	
LINEAR HEAT GENERATION RATE	> 72kW/m (> 21.9kW/ft)	
• <u>REACTORS:</u>		
<u>POWER REACTORS:</u>	<u>NO. OF FUEL RODS</u>	<u>REFERENCES</u>
BIG ROCK POINT	> 4400	36, 42, 61-66
DRESDEN-1	468	63
GARGLIANO	4 BUNDLES (POSSIBLY ≤ 128 RODS)	37, 45
DODEWAARD	* (BUT ≥ 3)	40, 45
MZFR	148	67
SAXTON	162	42, 43, 61, 68, 69
HBWR (HALDEN)	* (< 90)	30, 46, 47, 70-77
BR 3/VULCAIN	* (≥ 12)	45, 78-80
EBR-11	* [ESTIMATE: >56]	52, 58, 59, 81-86
DFR	* [ESTIMATE: 15-31]	87, 88
RAPSODIE	*	87
KNK-11	22	87
<u>OTHER REACTORS:</u>		
PRTR	~2430	41, 42, 50, 61, 89-94
EBWR	1296	42, 44, 50, 61
VBWR	*	63, 95
JPDR	108	63, 96
GETR-PWL	* [ESTIMATE: ~6]	75, 76, 97-101
R2 (STUDSVIK)	* [ESTIMATE: <30]	102-104
DIORIT	* (≥ 4)	35, 45, 79
ORRR	* (≥ 2)	33, 53, 55, 85, 105, 106
BAWTR	* (≥ 37)	82, 83, 86
ETR	* [ESTIMATE: <29]	42, 53, 55-57, 61, 85, 107-109
MTR	32	42, 49, 61
BR-2	* (≥ 17)	45, 51, 79, 87, 110
HFR (PETTEN)	* [ESTIMATE: <31]	71
SILOE	4	102, 103
FR-2	*	111, 112
JRR-2	1	113
HWCTR	45	95
RS-1	* [ESTIMATE: < 4]	73
SM-2	NOT STATED	114
• <u>RAMPING EXPERIENCE</u>		
<u>REACTORS</u>		
DR3 (RISO)	2	115
• <u>DEFECT BEHAVIOR</u>		
<u>REACTORS</u>		
PRTR		36, 41, 42, 61, 72, 89, 116, 117
ETR		16, 41
BIG ROCK POINT		65, 118
• <u>TRANSIENT BEHAVIOR</u>		
<u>REACTORS</u>		
TREAT	* (5 TO ≤15)	55, 119-123
SPERT	12	124-127

* NUMBER OF PACKED-PARTICLE FUEL RODS NOT CLEARLY STATED

(27,000 MWd/MTM) were achieved in tests which included abnormally high linear heat generation rates (i.e., sufficiently high to produce center fuel temperatures greater than melting). In addition, these tests were supported by a large number of packed-particle fuel capsule experiments conducted in test facilities to evaluate and compare specific performance characteristics.

As summarized in Table 2, vipac fuels have been irradiated in commercial power reactors including Big Rock Point, Dresden-1, Garigliano, and Dodewaard (all BWRs).⁽³⁵⁻⁴⁰⁾ Some of the more significant prototype irradiations in support of vipac fuel development have been conducted at high power in PRTR, to high burnups in Saxton, and in EBWR.⁽⁴¹⁻⁴⁴⁾ Numerous experiments with packed-particle fuel have been conducted in test reactors.⁽⁴⁵⁻⁵¹⁾ In addition, a significant amount of relevant packed-particle development work, including numerous irradiation tests, has been conducted in support of the LMFBR program.^(33,52-59) These irradiation tests were conducted in both thermal and fast reactors and consisted mostly of sphere-pac UO_2 - PuO_2 fuel. The Kilorod Project described by Haws et al.⁽⁶⁰⁾ involved nearly 1200 packed-particle fuel rods.

The packed-particle fuel irradiations involved several general forms of fuel and types of cladding as summarized in Table 3. A more detailed breakdown of the different kinds of UO_2 and UO_2 - PuO_2 feed material for packed-particle fuels that have been investigated to various degrees is summarized in Table 4. Remarkably few significant differences are reported in the irradiation behavior of the various packed-particle fuel types. In-reactor sintering and restructuring tends to reduce any differences which may

TABLE 3. Packed-Particle Fuel Irradiations: Fuel Forms and Cladding Types Used (Reference Numbers Shown in Table)

FUEL FORM	CLADDING TYPE			
	ZIRCALOY	STAINLESS STEEL	OTHER	NOT STATED
MICROSPHERES	73, 74, 82, 102, 103	3, 33, 52, 55-57, 71, 73, 83, 85, 86, 105-109, 120, 121		45, 104, 128, 129
ANGULAR AND OTHER	41-44, 46, 47, 49, 50, 61, 62, 68-70, 72, 75, 76, 82, 87, 89-95, 97, 100, 119	35, 43, 51, 58, 59, 68, 69, 71, 75, 76, 78, 80, 83, 84, 86-88, 98, 101, 110, 111	59, 84, 113	79
NOT STATED	36, 48, 63, 66, 72, 77, 102, 103, 115, 124	63, 99, 112, 122	60, 63, 64	30, 37, 40, 53, 67, 81, 114

TABLE 4. Packed-Particle Fuel Irradiations: Feed Materials Used

<u>Feed Material</u>	<u>References</u>
Arc fused UO_2	36,72,100
Induction melted UO_2 and UO_2-PuO_2	45,71,79,80,87
Pneumatically impacted (Dynapak) UO_2 and UO_2-PuO_2	41,44
Pressed, sintered, and crushed UO_2 and UO_2-PuO_2	47,70,88,98,99,111
Sintered UO_2-PuO_2 micro-pellets or nodules	87
Electrodeposited UO_2	71
Sol-gel microspheres of UO_2 and UO_2-PuO_2	3,33,52-55,73-75,103
Sol-gel angular particles (shards) of UO_2 and PuO_2-PuO_2	46,75

exist among the various types and leads to a common irradiated fuel structure. This restructuring is also responsible for the reduction in the behavioral differences that exist between packed-particle and pellet fuel types.

Examinations of irradiated fuel rods by Hoffman et al.⁽¹³⁰⁾ showed that localized cladding deformation is virtually absent with packed-particle fuel rods. However, Rubin et al.⁽¹³¹⁾ have indicated that there is some evidence with high burnup (10 at.%) fast reactor fuel pins that even with vipac fuel, a significant mechanism for mechanical interaction still exists. Lotts⁽¹³²⁾ has described irradiation tests with sphere-pac fuel associated with the fast breeder fuel development program. Some evidence exists according to Lotts⁽¹⁴⁴⁾ that sphere-pac fuels may give better performance than pellet fuels in a fast reactor. There are several variations on the sphere-pac fuel concept. One variation patented by Sease and Harrington⁽¹³³⁾ is the use of vibrationally compacted microspheres surrounding a solid pellet column (the pellets tend to center themselves in the fuel rod). The purpose of the thin annular layer of microspheres is to reduce adverse mechanical and chemical interactions between the fuel and cladding. Another variation is the TRISO-type microsphere (i.e., a carbon-coated fuel microsphere that is then coated with SiC to retain fission products) described by Gulden et al.⁽¹³⁴⁾ for use in High-Temperature Gas-cooled Reactors (HTGRs); however, it does not appear likely that TRISO fuel microspheres would be considered for use in LWRs.

Failures of vipac (Type C) Zircaloy-clad UO_2 fuel in Big Rock Point are described in a semiannual report⁽⁶⁵⁾ and in a paper by Walke⁽¹¹⁸⁾. Sipping tests detected leaky fuel rods in 29

out of 33 Type C Fuel assemblies. The failures were attributed to impurities,^(a) which were either mixed with or adsorbed on the fuel particles, that reacted with the cladding at isolated spots to form local blisters of massive hydride. G. F. Pratt of Consumers Power Company has indicated that an off-gas treatment solved the problem and that peak burnups as high as 3230 GJ/kgM (37,400 MWd/MTM) were attained at linear heat generation rates to 49 kW/m (15 kW/ft).

The fabrication problems associated with PRTR fuel assemblies of the first-generation design have been described by Freshley^(41,42,61) and the NRC.⁽¹⁶⁾ After removal of impurities in the fuel, the behavior of various experimental UO_2 - PuO_2 fuel types, including vipac, under high performance conditions in the PRTR was generally excellent. The defects that occurred in first-generation-design PRTR fuel rods provided some of the first experience with gas-phase hydriding in Zircaloy-clad oxide fuel rods and led to a better understanding of the phenomenon. Even though hydriding of the cladding led to severe localized embrittlement and, in some cases, loss of cladding fragments, little or no fuel loss into the coolant occurred and no severe reactor operating difficulties were experienced. As a result, improvements in fuel fabrication techniques were developed and no defects occurred in vipac fuel rods of the more advanced design (i.e., High Power Density) irradiated in the PRTR during the Batch Core Experiment.

Mechanical damage to the lower end cap weld region during vibration for fuel particle compaction was also suspected as a slight possibility as the cause of leaks in the fuel rods of Type C fuel assemblies at Big Rock Point.⁽⁶⁵⁾ Bean et al.⁽⁴⁴⁾ reported that this kind of mechanical damage was

(a) The specific impurities were not stated in the report;⁽⁶⁵⁾ hydrogenous contamination was mentioned in the paper.⁽¹¹⁸⁾

encountered during the fabrication of vipac fuel rods for the EBWR. Methods of improved fuel rod support during vibration for fuel particle compaction were developed which eliminated this problem.

The experimental data show that the fission gas release is somewhat greater for packed-particle fuels than for sintered UO_2 pellet fuels operating at comparable heat ratings.

Experience obtained to date shows that the defect performance of packed-particle fuels is satisfactory and is comparable with the performance of sintered pellet fuels.

Relatively few experiments (e.g., in TREAT and SPERT) have been conducted to compare the transient behavior of packed-particle and pellet-type fuels. Results of those experiments have been reported by Miller and Lussie,⁽¹²⁵⁻¹²⁷⁾ Freshley and Harrison,⁽¹¹⁹⁾ and PNL.⁽¹²³⁾ In 1973, D. T. Aase of PNL summarized the results of Zircaloy-clad UO_2 transient experiments (included 14 packed-particle fuel rod experiments) in SPERT and TREAT. The results show that the cladding failure threshold behavior characteristics of packed-particle fuel and pellet fuel are comparable. There were some indications that the cladding failure mechanisms may differ.

A paper by Knudsen et al.⁽¹¹⁵⁾ describes overpower ramp tests recently conducted in DR3 at Risø that involved vipac fuel (2 rods; 84% TD smear density) and pellet fuel (3 rods; 95% TD pellets). Failures of all three pellet rods occurred fairly consistently at a linear heat generation rate, at the time of failure, of around 45-48 kW/m; one vipac rod failed at 64 kW/m. Survival of another vipac rod may be due to the slower ramp rate to which it was subjected; however, the associated model analysis does not support that view.

Overall, the packed-particle fuel performance has been demonstrated to be satisfactory and no inherent performance limitations are evident. Packed-particle fuel has been shown to perform equally as well as pellet fuel and in some instances the behavioral characteristics of packed-particle fuel are notably superior. Most behavioral problems encountered with Zircaloy-clad packed-particle fuel can be attributed to the entrapment of excessive amounts of hydrogenous impurities (moisture) within the fuel rods. However, this fabrication-technology related problem is not unique to packed-particle fuels. It has been successfully demonstrated that the problem can be alleviated for packed-particle fuels by implementing sound fuel fabrication methods and procedures.

5.4 Consideration of Other Possible Improved Concepts

Several other fuel design concepts, which have potential for improved power ramping performance, were considered. These design concepts fall into three basic categories: those associated with the fuel, those associated with the cladding, and those associated with other aspects of the fuel rod. The candidates and categories are described briefly in the following three subsections: 5.4.1 through 5.4.3. In general, these concepts were considered to be lacking when compared to the selection criteria, i.e., 1) a low degree of behavioral improvement was anticipated, 2) efforts to develop, fabricate, and license were considered to be excessive or the licensing margin was significantly degraded, or 3) the concept was considered to be a major deviation from current technology and/or had a low probability of development. Several concepts were identified which show promise for meeting the failure improvement criteria and were rejected for a lack of an adequate supportive data base. Among these concepts, some were identified for possible development within this program. The remainder are generally included in other PCI-related programs, the results of which will be monitored. The discussions are summarized in Section 5.4.4.

5.4.1 Other Fuel-Related Concepts

The possible fuel-related improved concepts fall into two general categories, i.e., those related to geometry and those related to properties. Each possible concept is discussed below.

5.4.1.1 Short Pellets

By employing shorter pellets, the number of pellet-pellet interfaces would be increased, thus distributing the axial strain concentrations. Also, short pellets would tend to reduce pellet shape distortion (hourglassing) and hence, the circumferential interfacial strain concentration and the resultant cladding ridging. In a series of tests described by Whatham⁽¹³⁵⁾ it was found that a significant reduction in ridge height occurred when the pellet length-to-diameter ratio was one-third of the value in a typical reactor. Both effects would be operative prior to and during a power transient. With regard to fission product release, the shorter pellet appears to be indistinguishable from the reference solid pellet design. Significantly increased fabrication efforts are associated with producing more pellets per rod.

Because the length of the reference fuel pellets is already fairly short, e.g., $L/D \sim 0.8$, it was judged that any improvement in behavior from additional pellet length reduction would be minor and this concept was therefore deleted from consideration within the context of this program.

5.4.1.2 Chamfered Pellets

The axial and circumferential interfacial strain concentrations and, hence, cladding ridging would be reduced if the pellets were chamfered.^(a) The axial strain concentration would be distributed over a greater length. Fuel temperatures and fission gas release would be expected to increase slightly due to the volume of gap that would never close. The above effects would be operative before and during a power transient. Chamfered pellets are currently used in some fuel rod designs.

It was judged that inclusion of pellet chamfers in the test rods would result in a minor improvement in fuel rod behavior. Results from other programs which utilize chamfered pellets will be monitored.

5.4.1.3 Dished Pellets

For fuel rods with dished pellets, the force system developed tends to increase circumferential ridging of the cladding because dishing would be expected to accentuate hourglassing and would increase the axial and circumferential interfacial strain concentration before and during a power transient. Dishing would decrease the general axial strain during a transient by providing space for axial expansion of the central portion of the fuel. If fuel swelling can be partially accommodated by the dishes or if compressive axial stresses on the pellet edges promote flow of material from the edge

(a) A chamfered pellet has beveled or rounded corners (a corner being the intersection of the cylindrical and end surfaces).

of the pellet to the dish during steady-state operation, the general axial strain and, to a lesser degree, the general circumferential strain prior to a power transient would be decreased.

The "reference" solid pellet fuel utilizes dished ends and thereby provides a basis of comparison.

5.4.1.4 Barreled Pellets

A pellet with a barrel shape or very long chamfers would tend to reduce pellet-pellet interfacial strain concentrations. The increased residual gap would increase fuel temperatures and fission gas release before and during a power transient. The higher fuel temperatures would be expected to promote fuel creep, thus reducing the general strain condition prior to the transient. The higher fuel temperatures would be of concern in safety-related areas (e.g., stored energy and LOCA).

The exterior surface shaping of individual fuel pellets was judged to represent a major deviation from current fabrication technology and was therefore deleted from consideration within the context of this program.

5.4.1.5 Axially Slit Pellets

As described in a patent by Ockert⁽¹³⁶⁾, pellets with several axial slits (artificial cracks) cut into the interior region from the outer surface of the pellet would tend to distribute the circumferential strain concentration before and during power transients. The slit volumes would also provide a region for swelling accommodation, thus

reducing the general strain concentrations prior to a power transient. Because a significant amount of material would be removed for the slits, the specific power, average fuel temperature, and fission gas release would increase for a given linear heat generation rate. Though the safety margins would not drastically change, significant efforts to license the concept may be required.

The production of several axial slits in individual fuel pellets was judged to represent a major deviation from current fabrication technology. This concept was therefore deleted from consideration within the context of this program.

5.4.1.6 Axially Grooved Pellets

Pellets with several axial grooves located in a manner as described for the axially slit pellets would be expected to promote controlled pellet cracking during operation. Thus, the circumferential strain concentration would be more evenly distributed before and during a power transient. The average fuel temperatures would be similar to those for the reference solid pellet case. Although substantial, the licensing and development efforts can be expected to be much less than for the axially slit pellet concepts.

Axially grooved pellets would require surface alteration of individual pellets. Therefore, it was judged that the anticipated minor improvement in behavior would not warrant the increased fabrication effort (major deviation from current practice involved).

This concept was therefore deleted from consideration within the context of this program.

5.4.1.7 Circumferentially Grooved Pellets

Pellets with circumferential grooves would crack transversely during operation, thus, in effect, producing short pellets. The benefits of short pellets would be expected without the associated high level of effort involved in producing large amounts of such pellets. The licensing efforts would be expected to be insignificant. Developmental efforts would be moderate.

It was judged that the minor improvement in anticipated behavior would not warrant the increased fabrication effort (major deviation from current practice involved) associated with the alteration of individual pellet surfaces. This concept was therefore deleted from consideration within the context of this program.

5.4.1.8 Microcracked Fuel

If fuel pellets could be developed in a form that tends to promote microcracking or fracturing on a very fine scale, they might be expected to behave in a manner similar to packed-particle fuel. In the absence of experience with microcracked fuel, the performance of such fuel with regard to mechanical behavior and fission product retention/release is largely unknown.

Timely development of this fuel concept is doubtful. Therefore, it was judged that this concept would be deleted from consideration within the context of this program.

5.4.1.9 Low Swelling Fuel

If a low swelling fuel could be developed, it should reduce the general and, to a lesser degree, the concentrated strains in the cladding prior to a power transient. The time to fuel-cladding interaction would be extended.

The probability of development of a low swelling fuel is considered to be low. Therefore, it was judged that this concept would be deleted from consideration within the context of this program.

5.4.1.10 Increased Plasticity Fuel

A fuel pellet with a high degree of plasticity in the operating temperature range would be expected to reduce the general and concentrated strains in the cladding during steady state operation prior to a transient. In order to be beneficial during a power transient, the fuel would need to be extremely plastic. Because fuel additives would probably be required, fuel properties such as melting point, thermal conductivity, and fission product release rate would most likely be adversely affected.

Development efforts can be expected to be large and therefore the probability of developing such a fuel is judged to be low; hence, this concept was deleted from consideration within the context of this program.

5.4.1.11 Lower Density Fuel

Lower density fuel would be expected to better accommodate fuel swelling, thus reducing cladding strains prior to a transient. This advantage may

be offset by increased fuel temperatures, larger fission product release, and higher stored energy. Considering the problems recently experienced with in-reactor densification, it would be necessary but not difficult to demonstrate the physical stability of any low density fuel concept. Assuming the capability of in-reactor stability, licensing and fabrication development efforts would be small.

Any improvement in PCI behavior resulting from the use of lower density fuel can be expected to be minor. Therefore, it was judged that this concept would be deleted from consideration within the context of this program.

5.4.1.12 Higher Density Fuel

Increased fuel density would be expected to improve thermal conductivity, reduce fuel temperatures, and thus reduce the fission product release and the stored energy. These advantages may be offset by increased fuel strength and lower creep rates which would lead to higher general cladding strains. Also, higher density pellets would be less able to accommodate high burnup swelling. Licensing and fabrication development efforts would be expected to be small.

Any improvement in behavior resulting from the use of higher density fuel can be expected to be minor and therefore it was judged that this concept would be deleted from consideration within the context of this program.

5.4.1.13 Fission Product Retaining Fuel

Fuel that is doped with an additive to reduce fission product release would presumably reduce the propensity for stress-corrosion cracking. Effects on the other criteria are unknown. Another way to reduce fission product release would be to develop fuel with a large grain size.

The probability of developing a fuel with an additive that retains essentially all the potentially harmful fission products is low and therefore it was judged that such a concept would be deleted from consideration within the context of this program.

5.4.1.14 Variable (Radially) Enrichment Fuel

Having a higher fissile density near the exterior of the pellet would reduce fuel temperatures and hourglassing. Designs for such a fuel include: 1) a whole pellet in which the fissile content is varied radially, and 2) a two-pellet design consisting of a depleted fuel pellet surrounded by an enriched annular pellet. Peak fuel temperatures, fission product release and, in particular, stored energy would be expected to be significantly reduced. Because the power density is greater at or near the surface of this type of fuel than in the reference pellet, the radial temperature gradient is also steeper in that region. It is uncertain whether or not the steeper radial temperature gradient promotes increased radial cracking in the fuel pellet. Development and fabrication efforts can be expected to be large.

The depleted-core/enriched-annulus pellet design is being developed in Denmark,⁽ⁱ³⁷⁾ The results of that program will be monitored.

5.4.1.15 Fuel with Reduced Thermal Expansion and/or Increased Thermal Conductivity

If the thermal expansion of the fuel could be reduced or the conductivity increased, the general and localized strains would be reduced during steady state and during a transient. It is not likely that the expansion or conductivity properties of UO_2 can be significantly altered. Therefore, a modified or new fuel with a lower expansion coefficient and/or higher thermal conductivity would be required.

A very large development effort would probably be required to develop a new or modified fuel. This is an extreme deviation from current technology and therefore it was judged that this concept would be deleted from consideration within the context of this program.

5.4.2 Other Cladding-Related Concepts

The possible cladding-related improved concepts fall into two general categories, i.e., those related to geometry and those related to properties. Each possible concept is discussed below.

5.4.2.1 Cladding with Optimized Radius-to-Wall Thickness Ratio

Thicker cladding would reduce the general and the concentrated strains before and during a power transient. Only large increases in cladding thickness

would be expected to be effective. Cumulative effects due to repeated power ramping would be expected to be decreased. Fuel temperatures would increase slightly. Fabrication efforts can be expected to increase because higher enrichment uranium would be required (see comments in Section 5.1.2). Licensing efforts would be expected to be small.

Any improvement in behavior that might be expected to result from optimizing the cladding radius to wall thickness ratio might be minor. It was judged that this concept would be deleted from consideration within the context of this program.

5.4.2.2 Cladding with Noncylindrical Inside Surface

Cladding with several axially oriented flats or raised ridges on the inside surface of the cladding would tend to distribute strain concentrations caused by fuel cracks, and, to some extent, pellet-pellet interfaces before and during a power transient and result in a different stress state on the inside surface of the cladding. Due to a residual gap that would not close, fuel temperatures would tend to be higher. General strains prior to a power transient would be reduced, and fission product release and stored energy would be higher. Cladding of this type has been recently manufactured. Therefore, fuel rod fabrication development efforts can be expected to be low. Licensing efforts can be expected to be moderate.

Mogard⁽¹³⁸⁾ has reported that the noncylindrical inside surface concept is being developed in Sweden. The results from that program will be monitored.

5.4.2.3 Fully Recovered, Nonrecrystallized Cladding

Full recovered, nonrecrystallized Zircaloy-2 cladding would have a higher strength and, possibly, a lower creep rate than the "reference" cladding. Therefore, cladding strains may be expected to be somewhat reduced. Some improvement may be anticipated because there would be less variation in the cladding properties. The efforts for licensing and fabrication development are expected to be small.

Any improvement in behavior resulting from the use of fully recovered, nonrecrystallized cladding can be expected to be minor. Any results obtained from the use of this material in other programs (e.g., by General Electric Company) will be monitored.

5.4.2.4 Fully Recrystallized Cladding

Fully recrystallized Zircaloy-2 cladding would have a lower strength than the "reference" cladding. Therefore, cladding strains may be expected to be somewhat increased. However, the uniform strain properties may be better than those of the "reference" cladding. Some improvement may be anticipated because all the grains in the cladding would be in the same physical state. The efforts for licensing and fabrication development are expected to be small.

Results of inclusion of fully recrystallized cladding in other programs will be monitored.

5.4.2.5 Optimum Texture

Some stress corrosion studies indicate that cleavage along the basal planes in Zircaloy may require

lower stresses than intergranular penetration. Perfect alignment of the basal planes of individual grains in the tangential direction of cladding tubes may possibly lower the susceptibility of Zircaloy-2 to stress-corrosion cracking.

The reference cladding has a high degree of alignment of the basal planes at about 30° to the tangential direction. Only a minor improvement would be expected for perfect alignment, therefore it was judged that results from other programs studying this concept will be monitored.

5.4.2.6 Zirconium Alloys with Improved Creep Strength

Improved zirconium alloys with superior in-reactor creep strengths (e.g., Zr-1% Nb or Zr-2.5% Nb) would be expected to reduce cladding strain and, possibly, the propensity for stress-corrosion cracking. A high operational reliability of fuel element cladding of Zr-1% Nb alloy has been indicated by Votinov and other Russian investigators.^(139,140)

Licensing and fabrication development for existing alloys would be minimal, while efforts for a new developmental alloy would be significant.

Results from programs utilizing zirconium alloys with improved creep strength will be monitored.

5.4.2.7 Type 316 Stainless Steel

Ferrari⁽¹⁴¹⁾ has reported that during the early years of commercial nuclear power, stainless-steel cladding was used in most Westinghouse PWR fuel rods. The experience with such fuel in six PWRs (Yankee,

Indian Point-1, Haddam Neck, San Onofre, Chooz, and Trino) was excellent.

Pashos et al.⁽⁶³⁾ have indicated that, contrary to expectations, Type 304 stainless-steel-clad fuels have proven unsatisfactory by BWR service for peak burnups greater than about 1300 GJ/kgM (15,000 MWd/MTM). The intergranular cracking of unsensitized Type 304 stainless steel in a high-temperature water-reactor environment was an unanticipated phenomenon; however, though not widely reported, this phenomenon has occurred in PWR as well as BWR environments.

As a result of the LMFBR programs, improvements have been made in the quality of Type 316 stainless steel. Some stainless steel cladding is currently being used in commercial reactors. In comparison to the "reference" cladding, the more uniform ductility of stainless steel may be an advantage. Stainless steels are susceptible to intergranular cracking in both BWR and PWR environments, but especially the former. Parasitic neutron capture is higher in stainless steels than in Zircaloy-2.

Results from other programs utilizing stainless steel cladding will be monitored.

5.4.2.8 Cladding with Shot-Peened Inside Surface

A residual compressive stress would be induced on the inside surface of the cladding by using the shot-peening technique. This compressive stress would be expected to counteract tensile stresses in the cladding produced during fuel rod operation. Thus, the

propensity for stress-corrosion cracking may be significantly reduced. The effects of irradiation, particularly irradiation creep, on the retention characteristics of the compressive stress are unknown. Efforts to develop and license shot-peened cladding would be expected to be minimal.

Results from other programs will be monitored.

5.4.2.9 Cladding with Improved Inside Surface Properties

An improved inside surface treatment, e.g., elimination of surface imperfections and defects, improved plasticity of the oxide coating, and impervious platings or coatings, may reduce the propensity of the cladding to SCC. The "reference" cladding has an etched inside surface; the etching may reduce the number of surface imperfections. Licensing efforts can be expected to be small. Significant developmental efforts might be required, depending upon the chosen improvement.

Results from other programs will be monitored.

5.4.3 Other Fuel Rod Concepts

Possible improved concepts which fall into neither the fuel nor cladding categories are discussed below.

5.4.3.1 Improved Coating

An alternate coating that provides for better slippage between fuel and cladding and/or functions as an impervious fission product barrier might be better than graphite. A material that has been shown to have considerable potential as an effective coating is siloxane. Development and licensing

efforts would be expected to be somewhat more difficult than those required for the graphite coating.

Out-of-reactor development of an improved coating will be part of this program.

5.4.3.2 Amorphous Layer

Production of a treated layer on the inside surface of the cladding that is amorphous would eliminate cladding grain boundaries and surface defects as sites for crack nucleation. Development efforts would be expected to be substantial. Licensing efforts would be minimal.

Results from other programs will be monitored. The emerging materials-processing technology by lasers was recently described by Breinan et al.⁽¹⁴²⁾

5.4.3.3 Barrier Between Fuel and Cladding

Use of a barrier on the inside surface of the cladding would prevent access of fission products to the cladding, would reduce strain concentrations before and during a power transient, and may act to arrest the propagation of cracks at the interface of the dissimilar materials. The general strain condition prior to a transient would also be expected to be reduced. One serious question concerning the use of a barrier would be its behavior in the event of a cladding breach. If the barrier is not bonded to the cladding, the space between the cladding and the barrier could become steam- or gas-blanketed resulting in a drastic reduction in radial heat transfer and serious overheating and possibly melting of the fuel. An

integral cladding-barrier (e.g., duplex or coextruded tubing) would be less susceptible to blanketing. Efforts to develop, fabricate, and license such a fuel concept would be significant.

Results from other programs will be monitored.

5.4.3.4 Perftube Liner

A perforated tube (perftube) liner in the fuel-cladding gap would also be soft and would behave better mechanically than a solid (i.e., nonperforated) soft barrier in reducing strains in the cladding. Perforations in the tube would prevent gas blanketing between the cladding and the liner if a cladding breach occurred. The perftube liner would not function as a fission product barrier. Efforts to develop, fabricate, and license such a liner would be significant.

Results from other programs studying perftube liners will be monitored.

5.4.3.5 Prepressurization

Prepressurization has been reported by Holzer et al.⁽¹⁴⁵⁾ and Garzarolli et al.⁽¹⁴⁶⁾ to have a beneficial effect by reducing fuel-cladding interaction in both BWR and PWR fuel designs and is not considered to be a major departure from current technology. Prepressurization with helium at 5-10 atmospheres would reduce cladding creepdown and delay fuel-cladding contact as well as increase fuel-cladding gap conductance, thereby reducing fuel temperature, fission product release, and thermal/mechanical interaction. Prepressurization would be most effective

in packed-particle fuels by increasing the effective thermal conductivity of the packed-particle fuel column. Because PWR fuel rods are commonly pre-pressurized, efforts to develop and license pre-pressurized fuel rods are expected to be insignificant.

Prepressurization, in combination with the primary fuel concepts, will most likely be evaluated in this program. Results from other programs on pre-pressurization will also be monitored.

5.4.3.6 Optimum Fuel-Cladding Gap

Theoretically there exists an optimum fuel-cladding gap which is a balance between maintaining low fuel temperatures while providing adequate space for fuel swelling. Thus, the time to fuel-cladding contact is delayed and fission product release is maintained at a low level.

Determination of the optimum gap is expected to be a minor improvement and therefore it was judged that this concept be deleted from consideration within the context of this program.

5.4.3.7 Lower Linear Heat Generation Rate

Lowering the linear heat generation rate of the fuel rod would extend the time required for the occurrence of fuel-cladding mechanical interaction and, if lowered enough, it would prevent the occurrence of such interaction. General cladding strains would be expected to be decreased due to reduced fuel swelling. The magnitude of a power increase would probably be lower for a typical reactor power step increase.

(However, PCI failures have occurred with high burn-up fuel rods at low liner heat generation rates.) Thus, general and concentrated strains would probably be lower during the power increase. Fission product release and stored energy would be reduced. Because more rods would have to be produced, i.e., either smaller rods or a larger core, the increase in fabrication effort would be significant. Although the safety margins would be increased, significant licensing efforts would be required to qualify new core configurations.

Results of other programs involving fuel elements with larger fuel rod arrays (e.g., 8 x 8 in BWRs and 17 x 17 and others in PWRs) will be monitored. It is suspected that the magnitude of the reductions required to prevent fuel rod failures is too large to be practical and is therefore judged not to be a viable solution.

5.4.3.8 Soft Spacers in the Pellet Stack

Utilization of axially deformable spacers, located between pellets at strategic points along the axis of a fuel rod, would have the effect of converting a single, long, fuel-pellet stack into several short stacks. Axial movement and adjustment of fuel would be more easily accommodated. The general and possibly the axial strain concentration before and during a power transient would be reduced. Page⁽²³⁾ has indicated that spacers of graphite between individual pellets would reduce fuel temperatures and stored energy. Higher fuel enrichments would be required to compensate for the decreased fuel volume. Efforts

for fabrication development and licensing would be expected to be moderate.

Results from programs utilizing pellet spacers will be monitored.

5.4.3.9 Fission Product Getters

Introduction of fission product getters within the fuel rod could possibly reduce stress-corrosion cracking. Incorporation of a fission product getter into the fuel-cladding annulus would be more effective, but more difficult to achieve, than placing a getter at the end of the fuel pellet column. Efforts for fabrication development and licensing would be expected to be considerable.

Results from other programs in which getters may be developed for specific fission products (i.e., those active species involved in SCC) will be monitored.

5.4.3.10 Buffers

Inclusion of a buffer to regulate the chemical activities of the fuel (e.g., by controlling the oxygen potential) and specific fission products might be beneficial in minimizing SCC. Development and licensing efforts would be expected to be substantial.

Results from other programs in which fuel buffers may be developed will be monitored.

5.4.3.11 Shrouded Fuel with Liquid Bond

Utilization of a perforated shroud tube to prevent fuel fragment movement together with a liquid metal

(or other) bond, as in some of the advanced LMFBR carbide fuel concepts, would eliminate fuel cladding interaction and the resultant interaction strains in the cladding, according to Kerrisk et al. (143)

Pressurization of the fuel rod would probably be required to prevent excessive ovalization of the cladding. Fission product release and stored energy would be reduced because of lower fuel temperatures. Serious questions concerning bond behavior during a LOCA or in the event of cladding breach would need to be addressed. Stored energy would be lower because of lower operating temperatures. Developmental efforts and the added fabrication effort would be very prohibitive. Use of the shroud tube in a pressurized helium-bonded element would be doubtful due to high shroud temperatures and resultant low strength.

Use of the concept of shrouded fuel with a liquid bond represents a major deviation from current LWR technology and therefore it was judged that this concept would be deleted from consideration within the context of this program.

5.4.4 Summary Discussion of Other Possible Improved Concepts

Table 5 summarizes the disposition, within the context of this program, of the other possible improved concepts which were considered. Consideration of these concepts with respect to the selection criteria yielded the following:

- 1) Compared to the failure criteria, several concepts had attributes which were deemed to have significant potential for improving power ramping behavior. However, the data base for the concepts was not sufficient to warrant irradiation testing. Two concepts, an

TABLE 5. Summary of Disposition of Other Potential Improved Concepts

<u>Fuel</u>	<u>Evaluate in This Program</u>	<u>Monitor Other Programs</u>	<u>Delete from Consideration Within the Context of this Program</u>
<u>Geometric</u>			
Short Pellets			MI
Chamfered Pellets		✓	
Barreled Pellets			MD
Axially Slit Pellets			MD
Axially Grooved Pellets			MI/MD
Circumferentially Grooved Pellets			MI/MD
<u>Property</u>			
Microcracked Pellets			LP
Low Swelling Fuel			LP
Increased Plasticity Fuel			LP
Lower Density Fuel			MI
Higher Density Fuel			MI
Fission Product Retaining Fuel			LP
Variable (Radially) Enrichment Fuel		✓	
Reduced Thermal Expansion and/or Increased Thermal Conductivity			MD
<u>Cladding</u>			
<u>Geometric</u>			
Optimized Radius/Thickness Ratio			MI
Noncylindrical Inside Surface		✓	
<u>Property</u>			
Fully Recovered, Non-recrystallized		✓	
Full Recrystallized		✓	

TABLE 5 (contd)

<u>Property (contd)</u>	<u>Evaluate in This Program</u>	<u>Monitor Other Programs</u>	<u>Delete from Consideration Within the Context of this Program</u>
Optimum Texture		✓	
Improved Creep Strength (Zr Alloy)		✓	
Type 316 Stainless Steel		✓	
Shot-Peened Inside Surface		✓	
Improved Inside Surface		✓	
<u>Fuel Rod</u>			
Improved Coating	✓		
Amorphous Layer		✓	
Barrier		✓	
Perftube Liner		✓	
Prepressurization	✓	✓	
Optimum Fuel-Cladding Gap			MI
Lower LHGR		✓	
Pellet Spacers		✓	
Fission Product Getters		✓	
Buffers		✓	
Shrouded Fuel with Liquid Bond			MD

MD = Major Deviation from Current Technology - Not viable
 LP = Low Probability of Development - Not viable
 MI = Minor Improvement

improved coating and prepressurization, are being considered for further development.

- 2) The majority of the remaining potential concepts are under study in other PCI-related programs. Among these concepts are chamfered pellets, variable (radially) enrichment fuel, barriers, noncylindrical inside cladding surface, pellet spacers, getters and other means for control of fission products, and several concepts involving fuel and cladding property variations. Results from these other programs will be monitored. Some of these concepts may be considered for inclusion in this program for evaluation at a later date.
- 3) Several possible concepts were deleted from further consideration because either they had a low probability of development, and/or they were a major deviation from current technology, and/or the degree of anticipated behavioral improvement was minor.

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