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EVALUATION OF IMPROVED
LIGHT WATER REACTOR CORE DESIGNS

FINAL PROGRESS REPORT

September, 1979

MASTER

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1. Introduction

This is the final, and final monthly, report under the subject contract. In addition to summarizing work done since the last monthly report (1), a brief synopsis of all tasks investigated during the course of the project will be presented.

Primary documentation for all results resides in the topical reports issued by the project, copies of which are available through NTIS. Supporting efforts in the form of otherwise unpublished MIT theses are also available; a specimen order form is appended.

(1) LWRC-19, Evaluation of Improved Light Water Reactor Core Designs, Monthly Progress Report, August 1979.

2. Synopsis of Overall Project Effort

The precursor contract which evolved into the present effort began in May 1976 as one component under a block grant to the MIT Energy Laboratory by DOE (then ERDA). The initial focus was on re-evaluation of the use of thorium in light water reactors (obviously in the recycle mode). From the beginning the emphasis was on uniform lattices, as opposed to the seed-and-blanket configuration of the LWBR under development by Naval Reactors. Attention was also concentrated on performance improvements achievable through variation of the fuel-to-moderator ratio. Another feature of this early effort was the use of standard and tight-pitch PWR core designs on the uranium/plutonium cycle as benchmarks against which the thorium designs were to be evaluated. Finally, the prospective use of tight pitch cores also required an examination of thermal-hydraulic constraints on core performance to define an allowable envelope bounding the physics and fuel management investigations.

As the contract progressed, the evolution of national and international policy, as reflected in the NASAP and INFCE efforts, led to a parallel re-orientation in the relative emphasis placed on the various subtasks within the MIT project. Accordingly, over the last 18 or 20 months, attention has been re-focused on the once-through uranium cycle, on a wide spectrum of measures to reduce ore consumption, and on concepts having retro-fit capability. Since it was established early-on that today's fuel-to-moderator ratios were near optimum for this purpose, there was also a corresponding diminution in the attention given to thermal-hydraulic concerns..

This historical perspective must be appreciated if one is to extract a sense of purpose from the otherwise diverse series of subtasks reflected in the project's published record. Appendix A contains reproductions of the abstracts from major topical reports and theses completed under project sponsorship, and Appendix B is a more complete bibliography of all publications associated with the project's efforts. Some of the listed students were supported in whole or in part by project funds, while others were self (or foreign-government) supported.

Although both general and specific conclusions are presented in the reports, theses and publications listed in Appendices A and B, it is of some use to review some of the major findings here, if for no other reason than to provide an overview. In retrospect, the following points now appear to have the greatest significance:

- (1) The effort to improve upon ore utilization divides naturally into two almost diametrically opposite strategies depending on whether the recycle or once-through modes are to be employed:

in the former case tight-pitch cores and only moderate discharge burnups are to be preferred (Correa)*; while in the latter case, conventional lattice designs and long burnup are optimal (Fujita).

- (2) Thus, thermal-hydraulic considerations (and the necessary plant redesign) are only of concern if advanced recycle cores are contemplated. For programmatic reasons alone this area would only be of long term interest--following extensive experience with recycle into more conventional cores. We can therefore separate discussion of these aspects from the more immediately interesting topic of improving ore utilization of the once-through fuel cycle.
- (3) In the once-through mode the most productive approach to increasing ore utilization lies in increasing fuel burnup and the number of staggered batches in the core; additional improvements can be achieved by the careful accretion of savings from a large number of changes in core design, material composition and operating strategy.
- (4) In particular, the use of routine coastdown (Driscoll et al.) and axial blankets (Kamal) give modest, but easily-realized improvements. (The verdict is still out on radial blankets for PWRs.)
- (5) If and when recycle becomes of interest, tight-pitch plutonium-uranium cores appear to be able to compete successfully with U-233-thorium cores in terms of conversion ratio (Correa) and fuel cycle economics (Abbaspour). A weakly negative temperature/void coefficient may pose difficulties, however.
- (6) As regards economics (Abbaspour), the objectives of ore conservation and lowest fuel cycle cost are generally compatible, particularly for the once-through cycle. Tight pitch cores show little overall short-term economic incentives (or disincentive) (Correa). In the long term the lower cost of ore should be taken into account: a start on characterization of this relationship has been made (Ghahramani).
- (7) Although most of the effort was focused on individual reactor performance, some overall system's considerations were investigated (Garel). The main finding was that reactor inventory could play a dominant role in a rapidly growing nuclear economy. Recent experience, however, suggests that growth will be slow enough to mitigate this concern. Another

*Names in parentheses refer to principal authors of topical reports and theses dealing with the points at issue.

important finding (Abbaspour) was that system costs should be considered (instead of merely the fuel component), since refueling downtime and replacement costs shift the optimum burnup toward higher values for both the once-through and recycle modes. A related negative consideration is that the same driving force may motivate utilities to adopt 18 month refueling intervals instead of increasing the number of staggered fuel batches in the core. This would reduce the savings achieved by increasing fuel discharge burnup.

Concurrent with core physics and fuel management investigations of tight pitch cores in the recycle mode, an investigation of the thermal-hydraulics has also been conducted. Preliminary parametric studies indicated that decreasing the pitch affected the core pressure drop more than either MDNBR or fuel centerline temperature. WABCORE, a single channel thermal-hydraulics code, was developed for the purpose of investigating tight pitch lattices (Boyd). Various schemes for reducing P/D were analyzed, resulting in a better understanding of the interrelationships between geometric and thermal-hydraulic parameters. A design study on the thermal-hydraulics of ultra-tight pitch cores was performed, resulting in an optimized core design which could be substituted into an existing PWR with some modification (Griggs). A transient analysis of the optimized ultra-tight core was performed for a loss of plant power with failure to scram (Sigg). This analysis was performed with the loop code RELAP3B and gave insight into the impact of the new core design on the accident behavior of a tight-pitch plant. A LOCA analysis of the ultra-tight pitch core was considered for inclusion in the design study, but proved to be cost prohibitive. Work was done to find a simple relationship among basic core design parameters such as MDNBR, pressure drop, temperature rise, fuel rod diameter and core length which could then be used in assessing new core designs. Data was generated for this purpose by the WABCORE code, and curve fits to the simple expressions were performed.

In conclusion, the work conducted under this research project has developed information which supports in all respects the U.S. position evolved under the NASAP/INFCE programs with respect to the near and intermediate term potential for ore conservation in LWRs on the once-through fuel cycle. Moreover, in the even longer term, we have confirmed that contention by Edlund and others that tight-pitch Pu/VO₂ PWR cores can achieve conversion ratios which may allow these reactors to provide a competitive energy source far into the ore-scarce post-2000 era.

Some work necessarily remains undone. Refinement of various leads uncovered in the current studies are recommended, particularly with respect to the use of blankets on PWRs; and, in addition, a continued effort to effect cycle reactivity control without the use of control poison should be made, since therein lies one of the greatest potentials for further ore savings.

3. Axial Power Shaping (September '79 Results)

The axial blanket calculations reported in last month's progress report have been improved upon by using a more representative end-zone composition containing stainless steel to account for core structure. As expected, lowering the reference case albedo by introducing more stainless steel (replacing Zircaloy) results in an enhancement of blanket ore savings.

Figure 3.1 shows the cases examined: the new reference case (Ref. Case II--to distinguish it from the prior reference case using Zircaloy in the end-zone), Blanket Case I which has 6" natural UO₂ axial blanket inserts, and Case II in which the displaced U-235 is re-distributed in the central fuel zone (to simulate calculational procedures used by other investigators).

Table 3.1 gives the ore utilization results. As can be seen, savings of 2.6 to 3.6% are now predicted, in good agreement with the values quoted by others.

Several points are worthy of note:

- (1) The change from ~2.5% more (last month) to ~2.6% less ore (this month) for Zircaloy vs Stainless Steel end structure shows the sensitivity of the results to composition, and hence the need for careful attention to reflector modeling.
- (2) We did not account for banked control poison in the end-zone above the core on the advice that the rods were 6" above the active fuel. If there is an effect it would be to further enhance the ore savings when blankets are used. This aspect deserves further examination on a case-by-case basis.
- (3) Case (5), in which an analytic correction for U-235 mass is made, and Case(6) in which U-235 mass was actually preserved in the PDQ calculations, show a difference of ~1% in savings. This demonstrates a need for careful attention to methodology in evaluating small design changes.

It is concluded that the use of axial blankets is an effective and easily implemented means to conserve on ore consumption in PWR's. Additional productive work could be done in the following areas:

- (1) variation of blanket thickness to find an optimum
- (2) use of more sophisticated k-averaging methods to evaluate the savings (see August monthly, for example)
- (3) use of multigroup transport calculations to confirm the end-zone albedos and reactivity changes for the reference and blanketed cases
- (4) investigation of non-fuel blankets, such as beryllium metal slugs.

Fig. 3.1 Cases Examined

- Composition 1: 3.0% enriched U-235, as UO_2
Composition 2: 3.218% enriched U-235, as UO_2
Composition 3: Natural Uranium dioxide (Blanket)
Composition 4: (New) Structure - 50% Stainless Steel,
50% borated water.

Key Characteristics:

Blanket Case I: For this case the ore requirement is 7.1% less than, the U-235 content is 6.6% less than, and the total heavy metal requirement is equal to, the reference case.

Blanket Case II: For this case the ore requirement, the U-235 content, and the total heavy metal requirement, are all equal to the reference case.

Table 3.1
Ore Usage Results

<u>Condition*</u>	<u>Ratio: (U*/U_{II})</u>	<u>% ore savings relative to Reference Case II</u>
BLANKET CASE I:		
1. Same batch heavy metal content (as run in PDQ-7)	0.9703	2.96%
2. Same efph	0.9727	2.73%
3. Same ore/batch (or <u>total</u> U-235 use)	0.9742	2.58%
4. Same burnup	0.9728	2.72%
5. Same U-235 mass charged	0.9742	2.58%
BLANKET CASE II:		
6. Same batch heavy metal content (as run in PDQ-7)	0.9637	3.63%

* See August 1979 monthly for details of the methodology used to calculate these numbers.

4. Administrative Items

The attached table summarizes the status as of 9/30/79 of project expenditures. Since a no-cost extension to permit completion of documentation was negotiated, the figures quoted under cumulative headings are not yet final.

Personnel participating in the project, including all predecessor accounts, have been as follows:

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K. Garel, Research Assistant, ScD Thesis Student
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M. Massoud, Special Graduate Project
M. Plys, Undergraduate Research Project
A. Salehi, ScD Thesis
J. Sefcik, Research Assistant, ScD Thesis Student
D. Sigg, SM Thesis student

Appendix A

Abstracts of Major Topical Reports and Theses

Abstracts removed

The following compilation contains abstracts of the topical reports and major theses issued under project auspices. All topical reports are also available as theses, submitted by the principal author in each instance. Topical reports are available from NTIS; theses are available from MIT under arrangements as specified in the attached order form.

Not abstracted here are two theses still in the rough-draft stage:

A. Kamal

"The Effects of Axial Power Shaping on Ore Utilization in PWRs" (tent.)

SM Thesis, MIT Nuclear Engineering Dept., Nov. 1979 (est.)

D. Griggs

"Steady State and Transient Thermal-Hydraulic Design of an Ultra-Tight Pitch Pressurized Water Reactor Core" (tent.)

Nucl. Eng. Thesis, MIT Nuclear Eng. Dept., Nov. 1979 (est.)

These theses will be available shortly after submission under the same conditions as the other unpublished MIT theses listed here.

Appendix B

Bibliography of Publications

The compilation below lists, under several categories, publications of work associated in whole, or in part, with project efforts.

A total of some 22 progress reports, initially on a quarterly, and later on a monthly basis were also issued. However, no formal compilation of these documents has been published subsequent to their issue-by-issue distribution. Moreover, it is recommended that topical reports be relied upon as the final word on the status of all findings.

1. Major Topical Reports

- (1) Salehi, A. A., M.J. Driscoll, and O.L. Deutsch, "Resonance Region Neutronics of Unit Cells in Fast and Thermal Reactors," COO-2250-26, MITNE-200, May 1977.
- (2) Garel, K.C. and M.J. Driscoll, "Fuel Cycle Optimization of Thorium and Uranium Fueled PWR Systems," MIT-EL-77-108, MITNE-204, October 1977.
- (3) Fujita, E.K., M.J. Driscoll and D.D. Lanning, "Design and Fuel Management of PWR Cores to Optimize the Once-Through Fuel Cycle," MIT-EL-78-017, COO-4570-4, MITNE-214, August 1978.
- (4) Abbaspour, A.T. and M.J. Driscoll, "The Fuel Cycle Economics of Improved Uranium Utilization in Light Water Reactors," MIT-EL-79-001, COO-4570-9, MITNE-224, January 1979.
- (5) Correa, F., M.J. Driscoll and D.D. Lanning, "An Evaluation of Tight-Pitch PWR Cores," MIT-EL-79-022, COO-4570-10, MITNE-227, August 1979.

2. Doctoral Theses

- (1) Salehi, A.A., "Resonance Region Neutronics of Unit Cells in Fast and Thermal Reactors," May 1977.
- (2) Abtahi, F., "Out-of-Reactor Aspects of Thorium Utilization in Light Water Reactors," July 1977.
- (3) Garel, K.C., "Fuel Cycle Optimization of Thorium- and Uranium-Fueled PWR Systems," October 1977.
- (4) Fujita, E., "Design and Fuel Management of PWR Cores to Optimize the Once-Through Fuel Cycle," August 1978.

- (5) Correa, F., "An Evaluation of Tight-Pitch PWR Cores," August 1979.

3. SM and Nucl. Eng. Theses

- (1) Atefi, B. "Specific Inventory and Ore Usage Correlations for Pressurized Water Reactors," May 1977.
- (2) Boyd, W.A. "Thermal-Hydraulic Analysis of Tight-Lattice Light Water Reactors," May 1977.
- (3) Chen, R., "A Simple Model for Analysis of LWR Fuel Cycle Economics," May 1977.
- (4) Beard, C.L., "An Improved Long-Range Fuel Management Program," May 1978.
- (5) Ghahramani, K., "An Analysis of Prospective Nuclear Fuel Cycle Economics," August 1978.
- (6) Sigg, D.R. "Analysis of ATWS in a Tight-Pitched Thorium Fueled PWR," September 1978.
- (7) Abbaspour, A.T.m "The Fuel Cycle Economics of Improved Uranium Utilization in Light Water Reactors," January 1979.
- (8) Kamal, A., "The Effect of Axial Power Shaping on Ore Utilization in PWRs" (tent.), expected November 1979.
- (9) Griggs, D., "Steady State and Transient Thermal-Hydraulic Design of an Ultra-Tight Pitch Pressurized Water Reactor," (tent.), est. November 1979.

4. Other Publications

- (1) Aminfar, H., M.J. Driscoll and A.A. Salehi, "Use of Fast Reactor Methods to Generate Few Group Cross Sections for Thermal Reactors," Proceedings ANS Topical Meeting, Advances in Reactor Physics, Gatlinburg, Tennessee, April 1978.
- (2) Ghahramani, K. and M.J. Driscoll, "Ore Price Escalation in Fuel Cycle Economic Analyses," Trans. Am. Nuc. Soc. 28, 383, June 1978.
- (3) Driscoll, M.J., E.K. Fujita, and D.D. Lanning, "Improvement of PWR's on the Once-Through Fuel Cycle" (invited paper), Trans. Am. Nuc. Soc. 30, Nov. 1978.
- (4) Driscoll, M.J., et al., "Routine Coastdown in LWRs as an Ore Conservation Measure," Trans. Am. Nuc. Soc. (in press), November, 1979.
- (5) Driscoll, M.J. and F. Correa, "The Reactor Physics of Tight-Pitch PWR Cores," (invited paper) Trans. Am. Nuc. Soc. (in press), November 1979.

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October 31, 1979

MEMORANDUM

TO: External and Internal Distribution
FROM: M. J. Driscoll *mjd*
SUBJECT: Final Progress Report, September 1979,
"Evaluation of Improved Light Water Reactor
Core Designs"

The enclosed report summarizes the research carried out on the evaluation of improved LWR's carried out within the MIT Department of Nuclear Engineering through the MIT Energy Laboratory, under DOE contract.

Comments and questions should be addressed to:

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