AIM

Association for Information and Image Management

1100 Wayne Avenue, Suite 1100
Silver Spring, Maryland 20910

301/587-8202

Centimeter

Inches

MANUFACTURED TO AIM STANDARDS
BY APPLIED IMAGE, INC.

1 of 1

OFFICIALS

RL-REA-663

DATE _____

February 15, 1965

GENERAL ELECTRIC

HANFORD ATOMIC PRODUCTS OPERATION - RICHLAND, WASHINGTON

X

THIS CURRENT CONTAINS RESTRICTED DATA
DEFINED BY ATTILIO PERAZZOLI 354
ITS DISCLOSURE OF THE SOURCE OF ITS
CONTENTS TO ANY OTHER PERSON AUTHORIZED
PERSONNEL PROHIBITED.

TITLE

TECHNICAL FEASIBILITY OF USING URANIUM OXIDE FUELS AT HANFORD

7

OTHER OFFICIAL CLASSIFIED INFORMATION

THIS MATERIAL CONTAINS INFORMATION AFFECTING THE NATIONAL DEFENSE OF THE UNITED STATES WITHIN THE MEANING OF THE ESPIONAGE LAWS, TITLE 18, U. S. C. , SECS. 793 AND 794, THE TRANSMISSION OR REVELATION OF WHICH IN ANY MANNER TO AN UNAUTHORIZED PERSON IS PROHIBITED BY LAW.

AUTHOR

Engineering Staffs of

IPD

NRD

CPD

ISSUING FILE

THIS DOCUMENT MUST NOT BE LEFT UNATTENDED OR WHERE AN UNAUTHORIZED PERSON MAY HAVE ACCESS TO IT. WHEN NOT IN USE, IT MUST BE STORED IN AN APPROVED LOCKED REPOSITORY WITHIN AN APPROVED GUARDED AREA. WHILE IN YOUR POSSESSION AND UNTIL YOU HAVE OBTAINED A SIGNED RECEIPT FROM COMSISD FILES, IT IS YOUR RESPONSIBILITY TO KEEP IT AND ITS CONTENTS WITHIN THE LIMIT OF THIS PROJECT AND FROM ANY UNAUTHORIZED PERSON. ITS TRANSMITTAL TO AND STORAGE AT YOUR PLACE OF RESIDENCE IS PROHIBITED. IT IS NOT TO BE DUPLICATED. IF ADDITIONAL COPIES ARE REQUIRED OBTAIN THEM FROM THE RELATED ASSIGNED FILE. ALL PERSONS READING THIS DOCUMENT ARE REQUESTED TO SIGN IN THE SPACE PROVIDED BELOW.

ROUTE TO:

PAYROLL NO.

LOCATION

FILE	ROUTE	DATE
100-443888-100	100-443888-100	100-443888-100

SIGNATURE AND DATE

R. E. Weinman

30616

BNW3-20

2-24-65

MASTER

54-3000-340 (3-57) AEC-GE RICHLAND, WASH.

(CLASSIFICATION)

THE

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DECLASSIFIED

RL-REA-663

This document contains restricted data and its transmission or disclosure of its contents in any manner to an unauthorized person is prohibited.

This document consists of
35 pages.

TECHNICAL FEASIBILITY OF USING URANIUM OXIDE

FUELS AT HANFORD

Classification Cancelled and Changed To

DECLASSIFIED

By

By Authority of DS Lewis,
CG-NMP-1, 5-3-94
By D. K. Hanson, 5-23-94
Verified By Jerri Mally,
5-27-94

Engineering Staffs of:

Irradiation Processing Department
N-Reactor Department
Chemical Processing Department

February 15, 1965

HANFORD ATOMIC PRODUCTS OPERATION
RICHLAND, WASHINGTON

NOTICE

This report was prepared for use within General Electric Company in the course of work under Atomic Energy Commission Contract AT(45-1) - 1350, and any views or opinions expressed in the report are those of the author only. This report is subject to revision upon collection of additional data.

LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:

- A. Makes any warranty or representation, expressed or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or
- B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission, or employee of such contractor, to the extent that such employee or contractor of the Commission, or employee of such contractor prepares, disseminates, or provides access to, any information pursuant to his employment or contract with the Commission, or his employment with such contractor.

DECLASSIFIED

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISTRIBUTION

1-6. AEC-RLOO: Attn: JE Travis	43. L. E. Kusler
7. F. W. Albaugh / BNW	44. L. W. Lang / BNW
8. T. W. Ambrose	45. M. C. Leverett
9. R. S. Bell	46. C. G. Lewis
10. W. A. Blanton	47. M. Lewis
11. C. E. Bowers	48. A. R. Maguire
12. P. A. Carlson	49. J. W. McCurry
13. D. L. Condotta	50. J. S. McMahon
14. R. A. Connell	51. R. W. McMichael
15. D. W. Constable	52. J. Milne
16. F. G. Dawson, Jr. / BNW	53. W. S. Nechodom
17. D. R. DeHalas / BNW	54. R. Nilson
18. R. L. Dickeman	55. G. F. Owsley
19. K. Drumheller / BNW	56. R. S. Peterson
20. R. E. Dunn	57. A. M. Platt / BNW
21. E. A. Eschbach / BNW	58. H. C. Rathvon
22. T. W. Evans	59. R. W. Reid
23. J. B. Fecht	60. J. W. Riches
24. W. J. Ferguson	61. W. E. Roake / BNW
25. N. F. Fifer	62. C. A. Rohrmann / BNW
26. E. J. Filip	63. A. Russell
27. G. C. Fullmer	64. O. C. Schroeder
28. S. M. Graves	65. A. J. Scott
29. O. H. Greager	66. H. P. Shaw
30. A. B. Greninger	67. H. G. Spencer
31. K. G. Grimm	68. D. R. Stenquist
32. C. N. Gross	69. J. T. Stringer
33. R. O. Gumprecht	70. W. H. Swift / BNW
34. M. K. Harmon	71. R. E. Tomlinson
35. W. M. Harty	72. A. D. Vaughn
36. H. W. Heacock	73. M. T. Walling, Jr. / BNW
37. R. E. Heineman / BNW	74. J. H. Warren
38. P. L. Hofmann / BNW	75. W. K. Woods
39. D. L. Hovorka	76. J. R. Young
40. R. E. Isaacson	77. L. L. Zahn
41. R. T. Jessen	78. 700 Files
42. W. E. Johnson	79. Records Center
	80.-82. Extra

DECLASSIFIED

TABLE OF CONTENTS

	<u>Page</u>
I. INTRODUCTION	5
II. SUMMARY AND CONCLUSIONS	5
III. K AND SMALL REACTORS	7
A. REACTOR PHYSICS	7
1. Qualitative Physics Aspects of Uranium Oxide Fuel in the K and Small Reactors	7
a. No Channel Enlargement	7
b. Channel Enlargement	8
2. Key Factors Affecting Feasibility	9
a. Total Control	9
b. Speed-of-Control	12
3. Production Capability	16
B. REACTOR ENGINEERING	17
1. Reactor Safety Considerations	17
a. Local Fuel Burnout	17
b. Instability Limits	17
c. Coolant Backup	18
2. Economics and Reactor Life	19
a. Fuel Performance	19
b. Graphite Temperature Considerations	20
c. Bulk Temperature Limits	23

DECLASSIFIED

TABLE OF CONTENTS (cont'd.)

	<u>Page</u>
3. Fuel Fabrication	23
a. Density Requirements	23
b. Uranium Oxide Specification	23
c. Fabrication Techniques	24
4. Uranium Oxide Fuel Handling	25
a. Storage	25
b. Shipment	26
c. Charge-Discharge	26
5. Reactor Modification	27
IV. N-REACTOR	27
A. PHYSICS ASPECTS	27
1. Operational Reactor Transients	27
a. Feed Enrichment	27
b. Cold Xenon-Free Reactivity and Operational Reactivity Transients	28
2. Reactivity Behavior Under Accident Conditions (Total Control)	28
a. Cold Water Injection	28
b. Graphite Stack Flooding	28
c. Primary Coolant Loss	29
3. Reactivity Behavior Under Accident Conditions (Speed-of-Control)	29
B. EFFECT ON PRODUCTION FLEXIBILITY	30
C. PERFORMANCE OF URANIUM OXIDE FUELS IN N REACTOR	30
V. CHEMICAL PROCESSING	32
VI. REFERENCES	35

DECLASSIFIED

TECHNICAL FEASIBILITY OF USING URANIUM OXIDE FUELS AT HANFORDI. INTRODUCTION

The use of uranium oxide fuel and the dispensing with metallic fuel elements in the Hanford production reactors have been contemplated in the past but have not been examined in any detail. This report reviews the technical feasibility of using oxide fuel and discusses the reactor limitations and changes in plutonium and isotope production. These results are based on preliminary calculations and a research and development program would be required to establish the validity of the calculated values. The research and development program which is discussed in greater detail in Reference 1* is estimated to require \$3.6 million over a three-year period, however, this time schedule may be shortened if early development efforts produce favorable results.

Technical aspects of using oxide are discussed in general for N, K, and the smaller reactors. The variations in uranium-to-graphite weight ratio and operating conditions vary the limitations encountered with each reactor type with an oxide fuel cycle. Plutonium separation and uranium oxide recycle on site have been examined, and a technical review of the limitations and the additional process requirements are presented.

The economic aspects of using uranium oxide and closing the fuel cycle on site have not been addressed and are considered beyond the scope of this report.

II. SUMMARY AND CONCLUSIONS

Reactor operating and safety characteristics differ considerably when the loading is converted from metallic uranium fuel to uranium oxide fuel. Physics was thought to be the principal determining factor in the technical feasibility of using uranium oxide. Preliminary calculations and study, however, indicate that despite the severer reactivity transients, the nonoverbored K and small reactors are not precluded from oxide fuel utilization by physics considerations. This conclusion, based on more recent detailed calculations, is opposite to earlier ones and, if proved correct by experiment, represents a possible method of operation. Significant additional control (20 to 30 mk) would be needed to meet total control requirements in the event of coolant loss and to provide adequate control during reactor startup. This additional control could be provided by splines.

The area of greatest concern is that of graphite temperatures which, with a 100 per cent helium atmosphere, are estimated to increase by 100 to 300 C with uranium oxide fuel. The higher temperature range is expected at the K Reactors and the lower range at the smaller reactors. Operation at these higher temperatures may be possible, however, continued development would be required to define the water vapor-graphite reaction rate, and higher

* See Section VI - References.

DECLASSIFIED

reactor gas dryer system efficiency would be mandatory. The rate of irradiation induced contraction at these graphite temperatures is not well known, and some investigation in this area would be required.

Production of weapons-grade plutonium would be reduced 15 to 20 per cent, and the flexibility of using fuel target type loadings would be reduced because further uranium reduction in the reactor may not be feasible without reactor modifications.

Channel enlargement would overcome the graphite temperature, reactor safety, plutonium yield, and reactor flexibility disadvantages posed with the irradiation of uranium oxide in the present reactor lattice. The uranium-to-graphite weight ratio can be increased to where conversion values for weapons-grade plutonium are five per cent greater than present values, and graphite temperatures would be reduced to the range encountered in today's operation. Reactivity transients become more negative, and a reactivity fail-safe lattice upon coolant loss can be achieved. Flexibility for using uranium oxide co-product loadings would be superior to uranium oxide loadings without overboring.

The technical feasibility of using uranium oxide fuel for production of weapons-grade products in N-Reactor is reasonably assured. Review of the technical aspects of fuel fabrication, in-reactor fuel performance and reactor safety revealed no problems of technical feasibility that could not be solved by a modest incremental research and development program. Demonstration of practical feasibility would require about two years at which time full scale fuel production could begin. Complete conversion to an oxide cycle could be accomplished within three years; however, if the incentive to accelerate conversion was larger it is probable that this schedule could be bettered through appropriate priorities and level of effort.

Conversion of N-Reactor to an oxide fuel cycle would result in a decrease in weapons-grade plutonium production and a sizeable increase in product cost for this case. However, the total quantity of weapons-grade product (plutonium plus tritium) would be approximately that produced in N-Reactor with the uranium metal fuel, co-product case, and have approximately the same unit cost for the combined products.

In addition, our preliminary studies indicate that the oxide fuel cycle may expand the flexibility of N-Reactor to supply Commission requirements for high exposure plutonium; Np-237, Pu-238, Po-210, or combinations of these nonweapons materials either concurrently or in the absence of weapons material production.

Chemical processes required for a closed uranium oxide fuel cycle have been demonstrated. The existing Purex plant could be used for chemical separation, and the existing UO₃ plant for conversion of uranium to the oxide form. Other required processing operations, not presently in place, could be provided based on processes that are in use on a production basis at other sites. While the technical feasibility of the chemical processes is assured, the production capacity of existing facilities is a consideration that remains to be assessed.

DECLASSIFIED

III. K AND SMALL REACTORS

A. REACTOR PHYSICS

Physics is one of the principal determining factors of the technical feasibility for using UO_2 fuel in the graphite-moderated Hanford reactors. The operating and safety characteristics of the present reactors fueled with uranium oxide would differ considerably from the present loadings. Accident reactivity transients are expected to be severer; so severe in certain circumstances, that a cursory safety review would tend to rule out UO_2 fuel altogether.

However, avenues do exist which can make uranium oxide-graphite lattices produce as efficiently (or even more efficiently) than the present metal-graphite lattices and, at the same time, operate as safely (or safer). The obvious avenue is overboring, which was proved feasible in the C Reactor a few years ago; the compensating physics factors resulting from such a modification are discussed later.

Recent calculations (looking considerably beyond the cursory safety reviews of the past) indicate that, despite the increased reactivity transients, the uranium oxide-graphite lattice can meet our safety criteria in K and small reactors without overboring. This conclusion is opposite to earlier ones and, if proved correct by experiment, represents an acceptable method of operation from a physics standpoint.

1. Qualitative Physics Aspects of Uranium Oxide Fuel in K and Small Reactors

a. No Channel Enlargement

Without enlarging process tubes, the use of uranium oxide fuel in the K and small reactors means a reduction in the fuel-to-moderator ratio of the reactor. The reactors, being already overmoderated, become further overmoderated, and would gain considerably more reactivity upon coolant loss than at present. Calculations indicate about a two-fold increase in the integral void coefficient.

The Doppler coefficient will remain negative but will be about 30 per cent lower in magnitude; however, the Doppler defect will be about doubled due to the higher fuel temperature. Calculations show that the positive graphite temperature coefficient becomes smaller, but, due to higher expected graphite temperatures, the reactivity contribution from graphite heating should be approximately the same as when using metallic uranium.

DECLASSIFIED

Short-term reactivity losses, such as from xenon, samarium, and neptunium holdup, are expected to be slightly greater. In general, the excess reactivity needed to sustain the net short-term reactivity loss should be higher by about 10 mk. The net long-term effect due to burnup and buildup is expected to be considerably less positive, principally due to the higher U-235 content in the fuel; in the B, D, and C Reactors, the long-term effect may actually be a loss. Poison compensation for the long-term effects will thus be less of a problem than in the uranium metal reactor loadings. The more negative short-term reactivity transient should be beneficial to reactor safety; the familiar turnaround peak following reactor startup will not be present. Thus, following critical and during ascension to equilibrium operation, poison will never have to be inserted, but can continually be removed to keep up with a monotonically decreasing reactivity transient. Poison removal rates are slow, however, and the effect of removing large amounts of supplemental control will reduce startup efficiency.

None of the aforementioned operational reactivity effects rule out the technical feasibility of uranium oxide fuel. Upon close evaluation, the greater void coefficient turns out not to be an obstacle; additional discussion is given in a later section on the problems of operating the reactors under such circumstances.

b. Channel Enlargement

By enlarging the channels of the reactors, additional fuel space is provided, and the uranium-to-graphite weight ratio with uranium oxide fuel can be returned to or beyond the present values. This has two important consequences: (1) plutonium conversion is restored or improved, and (2) the autocatalytic nature of the lattice on coolant loss is significantly moderated or even eliminated. Short-term and long-term reactivity transients become more negative, meaning increased efficiency losses, but safer operation. Thus, feasibility from a physics standpoint is readily assured, and the effort required to determine physics parameters important to a hazards review would be significantly less than in the case where uranium oxide fuel were used without overboring.

A third advantage of channel enlargement is that the flexibility of the reactors, after such a modification, is increased; preliminary evaluations of the possibility of co-product loadings using oxide fuel in the present reactor lattice are not encouraging. Such loadings would require removal of uranium from the reactor which further overmoderates the reactors -- the unsafe direction insofar as the coolant-loss accident is concerned.

DECLASSIFIED

2. Key Factors Affecting Feasibility

From the preceding discussion, it appears that the use of uranium oxide fuel in the K and small reactors is readily feasible from a physics standpoint if the reactors are overbored. In other words, if essentially the same degree of moderation presently existing is preserved.

The question of whether oxide fuel can be safely used without overboring is an important one, particularly in the K Reactors. The key physics factor involved is the ability of the reactors to continue meeting long-established control criteria in the event of the worst accident, namely loss of coolant. As previously stated, overboring solves this problem automatically in either reducing the void coefficient or in reversing its sign.

To permit an answer to the feasibility question without overboring requires detailed evaluation. This has been done, and the remaining portions of this section pertain to these evaluations. The results are entirely theoretical but are related to past experience with metal loadings. Despite purposeful conservatism in the calculations, many of the assumptions and theoretical factors employed must be tested by experiment and, of course, formal ACRS review and approval would be required before such a reactor modification could be considered. This is particularly true since, on the surface, the use of uranium oxide in reactors appears less reactivity fail-safe than the reactors with metallic uranium loadings upon loss of coolant.

a. Total Control

In the K and small reactors, the highest potential reactivity state is that associated with the dry, uncooled reactor. The possibility that the reactor coolant supply (including its backup provisions) will fail is extremely remote. However, it is still considered necessary to stipulate nuclear control requirements under dry-reactor conditions to accommodate the loss-of-coolant accident and to ensure that the consequences of such an accident would not be made more serious by a failure to provide the required nuclear control capacity.

The philosophy of control in the event of coolant loss is expressed in two criteria, one related to control response (discussed later) and one related to required control strength. This latter criterion is expressed as follows:

DECLASSIFIED

The operation of the Hanford reactors shall be such that in the event of any credible combination of events, and including complete, permanent loss of coolant, the total control strength will be sufficient to ensure that no reactivity state will develop which would significantly increase the consequences of the accident.

With respect to the complete loss-of-coolant accident which provides the limiting case, the present interpretation of the criterion is that no reactivity state will be permitted to develop in the dry reactor (after the scram and any excursion which may have accompanied the accident) which would decrease the probability of restoring coolant to the reactor. For example, a delayed neutron critical state would not be permitted until a significant number of process tubes had been rendered useless as coolant channels. A prompt critical state, if prevented at time of coolant loss, has been shown to be not possible at any later time.

Two factors must be considered in evaluating compliance with the Total Control Criterion: (1) the effective strength of the safety control system, and (2) the effective excess reactivity of the reactor at all times between coolant loss and the time when the process tubes are blocked, either by melting themselves or by fuel melting if the process tubes melt at a higher temperature than the fuel. Only the gravity-driven, semi-fluid, Ball 3X system is considered scammable from a total control standpoint. If calculations indicate that the strength of the Ball 3X system is not adequate to fulfill the control requirements, the system must be supplemented by other poisons which must have been inserted in the reactor prior to the accident to be considered in meeting total control.

The characteristics which will be different in the uranium oxide-fueled reactor and which have important bearing on the total control question are as follows:

- a. The positive void coefficient (cold) is about twice as large in the uranium oxide lattice (nonoverbored). This means a much higher reactivity to be controlled in the dry reactor.
- b. The short-term reactivity losses are about 10 mk higher in the uranium oxide reactor. This means a higher excess cold, clean reactivity is needed in the oxide reactor. This additional reactivity also adds to the dry-reactor reactivity, thus further increasing the control requirements in the dry reactor.

DECLASSIFIED

- c. In the case of the Zircaloy-tubed K Reactors, the dry reactor would have to be held subcritical for a longer time before tube blockage. With metal fuel, restoration of coolant would not be practical beyond uranium melting (1133 C); with oxide fuel, it may be prudent to hold the reactor subcritical until zirconium melting (1900 C). In the small reactors tubed with aluminum, the point at which total control could be relinquished would be no different with either metal or oxide fuel -- 660 C, the melting point of aluminum.
- d. Uranium oxide melts at (2750 C) a temperature considerably higher than any control elements presently in use in the reactors. Thus, during a meltdown, the eventual permanent poisoning effect of fuel melting and redistribution in the graphite stack (if the fuel is oxide) may well have been preceded by melting of the controls. It may be necessary to replace the boron-steel balls of the 3X safety system with ceramic balls containing rare earth poisons similar to those presently used in N Reactor. There are other incentives for such a changeout, and the cost would not be prohibitive. Also, splines would have to be redesigned with higher-melting carrier material, since they are presently aluminum alloyed.
- e. The worth of control elements in the oxide lattice is augmented by the fact that the oxide lattice is less black to neutrons, thus giving the control elements a more favorable competition for neutrons. The increase in nuclear strength is conservatively estimated at 25 per cent.

The first four characteristics are unfavorable to the meeting of total control in the oxide reactor; the last one is favorable. Combining all effects into a detailed control evaluation shows that, despite the significantly increased reactivity of the dry reactor and the delay in permanent poisoning due to the higher melting temperature of oxide fuel, total control can be met in any of the reactors fueled with oxide without overboring. The additional total control could be provided by splines; a supplemental control technique presently in common use. Control materials of higher melting temperatures could be substituted for present ones.

DECLASSIFIED

The supplemental control to meet total control requirements will be greatly in excess of those now required, and for at least B and D Reactors, supplemental control requirements may be so great for high fuel exposure cases (>500 MWD/T) that the wet reactor could not go critical. Thus, these may be an upper limit on average fuel exposure in these reactors; however, fuel charging and discharging can be staggered to keep average fuel exposures well under 500 MWD/T (goal is 700 MWD/T for oxide fuel). The supplemental control requirements for total control are not inconsistent with the extra control required during reactor startup to supplement the hold-down strength of control rods after safety rods are withdrawn. The calculated startup supplemental control requirements are about 25 mk for the reactors. This much reactivity held in supplemental control represents over 150 splines. At current spline removal rates of 15 per hour, about 10 hours would be required to remove these poisons or the reactor approached an equilibrium reactivity status resulting in some startup inefficiency.

b. Speed-of-Control

Loss of coolant to an entire Hanford production reactor while the reactor is operating at equilibrium power is the accident which has the greatest potential for a catastrophic excursion. Under most conditions of fuel exposure and reactor temperature, the loss of water introduces an increase in reactivity. Termination of any nuclear excursion associated with the accident must be rapid enough to prevent fuel melting while there is any possible means, for example, by the violent expulsion of water by boiling, to transport fission products outside of the reactor in a puff discharge. The importance of the Speed-of-Control Criterion lies in the fact that its compliance represents the best control guarantee available that any excursion, including the one induced by rapid coolant loss, would be terminated with the minimum amount of off site consequences.

The criterion is stated as follows:

The operation of the Hanford reactors shall be such that in the event of a power excursion resulting from any credible combination of events, and including complete and permanent loss of coolant, the response of the reactor safety control system (vertical safety rods) shall be sufficient to ensure that no energy state will develop during the excursion which would significantly increase the consequences of the accident.

DECLASSIFIED

Specifically, the criterion is interpreted as follows: the energy generated in the excursion shall be insufficient to cause the surface temperature of a fuel element at any point in the reactor to reach the melting point of uranium until the power generation at that point returns to its preaccident value. Intent of adherence to the criterion is to minimize the release of fission products from the reactor and the interpretation is believed to be consistent with this intent. Some fission products which may be present in the aluminum jackets and bond layers of the fuel elements or which may be oxidized off bared uranium surfaces may be swept down the process tube channels by the expulsion of the steam-water mixture during the boilout phase of the excursion. But, without uranium melting, the fraction of fission products removed will be very small and any actually removed will very likely be trapped in exit piping.

It is felt that for an accident of this type to occur, an earthquake of intensity of MM-8 or more would be required. Earthquakes of the required intensity are not considered credible in the Hanford area. Thus, these accidents fall in the "worst-conceivable" category. Nevertheless, the reactors are operated under exposure and power level limits (based on the Speed-of-Control Criterion) which seek to guarantee, even in the event of the worst loss-of-coolant accident, consequences which would not be significantly worsened beyond those resulting from the causative event alone.

Loss-of-coolant accident studies at Hanford to evaluate compliance to the Speed-of-Control Criterion have included simplifying assumptions which result in somewhat idealized cases and which represent compromises between possible real occurrences and theory. Analyses of the idealized loss-of-coolant at equilibrium operation assume (somewhat arbitrarily) that the fastest rate of coolant loss would be that resulting from a decrease in the inlet riser pressure to one-half of its initial value in one second. In addition, it is assumed that the Vertical Safety Rod System is the principal external shutdown mechanism and that the rod insertion times are not affected by the accident. After the reactor was made subcritical, heat from fission product decay would increase the temperature of reactor components above the uranium melting point. This would require one to two hours, depending on the power level at the time of the accident. Thus, the combined shutdown action of the safety rods and Doppler effect materially delays the fuel melting and prevents a

DECLASSIFIED

puff-type release of radioactive material. The ultimate outcome of such a "controlled" coolant-loss accident occurring during reactor operation would be a full-reactor meltdown. The meltdown would be in a subcritical reactor, however, and the release of fission products should occur nonviolently.

Many of the basic parameters pertinent to the speed-of-control problem following rapid coolant loss are altered by the use of oxide fuel. We consider here only the case in which uranium oxide is used in the reactors without overboring; there is little or no speed-of-control problem if the reactors are overbored.

- a. The positive void coefficient with uranium oxide under operating conditions is considerably larger than with a metallic uranium reactor. Thus, the driving force for an excursion is increased.
- b. The Doppler coefficient is reduced by about 30 per cent. This means less negative reactivity feedback from fuel heating during the excursion.
- c. The conductivity and heat capacity of uranium oxide relative to uranium metal combine to make the diffusivity of oxide about seven times smaller than for uranium. This results in a faster fuel heating rate (which is advantageous in Doppler effect but disadvantageous in shortening the time to melt) and a slower coolant boil-out rate.
- d. The worth of the safety rods in the oxide lattice is augmented by at least 25 per cent, as mentioned previously.
- e. The neutron lifetime is increased in the oxide lattice due to the reduced blackness. The neutrons also travel further before death (the migration area is increased by 25 per cent). These changes act to slow excursion rates and reduce localized peaking during an excursion.
- f. The effect of plutonium buildup on the delayed neutron fraction is smaller in the oxide lattice due to the better competition for neutrons by U-235 in the enriched fuel. Plutonium-239, having a smaller delayed neutron fraction, reduces the excess reactivity required for prompt critical.
- g. Uranium oxide melts at about 2750 C compared to about 1100 C for uranium. Thus, more energy must be generated during an excursion, all other things equal, to melt uranium oxide.

DECLASSIFIED

Some of the changes in basic parameters enumerated above are unfavorable to the meeting of the speed-of-control requirements. This is particularly true of the increase in the void coefficient; void coefficients as high as those computed for the oxide lattice are much higher than those now allowed for a metal fueled reactor. Several of the changes in basic parameters are favorable to the oxide reactor. The combined effect of lower diffusivity, stronger safety rods, increased neutron lifetime, and increased migration area all act to slow up the autocatalytic coolant-loss excursion sufficiently to permit emergency reactor shutdown within the requirements of the Speed-of-Control Criterion for void coefficients far in excess of those representative of metal lattices and also in excess of those calculated for the oxide lattices.

The calculations, whose details are given in another report², indicate meeting of speed-of-control requirements in K and the small reactors operating at current power levels, and without overboring, for the void coefficients listed below.

<u>Reactor</u>	<u>Power Level</u>	<u>Permitted Void Coefficient (Hot)</u>
K	4400 MW	+41 mk
B,D	2090 MW	+45 mk
C	2310 MW	+47 mk

Calculations indicate that the hot void coefficients (even at maximum exposure conditions) are smaller than the permitted values. For comparison, permitted void coefficients with metal fuel (for the same power levels assumed above) are about 20 mk for all reactors.

The void coefficients permitted for the various reactors relative to one another are the same as for metal fuel. The reason C Reactor can tolerate a higher void coefficient than the other small reactors is the fact that C Reactor has faster and stronger safety rods. The K Reactors have the fastest rods, but due to the larger size of the K Reactors the worth of their safety rods is lower. Other differences in the K Reactors which, together with the above differences, give the lowest permitted void coefficient of all the reactors, are a stronger Doppler coefficient, a shorter neutron lifetime, and a higher specific power. However, the K Reactors have never operated as close to speed-of-control limits as have the smaller reactors which is due to the inherently lower void coefficient in the less overmoderated K Reactors. This difference is still true with oxide fuel, but recent calculations have shown surprisingly that the advantage enjoyed by the K Reactors of a smaller void coefficient is not so pronounced with oxide fuel.

DECLASSIFIED

In summary, it has been shown from a physics standpoint with detailed calculations that, what had originally been thought to be an unsurmountable obstacle against oxide fuel without overboring -- particularly in the smaller reactors -- may no longer be true.

3. Production Capability

The discussion of the preceding section has shown that technical feasibility from a physics standpoint is readily assured with oxide fuel in the IPD reactors if the channels are enlarged. Technical feasibility also exists even if the reactors are not overbored, but economic disadvantages are introduced. (The overall economics of a closed cycle, which is not a subject of discussion here, may be good despite economic penalties associated with the reactor operations.) It is well to list the disadvantages for the non-overbored cases.

- a. The conversion ratio (g/MWD) for weapons-grade plutonium will be decreased between 15 and 20 per cent. This means a similar increase in unit cost, all other factors constant.
- b. The production of Np-237 will be reduced. Simple estimates show about a 50 per cent reduction in gratuitous production and a small reduction in the worth of recycling as a means to augment Np-237 production. There will be some advantage to a shorter U-236 turnaround time in the closed cycle.
- c. Almost all plans to co-produce in the Hanford reactors involve a fuel-target type loading. Such loadings result in further lowering of the U-238 inventory in the reactor, result in further overmoderation, and result in less fail-safeness or coolant loss. Although calculations have not been made on oxide-fueled co-product loadings, it is expected that without overboring, the flexibility of the reactors would be reduced if oxide fuel were the only fuel available.
- d. Modifications of moderate cost, such as control poisons of higher melting temperature, would be required in the reactors with oxide fuel. This may even be a requirement with half-inch channel enlargement; a full inch increase in channel diameters would quite likely result in a negative void coefficient which would put less reliance on external shut-down mechanisms in the event of full coolant loss and reactor meltdown.

DECLASSIFIED

B. REACTOR ENGINEERING

The following section discusses the effect of changing from metallic uranium to uranium oxide on reactor safety limits, fuel performance, economic limits, and reactor life. Three separate reactor cases were considered in this review. These include the K Reactors without modification, the B and C Reactors without modification, and with process channels enlarged one inch. In the channel enlargement case, it is assumed that the necessary reactor modifications and equipment changes have been accomplished to satisfactorily use the larger metallic fuel. Acceptable reactor safety limits for the larger metallic fuel case are also assumed.

1. Reactor Safety Considerations

a. Local Fuel Burnout

A limit is placed on the operating heat flux of Hanford fuel elements to prevent local film burnout at the fuel surface. The limit is applied by requiring that the calculated burnout heat flux exceed the operating heat flux by at least a factor of 1.45. In current reactor operations the burnout safety factor (BOSF) exceeds 2.0 in all reactor fuel columns. The use of uranium oxide fuels in place of present metallic fuels will not significantly alter the BOSF because the coolant conditions which determine the burnout heat flux, the fuel specific powers, and the fuel geometries need not differ appreciably in the two fuel loadings. Should the uranium oxide fuels be used in an overbored reactor, the BOSF would be expected to increase because the operating heat fluxes of the larger fuel elements would be less than those in present fuel elements, while burnout heat fluxes would remain about the same. Thus, as with metallic uranium fuels, the K and small reactors fueled with uranium oxide would operate well below the conditions which result in local film burnout at the fuel surface.

b. Instability Limits

The coolant temperatures at the outlet of the fuel columns in the reactors are limited to assure that there is no bulk coolant boiling in the fuel columns during normal operation. Bulk coolant boiling must be avoided because it might be irreversibly followed by a rapid, large reduction in coolant flow, referred to as flow instability. This is characteristic of low pressure systems (of which the higher-power Hanford fuel columns are examples) which do not have pressure to

DECLASSIFIED

overcome the increased resistance to flow when steam is formed. Film boiling occurs at the fuel surface at the low process tube flow rates resulting from flow instability, and fuel cladding will melt unless steps are taken to restore adequate cooling conditions in the channel.

The conditions which result in flow instability are determined by the hydraulic characteristics and heat generation rates of the process channels. The use of uranium oxide fuels similar to current metallic fuel designs will result in similar process channel hydraulic characteristics and power levels are assumed to be the same. Therefore, the use of uranium oxide fuels will not invalidate the methods used to predict the conditions which result in coolant flow instability or to establish pressure-gauge trip limits. The degree of protection provided by instability limits would remain basically unchanged by the substitution of uranium oxide for metallic uranium fuels.

c. Coolant Backup

A substitution of uranium oxide fuel elements at the same power level conditions as for metallic fuel introduces several important changes that affect the emergency backup coolant requirements. These changes are listed as follows:

- i. A 40 per cent increase in graphite temperature.
- ii. A 30 to 50 per cent increase in the heat generation in the graphite.
- iii. An approximate decrease in the fuel diffusivity by a factor of seven between the metallic and the oxide fuel.
- iv. An increase in the fuel sensible heat and in the fuel temperature of several 100 C.

The increased graphite temperature and heat generation will probably yield a longer graphite temperature decay period and more heat from the graphite at the critical time of emergency system take-over from the process pump flywheel flow decay.

The decreased fuel diffusivity and increased fuel temperature will yield a similar effect. An approximation of these two effects for an arbitrary tube power level of 1500 kw is shown in Table I.

DECLASSIFIED

TABLE I
APPROXIMATE EFFECT OF FUEL CHANGES

<u>Reactor</u>	<u>Fuel Change</u>	<u>Estimated Increase in Cooling Requirements</u>	
		<u>Secondary</u>	<u>Last-Ditch</u>
K	Metal-to-Oxide	10%	10%
B ₂ C	Metal-to-Oxide	15%	15%
B ₂ C	Metal Overbore-to- Oxide Overbore	10%	10%

The estimated increase in secondary system coolant flow requirements presents no problem with currently available secondary system components since more than adequate secondary flow for these conditions is already available. Some modification of the last-ditch coolant systems would probably be necessary to provide adequate emergency coolant flow with the use of uranium oxide.

2. Economics and Reactor Life

a. Fuel Performance

In many respects the performance of uranium oxide fuel elements during irradiation is superior to that of uranium metal fuels. Oxide fuels have been shown to be dimensionally stable during irradiation to high exposures with core temperatures near the melting point. The uranium oxide-water reaction is nil, so that the fuel elements are not subject to swelling following failure of the cladding and, thus, oxide fuel failures should be easily discharged which is not always the case with metallic uranium fuel failures. This property of the oxide fuels would also result in less radioactivity being released to the river following fuel failure. Examinations of irradiated oxide fuel elements have shown that there is sufficient sintering of the uranium oxide during operation to prevent fuel material being removed, even for large cladding failures.

The maximum economic fuel temperature for an aluminum-clad oxide fuel element is not precisely known, but is probably several hundred degrees below the oxide melting temperature because of the internal pressures developed by free fission and sorbed gases. This pressure could cause gross deformation or failure of the aluminum cladding. Considering the maximum

DECLASSIFIED

sorbed gas release for nuclear grade uranium oxide³ and free fission gas developed during irradiation at K Reactor conditions; the calculated⁴ internal pressure would exceed the strength of present aluminum cans. Thus, a tighter gas release specification, a higher-strength clad, and/or the provision of a void volume in the fuel design may be required for economic operation of the reactors at maximum power levels. The problem would be less acute with the tube and rod fuel design proposed for the reactors with enlarged process channels because these fuels would operate below the temperatures at which fission gases are released in uranium oxide fuels.

The uniform corrosion rates of the aluminum cladding of uranium oxide fuel elements would be no higher than those which are obtained with current uranium fuels. The fuel residence times are also comparable so total cladding loss by the uniform corrosion mechanism should be similar for the two fuel types. The uranium oxide fuel elements are unbonded which might result in a greater tendency for cladding hot spots to develop as compared with the bonded metallic fuels and, thus, a susceptibility to nonuniform cladding corrosion mechanisms. The low thermal conductivity of the uranium oxide, however, will tend to prevent hot spots on the cladding surface caused by a variable thickness in the gap between the core surface and inner can wall.

Another potential problem with uranium oxide fuels which is related to the unbonded design is the possible collapse of the can wall when the fuel is cold due to the external pressure exerted by the coolant. This would probably not be serious unless cladding corrosion losses were great enough to significantly reduce the clad strength. Considering the potential uranium oxide fuel problems which might result from either internal or external pressures on the can walls, cladding corrosion rates may need to be reduced or thicker jackets used than has been necessary with metallic fuels.

b. Graphite Temperature Considerations

One effect of replacement of metallic uranium with uranium oxide fuel is the reduction in self-shielding of gamma radiation by the fuel element. Gamma heating presently accounts for approximately 50 per cent of the total heat generated within the graphite. If metal is replaced by oxide and the fuel size remains the same, the gamma emission from the lower density oxide fuel will approximately double,

DECLASSIFIED

resulting in a 30 to 50 per cent increase in the graphite heat generation rate. The result is a 25 to 40 per cent increase in graphite temperature if no changes are made in gas composition. Table II summarizes the estimated graphite temperature and helium per cent which would be associated with fuel type and power level for K, C, and B Reactors. Considerable reactor experimentation and further analytical work is required to better define graphite temperatures expected with uranium oxide fuel.

From Table II, the following conclusions seem pertinent:

- a. Graphite temperatures in excess of the present limits would result if conversion to uranium oxide is not also accompanied by overboring. It is estimated that temperatures would be in excess of present limits at K Reactors by 300 C, at C Reactor by 100 C, and at B Reactor by 200 C without overboring. Operation at 100 per cent helium would be required.
- b. Graphite temperatures would remain essentially unchanged if the uranium oxide fuel size were increased to provide the same quantity of uranium as in the present metallic fuel. This could be accomplished with approximately a one-inch overbore at B and C Reactors.
- c. Operation at these higher temperatures may be possible. However, considerable effort will be required to better define the water vapor-graphite reaction rate. Undoubtedly, high dryer system efficiency will be required.
- d. The rate of irradiation induced contraction is unknown at graphite temperatures in the 1000-1100 C range.

In summary, to maintain current power levels with oxide fuel will require a significant increase in graphite temperature. There are no data presently available that would indicate that higher graphite temperature operation is now possible. However, considerable research and development effort would be required to assure that sustained operation at the higher temperature will be satisfactory.

DECLASSIFIED

TABLE II

K Reactors - No Overbore, Present Power

<u>Fuel</u>	<u>Metal</u>	<u>Metal</u>	<u>UO₂</u>
Power Level (MW)	4400	5000	5000
Helium (%)	75	100	100
Temperature (°C)	750	750	1050

C Reactor - No Overbore, Present Power

<u>Fuel</u>	<u>Metal</u>	<u>UO₂</u>
Power Level (MW)	2300	2300
Helium (%)	40	100
Temperature (°C)	650	750

C Reactor - Overbore

<u>Fuel</u>	<u>Metal</u>	<u>UO₂</u>	<u>UO₂</u>
Power Level (MW)	2500-2700	2500-2700	2300
Helium (%)	0	65- 85	40
Temperature (°C)	650	650	650

B Reactor - No Overbore, Present Power

<u>Fuel</u>	<u>Metal</u>	<u>UO₂</u>
Power Level (MW)	2000	2000
Helium (%)	85	100
Temperature (°C)	650	850

B Reactor - Overbore

<u>Fuel</u>	<u>Metal</u>	<u>UO₂</u>	<u>UO₂</u>
Power Level (MW)	2500-2700	2500-2700	2000
Helium (%)	50- 75	100	85
Temperature (°C)	650	750- 850	650

DECLASSIFIED

c. Bulk Temperature Limit

The change from metallic uranium to uranium oxide fuel will not have any effect on the bulk outlet temperature limit. The actual value of this administrative limit is chosen to prevent major damage to effluent coolant system piping from occurring following possible bulk temperature transient. Assuming tube powers and reactor flow rates to be comparable with oxide fuel to the companion metallic fuel case, no change in bulk limits or method of administration is foreseen.

3. Fuel Fabrication

a. Density Requirements

The chief deterrent to the use of uranium oxide is the low fuel/moderator ratio resulting from the relatively low density of uranium oxide. With a fixed fuel geometry, the lack of density must be compensated for by enrichment adjustments. If the geometry can be changed, for example, by overboring, then a favorable uranium-moderator ratio can be achieved. In practice, all three parameters, density, enrichment, and geometry should be balanced for optimum economy and operability.

The present reactors were designed to operate with metallic uranium, density 18.9, whereas UO_2 has a crystal density of 10.9. Present vibrational compacting techniques yield elements with 87 to 89 per cent of theoretical density, or approximately 9.5 g/cc. Higher effective densities could be attained by using pressed, sintered, and ground shapes rather than compacted powders. This type fuel is used in many power reactors, and densities of 10.65 are routinely achieved.

b. Uranium Oxide Specifications

The Ceramic Research and Development Operation, Battelle-Northwest, has published a "Specifications for High Density Uranium Dioxide" (Nuclear Grade).³ This specification was intended to define a UO_2 product for use in the vibrational compaction process for making power reactor fuel elements. Certain revisions of this specification would likely be in order if the oxide were to be used in a production type reactor.

REF ID: A66111

Briefly, this specification provides the following:

i. Chemical Properties

Minimum Uranium Content	88.0%
Oxygen/Uranium Atom Ratio	2.00 ± 0.02
Uranium Isotopic Composition	As Specified
Moisture Content	100 ppm maximum
Out Gas (Exclusive of Moisture) @ 1000 C	0.05 cc/g UO_2

ii. Impurities

The total impurity content shall not exceed an "Equivalent Boron Content" of 4 ppm on a weight basis. A formula for computing EBC is provided. Specific limits on certain impurities are as follows:

Carbon	100 ppm	Fluorine	10 ppm
Nitrogen	200 ppm	Calcium and Magnesium	50 ppm
Chlorine	10 ppm		

iii. Physical Properties

Particle density, as measured by the Mercury-Vacuum Techniques, shall be greater than 10.80 g/cc.

Particles, crystals, or inclusions of any material other than UO_2 and/or porous particles of UO_2 shall be limited to a total of one per cent by weight.

c. Fabrication Techniques

There are two basic processes available for canning UO_2 in aluminum. These are discussed briefly below:

1. Vibrational Compaction

The starting material for this process can be prepared by either arc fusion or high energy impaction (Dyna-Pac). Both processes give particle densities approximately 98 per cent of theoretical. The uranium oxide must be crushed, screened, and blended to give the optimum mix for compaction. This material is then compacted into the aluminum cans and the cans are closed by welding a suitable cap into the open end.

DECLASSIFIED

Maximum attainable density by this method would be in the 87 to 89 per cent of theoretical range. It does not appear that further compaction could be effected by swaging. The relatively soft aluminum clad, and the short length of the elements are not conducive to a successful swaging step.

2. Pressing and Sintering

The ultimate in density can be achieved by pressing powder to green pellets, sintering at high temperature to give a nonporous ceramic, and then grinding to close tolerance.

This process is now used for many of the presently operating power reactors. Densities of 98 per cent of theoretical are routinely achieved. These pellets are normally clad in Zircaloy or stainless steel. For a production reactor, they would be canned in aluminum and isostatically pressed to improve contact between the clad and the oxide.

The chief drawback to this cladding method is its relatively high cost when compared to the compacted powder method. However, the value of higher density, from the reactor economics and safety standpoint, may be sufficient to warrant consideration of this approach. Dissolution of the sintered pellets is apparently not difficult.

4. Uranium Oxide Fuel Handling

Problems related to the handling of uranium oxide fuels are briefly discussed. It is assumed that all basic "systems" associated with the use of metallic fuel elements in both the current and overbore cases are adequate and have been proven workable. All phases of the metallic fuel element concept, including fabrication, transfer, storage, and charging, have been developed. Further, it is assumed that uranium oxide within an element has no usable compressive strength before, during, or after irradiation and that aluminum components similar to present type will be used as cladding.

a. Storage

In both pre- and post-irradiation storage of uranium oxide elements, no major changes are required. Use of oxide may require a higher average enrichment level and, therefore, place some added restrictions on storage which would not be significantly different from those with metal of same enrichment level.

DECLASSIFIED

b. Shipment

No major changes in pre-irradiation shipment should occur as a result of changing from metal to oxide. Post-irradiation shipment probably would be altered somewhat when using uranium oxide fuel elements. To maintain the same maximum core temperature during shipment, the time from discharge would have to be extended for the same heat generation rates. No evaluation of the necessary changes in shipping procedures can be made now; it does not appear to be a large problem.

c. Charge-Discharge

Use of uranium oxide should not require any modifications to structural members in the system as the fuel elements will have less weight for a given volume than metallic uranium fuel elements.

The compressive strength of uranium oxide fuel elements will be essentially that of the aluminum components, so a marked decrease in strength will occur. Components would require redesigning with only a portion of the metallic element strength being regained. This decrease in strength may necessitate modifications of the charge-discharge system. Rupture or stuck charge removal problems would probably be increased many fold with uranium oxide fuel elements because of their lower strength. It is fair to state, however, that the probability of fuel swelling is considerably reduced with uranium oxide because of its irradiation stability and chemical inertness.

A redesign of fuel element supports may be required to prevent deformation of the can during handling and charging operations. More care in the handling of the uranium oxide fuel elements may be required to minimize cladding damage. Some modifications to the charging equipment might be required, especially if a gravity feed system were used. Tighter control on work procedures for charging would be necessary to prevent possible inhalation and ingestion of uranium oxide from a broken fuel element.

Nonaxial forces applied to the fuel column during charging and/or discharging could be more detrimental with uranium oxide fuel elements, again due to the low compressive strength. Discharging of uranium oxide fuel elements before a new fuel column is charged might be desirable to minimize the compressive forces applied to the fuel elements being charged. A lubricant might be quite effective for uranium oxide fuel elements.

DECLASSIFIED

5. Reactor Modification

Based on the conclusion reviewed in the reactor physics section, the only reactor modification required in K and the small reactors for the use of uranium oxide would be replacing control poisons with higher melting materials such as samarium oxide or gadolinium oxide in an aluminum base, or boron carbide. The additional supplemental control would be provided with splines which do not require reactor modifications. Nominal modifications would be required of the last-ditch coolant system and possibly charge-discharge equipment. Also with the higher graphite temperatures and use of 100 per cent helium in the nonoverbored reactors (K and small) some modifications will be required in the gas system to increase dryer efficiency.

If a decision is made to enlarge process channels for increased operating flexibility, this would include removing existing process tubes and hardware, boring the inner shielding and graphite channels to a larger diameter, and installing new tubes and hardware. Costs and construction schedule for channel enlargement are reviewed in another report.⁵

IV. N REACTOR

A. PHYSICS ASPECTS

Physics data are at hand which describe the behavior of a nominal tube-in-tube UO_2 fuel element in the N Reactor. These data result from a preliminary investigation into the problem of Phase III fuel design, and represent reactor operation at the Phase III power level of 3400 MW.⁶ The fuel design has not been optimized in geometry to maximize exposure life, product yield, or to minimize fuel cycle costs. Nevertheless, the data clearly indicate the technical feasibility of utilizing UO_2 from an operational and nuclear safety standpoint.

1. Operational Reactor Transients

a. Feed Enrichment

With a tube-in-tube uranium oxide fuel element which contains 11-12 pounds per foot of uranium, a feed enrichment of 1.0 to 1.1 per cent U-235 would be required. Redesign of the fuel element for the more economically attractive co-product case would raise the enrichment level to about 3 per cent.

DECLASSIFIED

b. Cold, Xenon-Free Reactivity and Operational Reactivity Transients

The cold, xenon-free reactivity would be about 40 mk, which is very close to that found with the Phase I metallic fuel (37 mk). The "prompt" negative temperature reactivity effect (coolant plus fuel) between room temperature and operating temperatures are calculated to be between -20 mk and -25 mk; the equivalent values for the Phase I fuel is about -29 mk. The positive graphite temperature coefficient of reactivity is calculated to be about +25 mk, while that for the Phase I fuel was found to be about 28 mk. From an operational physics standpoint, therefore, operation with the indicated uranium oxide fuel element would be virtually indistinguishable from operation with Phase I metallic fuel.

2. Reactivity Behavior Under Accident Conditions (Total Control)

Accidents which are found to introduce significant reactivity changes in relation to the total capacity of the safety control systems are those which involve changes in the quantity of coolant in the reactor, and its temperature. Under Phase I conditions the accident which results in the largest positive reactivity change in the "cold water injection" accident, which involves a dump of the primary coolant and activation of the last-ditch, once-through, emergency cooling system. Other accidents to be considered are: (1) flooding, or injection of water into the graphite stack, and (2) loss of the primary coolant without subsequent last-ditch activation.

a. Cold Water Injection

Inspection of the temperature coefficients of reactivity indicates that the pile reactivity resulting from a cold water injection accident would be essentially identical to that obtained in Phase I operation, where it is found that a margin of at least 5 mk exists between the maximum reactivity and the control worth of the horizontal rod system. With uranium oxide fuel elements of the indicated design, however, the worth of the rod system would increase about 8 mk, providing an even greater safety margin.

b. Graphite Stack Flooding

No calculations describing the reactivity effect of injecting water into the graphite stack are at hand. The maximum calculated reactivity effect with the reactor loaded with Phase I fuel is +5 mk. Considering the physics effects of

DECLASSIFIED

changing to the uranium oxide; a decrease in the epithermal-to-thermal flux ratio, an increase in the resonance escape probability, and a small increase in neutron migration area; the introduction of water into the graphite stack should result in a smaller positive, if not negative, reactivity effect. This conclusion is supported by calculations for lattices where opposing effects are found, and the reactivity effect of flooding becomes more positive.

c. Primary Coolant Loss

No calculations describing the reactivity effect of primary coolant loss are at hand. The reactivity effect with Phase I metallic fuel is -45 mk. The coolant temperature coefficient of reactivity, which includes the effect of a coolant density change from 1.0 to about 0.81, is still negative with oxide fuel, but about 60 per cent as large. Assuming that the effects are proportional, the reactivity effect of coolant loss would be about -25 mk. It is possible that, in the process of optimizing an oxide fuel design, this reactivity effect could become positive. The reactor safety system could control a reactivity gain on water loss of roughly +30 mk, beyond which this effect would become a limiting consideration.

3. Reactivity Behavior Under Accident Conditions (Speed-of-Control)

Studies of the reactor kinetic behavior when loaded with uranium oxide have not been performed; however, an inspection of the differences between metallic and uranium oxide indicate that power excursions and associated coolant temperature increases which result from rapid reactivity insertions will be less severe with uranium oxide than with metallic fuel of the same geometry:

- a. The negative Doppler effect, which is the major factor limiting the magnitude of a nuclear excursion, is smaller in uranium oxide (about 80 per cent or larger).
- b. The thermal conductivity of uranium oxide is lower than that of metallic fuel, thus resulting in higher fuel temperatures associated with a given power level, and an even larger negative Doppler reactivity defect. The temperature increases would not, however, approach the oxide melting point.

DECLASSIFIED

- c. The possible accidental reactivity insertion rates are essentially the same with both types of fuel, the largest being associated with accidental control rod withdrawal in an abnormal pattern and at an abnormally fast rate. The small increase in rod strength in the oxide case, resulting from a larger neutron migration area, will result in an equivalently larger reactivity insertion rate; this small increase is well within the range of conservative factors used in the original calculations.

B. EFFECT ON PRODUCTION FLEXIBILITY

A change to uranium oxide fuel would have both positive and negative effects on the flexibility of N Reactor to produce the various weapon materials and other isotopes useful as power sources in the space program. The lower density of the oxide fuel would increase the moderator-to-fuel ratio, leading to additional thermalization of the neutron flux spectrum, and would increase the thermal flux level by 1.5 to 2.0 times. The reduced epithermal flux ratio would reduce the conversion efficiency of reactions such as the production of Pu-238 from Np-237; however, the increased level of thermal flux would increase the production of isotopes such as Po-210 from bismuth and might increase the overall production of Pu-238 from Np-237.

The decreased concentration of U-238 in the lattice would result in a decreased weapons-grade plutonium production but would result in an increase in tritium production for a tube and target type fuel design.

Production schemes dependent upon packing the maximum density of fertile material in the lattice would suffer from a change from metal to oxide fuel. Optimum utilization of N Reactor's capabilities if operating on a uranium oxide cycle would require devising production schemes that capitalize on the reduced density of fuel to produce larger amounts of by-product isotopes.

C. PERFORMANCE OF URANIUM OXIDE FUEL IN N REACTOR

The expected performance of uranium oxide fuel in N Reactor was recently reviewed as a part of the study of alternate fuel cycles for power-only operation of N Reactor.⁷ At the reactor power level of 3400 MW for power-only operation, a uranium oxide, tube-and-tube fuel element would be expected to perform well in N Reactor to goal exposures in excess of 15,000 MWD/T. For dual-purpose operation at

DECLASSIFIED

reactor power levels of 4000 MW to 4800 MW, further provisions would be required in fuel design and fabrication to assure trouble-free operation. At the higher specific powers associated with dual-purpose operation, the maximum temperature of the uranium oxide would approach values where tests have shown high internal pressure from fission gas release and where sintering and densification progress to the point where clad collapse failure becomes a possibility.

For the production of weapons-grade plutonium a Zircaloy-2 clad, tube-and-tube fuel similar to the present N Reactor, metallic fuel element would probably be used. For co-product operation, a tube-tube and target might be used. These elements could be fabricated by vibratory compaction of UO_2 prepared by either fusion or high energy impact techniques. Substantial pilot plant experience at Hanford and Savannah River is available from which to scale up the production process for fuel fabrication. Only those problems associated with plant and process scale up are anticipated.

DuPont at the Savannah River Laboratory has performed a substantial number of irradiation tests on tubular oxide fuels in the HWTCR. Comparison of their results with the expected fuel environment in N Reactor indicates that a two tube, uranium oxide fuel design should perform satisfactorily; however, special fabricating techniques or a density graded fuel loading might be needed to assure adequate density of the uranium oxide in the central portion of the process tubes. Fuel densities of greater than 87 per cent of theoretical are required for the high-power fuel to avoid clad collapse type fuel failures. With careful process control, the vibratory compaction technique should produce an adequate number of fuel elements with densities above 87 per cent.

For goal exposures in the range of 1000 MWD/T to 3000 MWD/T for the production of weapons-grade plutonium, no problem should be encountered from the buildup of pressure from released fission gases. If long exposures in the range of 15,000 MWD/T to 25,000 MWD/T were to be employed for the production of plutonium containing large amounts of Pu-240 and Pu-241, pressure buildup from fission gas release would require investigation.

Special care would be required to design a fuel closure that could withstand the rigors of charge-discharge operations.

The thermal hydraulic characteristics of a uranium oxide fuel column should be similar to those of a metal fuel of the same design and operating at the same specific power. The fuel design would have to compensate for the lower density outer tube to avoid excessive power generation in the inner tube.

DECLASSIFIED

V. CHEMICAL PROCESSING

In the general analysis of the feasibility of processing UO_2 fuels by the Chemical Processing Department, both technical feasibility and production capability are important considerations. For purposes of this report, only technical feasibility has been considered in detail.

A conceptual processing scheme for a closed UO_2 fuel cycle at Hanford is shown by Figure 1. By this concept, the required uranium tonnage would be continuously recycled at the Hanford site and the U-235 required to make up burnout losses would be purchased as UF_6 from off site. The UF_6 would be of relatively high enrichment since steady-state U-238 additions would be based on the uranium loss in the overall cycle. By the cycle concept shown in Figure 1, facilities for performing the following chemical processing steps would have to be added to the existing Hanford complex.

- a. The highly enriched UF_6 would be converted to uranyl nitrate for aqueous-phase blending with the uranium product from the separations plant. Conceptually, this could be accomplished by a demonstrated process involving:
 - i. Hydrolysis of UF_6 to UO_2F_2 .
 - ii. Precipitation of uranium as ammonium diuranate.
 - iii. Calcination of the precipitate to an oxide, followed by dissolution in nitric acid.
- b. Following calcination of blended uranyl nitrate to UO_3 (in the existing UO_3 plant), the UO_3 product would be hydrogen-reduced to UO_2 .

Evaluation of the technical feasibility of processing UO_2 fuels by the Chemical Processing Department must be based on some assumptions of fuel element form. The preliminary Hanford fuel element concepts have been described approximately as follows:

- a. K and the small reactors would use aluminum-clad, low-enrichment (approximately one per cent U-235) fuel elements. The fuel element geometry would be similar to current metal models, except that a large fraction of the production might be larger-diameter (up to approximately 2-1/2 inches) elements, corresponding to overbored reactor channels.
- b. N Reactor would use Zircaloy-2-clad fuel elements, enriched to about one per cent U-235; if co-producer loads were employed, the enrichment would be increased, perhaps as high as three per cent to five per cent U-235. The fuel element geometry would be similar to current tube-in-tube models or co-producer (single tube) concepts.

REF ID: A663

FIGURE 1
UO₂ FUELS AT HANFORD

DECLASSIFIED

Assuming the fuel element forms described above, practicable chemical processes required for a closed UO_2 fuel cycle at Hanford have been demonstrated. Aqueous processing of irradiated UO_2 fuels could be accomplished at the Purex plant, using a processing flowsheet very similar to that which is used for uranium metal. The conversion of UNH to UO_3 could also be accomplished in existing equipment. Some equipment changes would have to be made in both Purex and the UO_3 plants to retain criticality safety when processing the enriched fuels. The required changes would be minimal at the one per cent U-235 level; new or modified dissolvers, additional Purex instrumentation, and calciner system modifications or replacement would be required to process the more highly enriched fuels safely. As indicated above, demonstrated technologies are readily available to support the construction and operation of the facilities required to re-enrich the irradiated uranium and to convert it to UO_2 .

Aside from technical feasibility, the relationship between the total production load and separations processing rate capability will be important considerations. It is expected that increasing the U-235 enrichment (say, above 1.5 per cent U-235) will decrease the obtainable processing rate in the Purex and the UO_3 plants. In addition, the lower density of the UO_2 fuels, as compared to uranium metal, will tend to reduce Purex dissolver capability. The magnitude of the effects of these variables will depend on the specific fuel element description. It is likely that the need to increase the Purex plant capability for these fuels would require some research and development effort.

DECLASSIFIED

VI. REFERENCES

1. Letter, W. E. Johnson to J. E. Travis, "Oxide Fuels at Hanford," February 3, 1965.
2. Hamric, J. P. and J. H. Scott, "Speed-of-Control - Urania Fuel," RL-REA-609. (Secret)
3. Anderson, H. J. and R. J. Anicetti, "Specification for High Density Uranium Dioxide (Nuclear Grade)," HW-74204 REV 1, September 2, 1963. (Unclassified)
4. Reynolds, M. B., "Measurement of Free Fission-Gas Pressure in Operation UO₂ Filled Fuel Rods," Nuclear Science and Engineering, 20, 386-391, December 1964.
5. IPD Staff, "Process Channel Enlargement B and C Reactors," RL-REA-556, February 5, 1965. (Secret)
6. "Alternate Fuel Cycles for Power-Only Operation of N-Reactor," RL-NRD-173, February 1, 1965.
7. N-Reactor Department, "Alternate Fuel Cycles for Power-Only Operation of N-Reactor, Appendix B," RL-NRD-173 PT2, February 1, 1965.

LE Kusler:jm

DECLASSIFIED

DATE

FILMED

11 / 01 / 94

END