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BURNING WEAPONS-GRADE PLUTONIUM IN REACTORS

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Burning Weapons-Grade Plutonium in Reactors

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Introduction

As a result of massive reductions in deployed nuclear warheads, and their subsequent dismantlement, large quantities of surplus weapons-grade plutonium will be stored until its ultimate disposition is achieved in both the U.S. and Russia. Ultimate disposition has the following minimum requirements: 1) preclude return of plutonium to the U.S. and russian stockpiles, 2) prevent environmental damage by precluding release of plutonium contamination, and 3) prevent proliferation by precluding plutonium diversion to sub-national groups or non-weapons states.

After the surplus weapons-grade plutonium is in safeguarded and secure storage, bilateral attention can be focused on implementation of ultimate disposition. Long-term storage is not a desirable option because it is extremely expensive and it does not preclude rapid rearmament. Incorporation of plutonium into high-level waste as a solid form does not relieve the material from continued safeguards and security requirements because it does not preclude diversion of the material and recovery of the plutonium by chemical processing. Furthermore, the mixing of plutonium with high-level waste makes it uneconomical as a future energy resource, and presents environmental and safety concerns in its processing and for geologic disposal.

The most efficient and effective way to dispose of surplus weapons-grade plutonium is to fabricate it into fuel and use it for generation of electrical energy in commercial nuclear power plants.

Incentives For Plutonium Burning

During its use in reactors, plutonium becomes adulterated with highly-radioactive fission products. The weapons-grade plutonium is partially consumed and transformed, after suitable irradiation exposure, to reactor-grade plutonium whose isotopic composition and radioactivity content are comparable to that of low-enriched uranium-based spent fuel discharged from commercial nuclear power plants. Substantial quantities of fissile ^{239}Pu are converted to fertile ^{240}Pu during irradiation to denature the plutonium. As a result, the plutonium remaining in spent fuel typically has in excess of 20% of the ^{240}Pu isotope. This spent fuel has a high degree of proliferation resistance. While it may not be technically impossible to utilize reactor-grade plutonium for rearmament, such use would pose considerably more technical difficulty than the use of weapons-grade plutonium. Another degree of proliferation resistance exists for plutonium contained in spent fuel if it is not reprocessed and separated from other constituents such as the uranium and fission products.

In the U.S., for example, there is more than 200 metric tonnes of reactor-grade plutonium contained in unreprocessed commercial spent fuel that has accumulated and is being stored at

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nuclear power plants. Burning weapons-grade plutonium in the form of a UO_2 - PuO_2 mixed oxide (MOX) destroys up to 30% of the plutonium inventory on a once-through fuel cycle. For maximum destruction of plutonium, non-fertile fuels could be developed that would annihilate up to 80% of the initial plutonium loading, without reprocessing. Spent plutonium fuels would not constitute a new proliferation pathway, nor would they significantly increase the proliferation potential beyond that of the existing unreprocessed spent fuel inventory.

Reactor Availability

The earliest available and least costly reactor options for burning surplus plutonium in the U.S. and Russia are the existing commercial nuclear power plants. Currently, there are 110 large commercial light water reactors (LWR) operating in the U.S. In Russia, there are 12 LWRs of the VVER type and 11 RBMKs (graphite-moderated boiling-water cooled channel-type reactors) in operations. Even if there are no new orders for additional nuclear power plants, there will be more than sufficient capacity to burn the surplus plutonium as it becomes available.

Plutonium Fuel Fabrication

Plutonium Fuels fabrication would, most likely, take place in modern facilities on government sites within the U.S. and Russia so that stringent materials controls could be maintained during the conversion of the plutonium to a more proliferation resistant and accountable form: as fresh fuel assemblies.

MOX fuels were successfully introduced into U.S. LWRs on a small scale prior to the U.S. government ban on commercial spent fuel reprocessing in the mid-1970s. In general, existing LWRs can accommodate at least one-third of the fuel in their cores as MOX within existing technical specifications. However, five years may be required for large-scale implementation of MOX fuel use in existing LWRs because of the necessity for plant license amendments, completion of NEPA documentation, and lead MOX assembly irradiation demonstrations. DOE has assembled a MOX fuel fabrication line in the Fuels and Materials Examination Facility (FMEF) at Hanford, but this Secure Automated Fabricated (SAF) line has not undergone hot testing or modifications that would be required for MOX fuel fabrication operations at the required capacity. Similarly, Russia has constructed a large MOX fuel fabrication plant at Chelyabinsk that has not yet been operated.

About 50 metric tonnes of surplus weapons-grade plutonium will have accumulated in the U.S. from weapons dismantlements by the year 2005, and an equivalent amount is expected to be available in Russia. The rate at which fuels would have to be fabricated and the reactor capacity required to utilize the surplus plutonium over a 20-year campaign depend on the type of reactors and their fuel composition that would be implemented for this purpose.

Pu Fuel Burnup Characteristics

For comparison of burnup characteristics of MOX fuels to conventional low-enriched UO_2 fuels, LWR fuel parameters typical of U.S. pressurized water reactors listed in Table I were used. The variations in reactivity of MOX fuels containing weapons-grade initial PuO_2 loadings in the range from 2% to 7% are shown in Figure 1, in comparison with 3.8% enriched UO_2 fuel, up to exposures of 42GWd/MT (1050 Effective Full-Power Days at 188 Watts/cm). The reactivity decrease of MOX with burnup is substantially less than that of UO_2. The reactivity decrease of MOX with burnup can be minimized by the use of a burnable neutron absorber, such as Er_2O_3,

moxed with the fuel. For 7% MOX with 2.5 volume % Er_2O_3, the reactivity decrease from beginning of life to 40GWd/MT (1000 EFPD) is only about 7%, as shown in Figure 2. The large reactivity decrease due to burnup of non-fertile plutonium fuel with the same initial PuO_2 loading as 7% MOX can be minimized by higher Er_2O_3 burnable absorber loadings, as shown in Figure 3. A comparison of net plutonium annihilation as a function of exposure in both MOX and non-fertile plutonium fuels is shown in Figure 4. At exposures of 1250 EFPD (equivalent to 50 GWd/MT in MOX) 50% of the fissile inventory remains in MOX, but only 10% of the fissile inventory remains in non-fertile fuel.

Table I. Typical LWR Fuel Parameters

Fuel Pellet Outer Diameter	0.821 cm
ZR Clad Inner Diameter	0.843 cm
ZR Clad Outer Diameter	0.965 cm
Square Pitch of Fuel Rods	1.337 cm
Effective Oxide Fuel Density	10.1 gm/cm^3
Hot Assembly H/U Atom Ratio	4.08
Average Fuel Temperature	977 K
Average Water Temperature	588 K
Average Fuel Rod Linear Heat Rate	188 W/cm

Economic Considerations

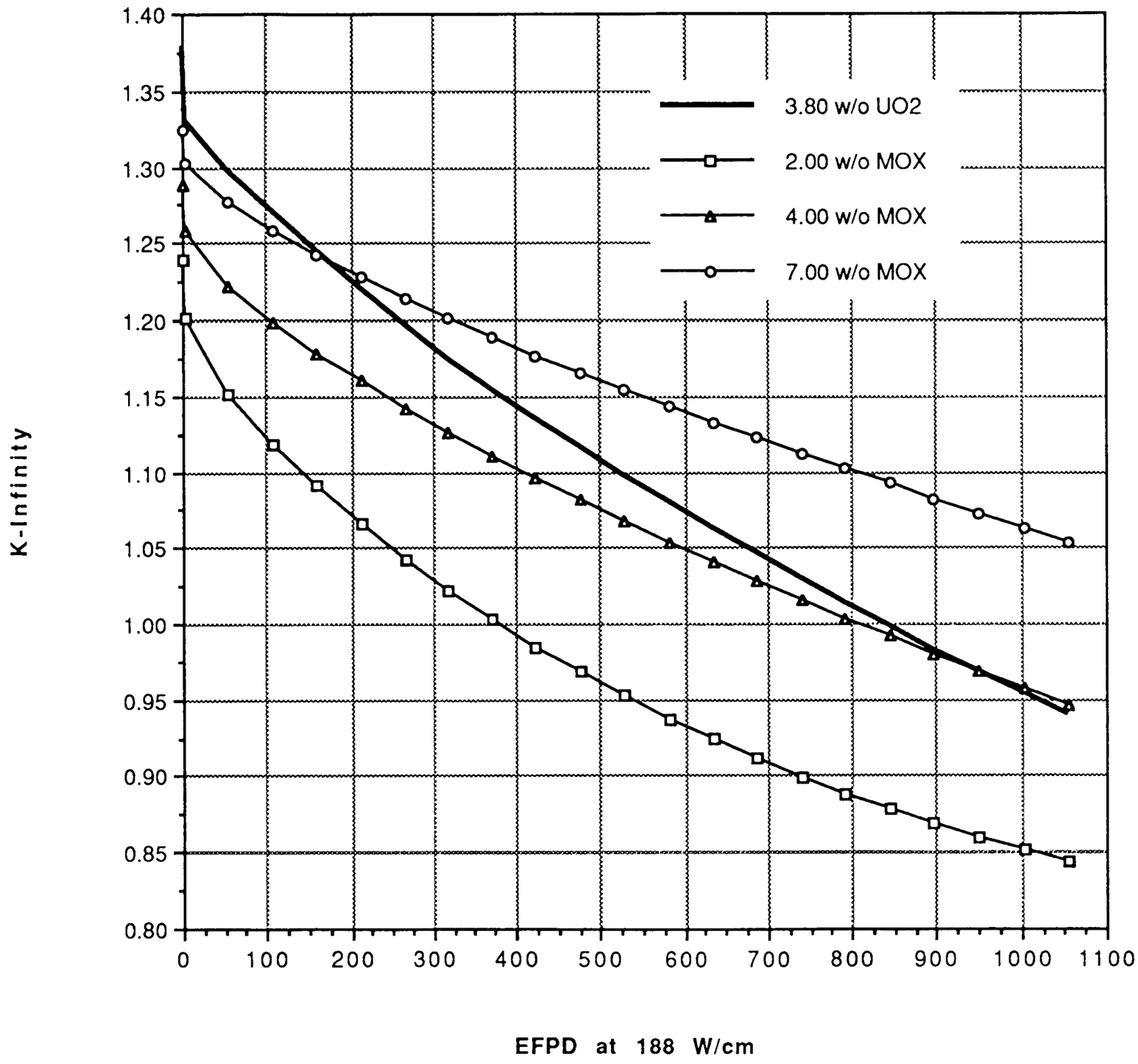
Plutonium fuels fabrication must be conducted in confined spaces to prevent the spread and release of contamination. As a result, the cost of fabricating fuels containing plutonium is about four times the cost of fabricating the same amount of UO_2 fuel. Increasing the PuO_2 loading in fresh fuel, and burning it to as high exposure as technically feasible, minimize the Pu fabrication cost. If surplus plutonium is available at no cost, the savings from displacing enriched UO_2 can offset the fabrication cost penalty of plutonium.

Summary and Conclusions

Weapons-grade plutonium can be used as fuel in existing commercial nuclear power plants, such as those in the U.S. and Russia. This recovers energy and economic value from weapons-grade plutonium, which otherwise represents a large cost liability to maintain in safeguarded and secure storage. The plutonium remaining in spent MOX fuel is reactor-grade, essentially the same as that being discharged in spent UO_2 fuels.

MOX fuels are well developed and are currently used in a number of LWRs in Europe. Plutonium-bearing fuels without uranium (non-fertile fuels) would require some development. However, such non-fertile fuels are attractive from a nonproliferation perspective because they avoid the insitu production of additional plutonium and enhance the annihilation of the plutonium inventory on a once-through fuel cycle.

Figure 1. Comparison of Reactivity vs. Burnup for UO2 and MOX Fuels



Enrichments represent U-235 in total uranium for UO2 fuel and Pu-239 in fissile metal for MOX

Figure 2. Erbium Burnup in MOX Fuel

PWR Fuel, 6.72 vol% PuO2 in UO2

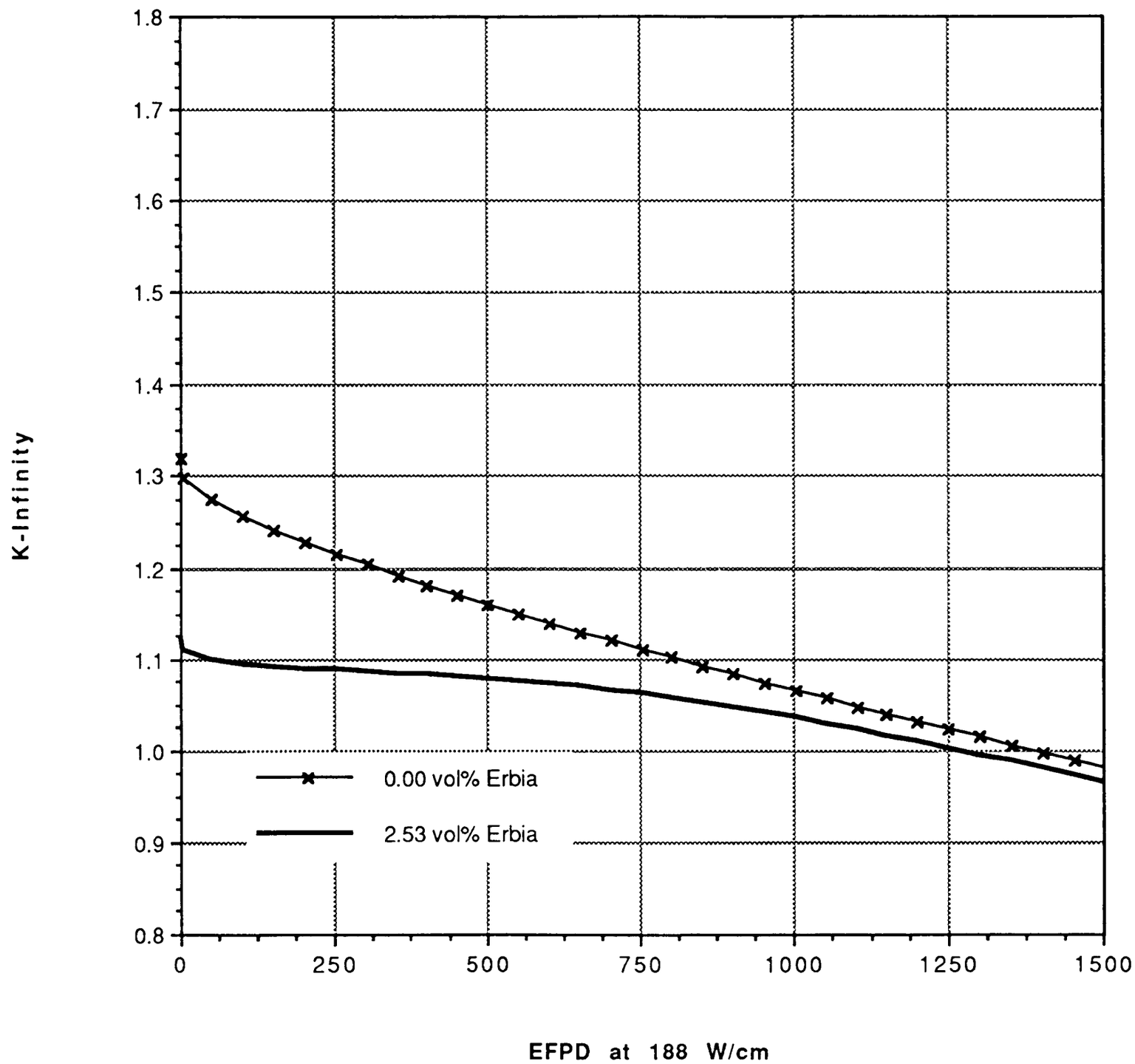


Figure 3. Erbium Burnup in Non-Fertile Fuel

PWR Fuel, 6.72 vol% PuO2 in Al2O3

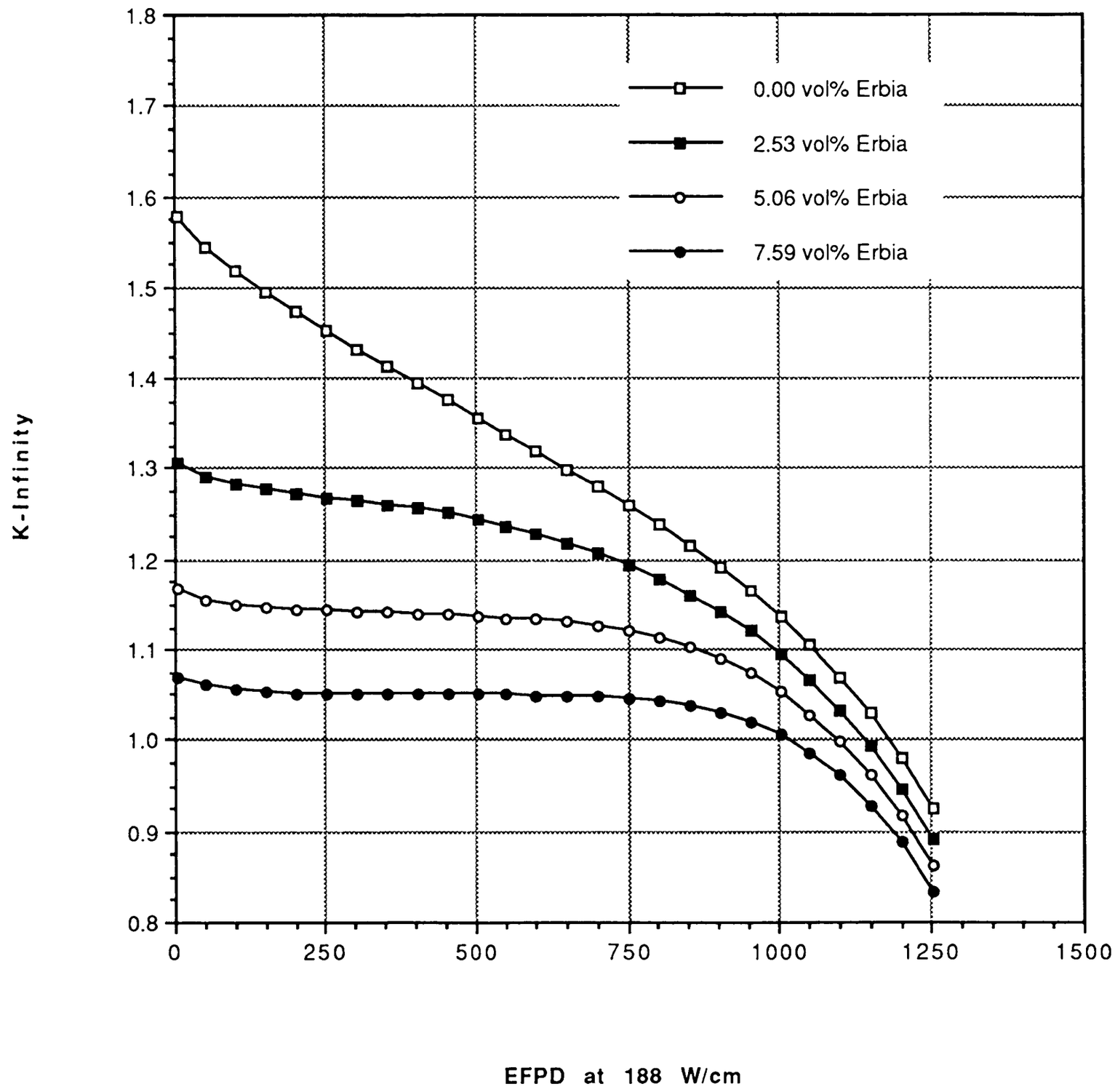
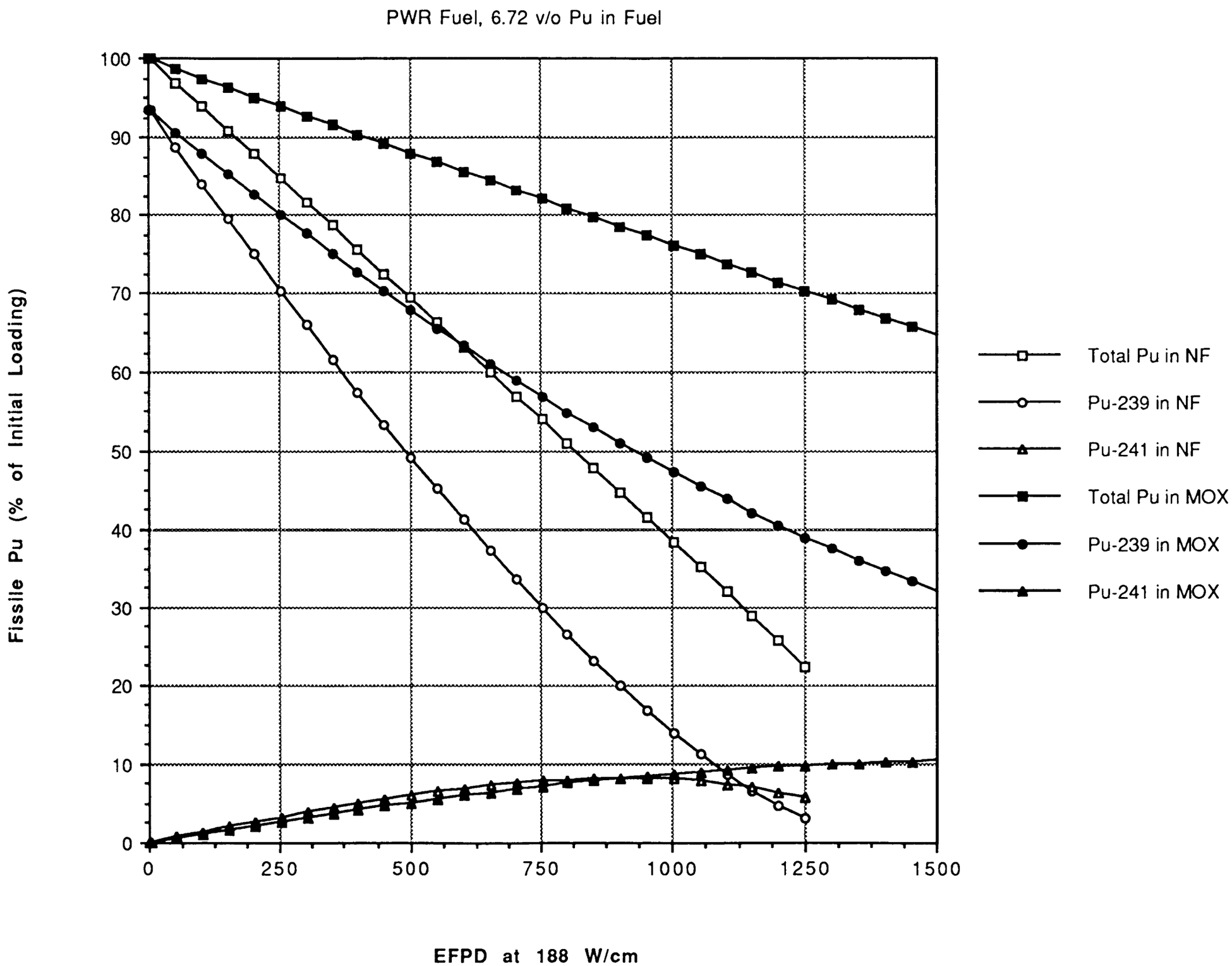


Figure 4. Plutonium Fissile Burnout



BURNING WEAPONS-GRADE PLUTONIUM IN REACTORS

Presented to
4TH ANNUAL NUCLEAR SOCIETY CONFERENCE
NIZHNI NOVGOROD, RUSSIA

by
DARRELL F. NEWMAN
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Pacific Northwest
Laboratory

PLUTONIUM DISPOSITION OPTIONS

- LONG-TERM PROTECTIVE STORAGE
- CONVERSION TO ACCEPTABLE WASTE FORM
- USE AS NUCLEAR REACTOR FUEL

Disposition Options
Excess Weapons Plutonium

Features	Long-Term Storage	Geologic Disposal	Burn in Reactors
Safeguards	◗	◒	●
Elimination	◗	◒	●
Threat Persistance	◗	◒	●
Irreversibility	◗	◒	●
Transparency	◒	◗	●
Reciprocity	◒	◗	●
Regulatory/Legal	◒	◗	●
Environmental Protection	◗	◒	●
Public Acceptance	◗	◒	?
Jobs for Russians	◗	◗	●
Technology Maturity	●	◗	◒
Resource Utilization	◗	◗	●
Startup Costs	●	◗	◒
Life Cycle Costs	◒	◗	●

● ◒ ◗
Best → Worst

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STORAGE ISSUES

- ULTIMATE DISPOSITION NOT RESOLVED
- SAFEGUARDS & SECURITY MAINTAINED
- RISK OF THEFT OR DIVERSION PERSISTS
- DILUTION TO LESS REVERSIBLE FORM DEGRADES VALUE AS ENERGY RESOURCE
- HIGH CUMULATIVE COST

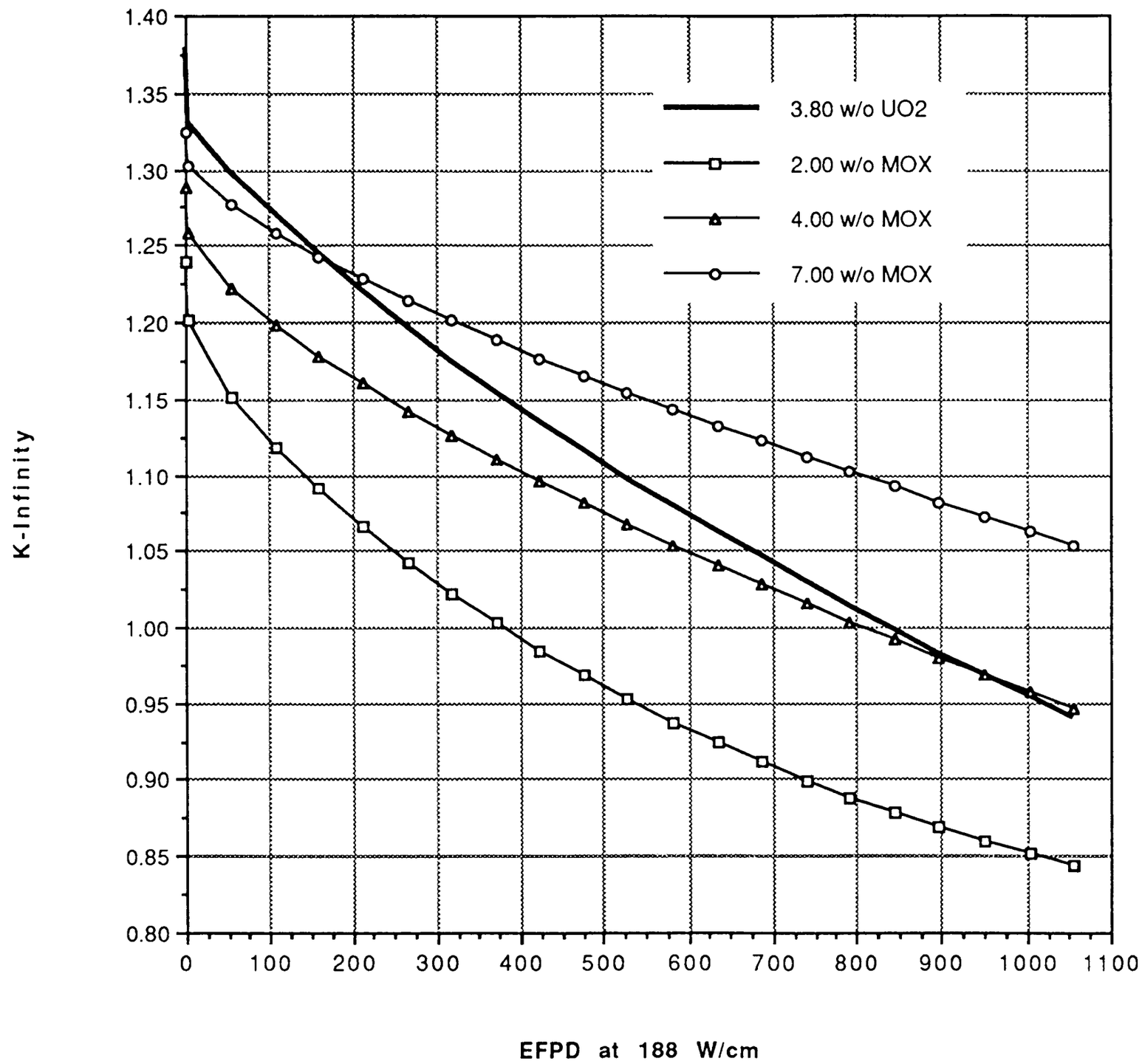
DISPOSAL ISSUES

- EASE OF RETRIEVAL NOT RESOLVED
- ENVIRONMENTAL, SAFETY & SAFEGUARD CONCERNS
- DELAYS IMPLEMENTATION OF HIGH-LEVEL WASTE VITRIFICATION
- RECRITICALITY FROM GEOLOGIC PROCESSES
- DELAYS STARTUP OF GEOLOGIC REPOSITORY
- INCREASED COSTS FOR HIGH-LEVEL WASTE DISPOSAL
- LOST ENERGY VALUE

REACTOR FUEL ISSUES

- FULL-SCALE IMPLEMENTATION OF PLUTONIUM FUELS
- 15 YEARS SINCE LAST COMMERCIAL USE OF PLUTONIUM IN U.S.
- AVAILABILITY OF FABRICATION FACILITIES
  - FMEF/SAF LINE AT HANFORD
  - MOX FACILITY AT CHELYABINSK
- ENVIRONMENTAL DOCUMENTATION
- REACTOR REGULATORY REQUIREMENTS
- NO NEED FOR REPROCESSING

Comparison of Reactivity vs. Burnup for UO2 and MOX Fuels



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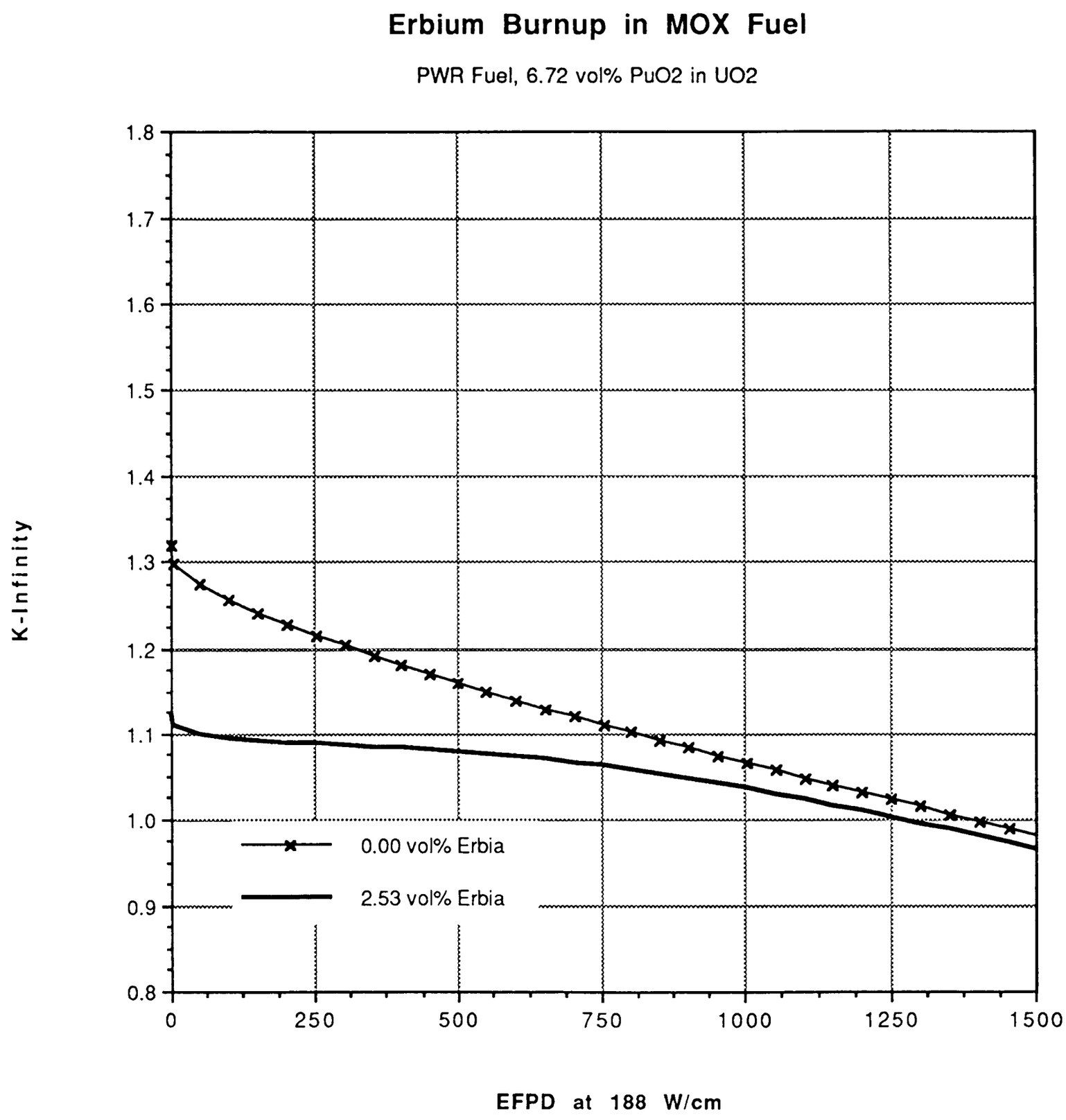
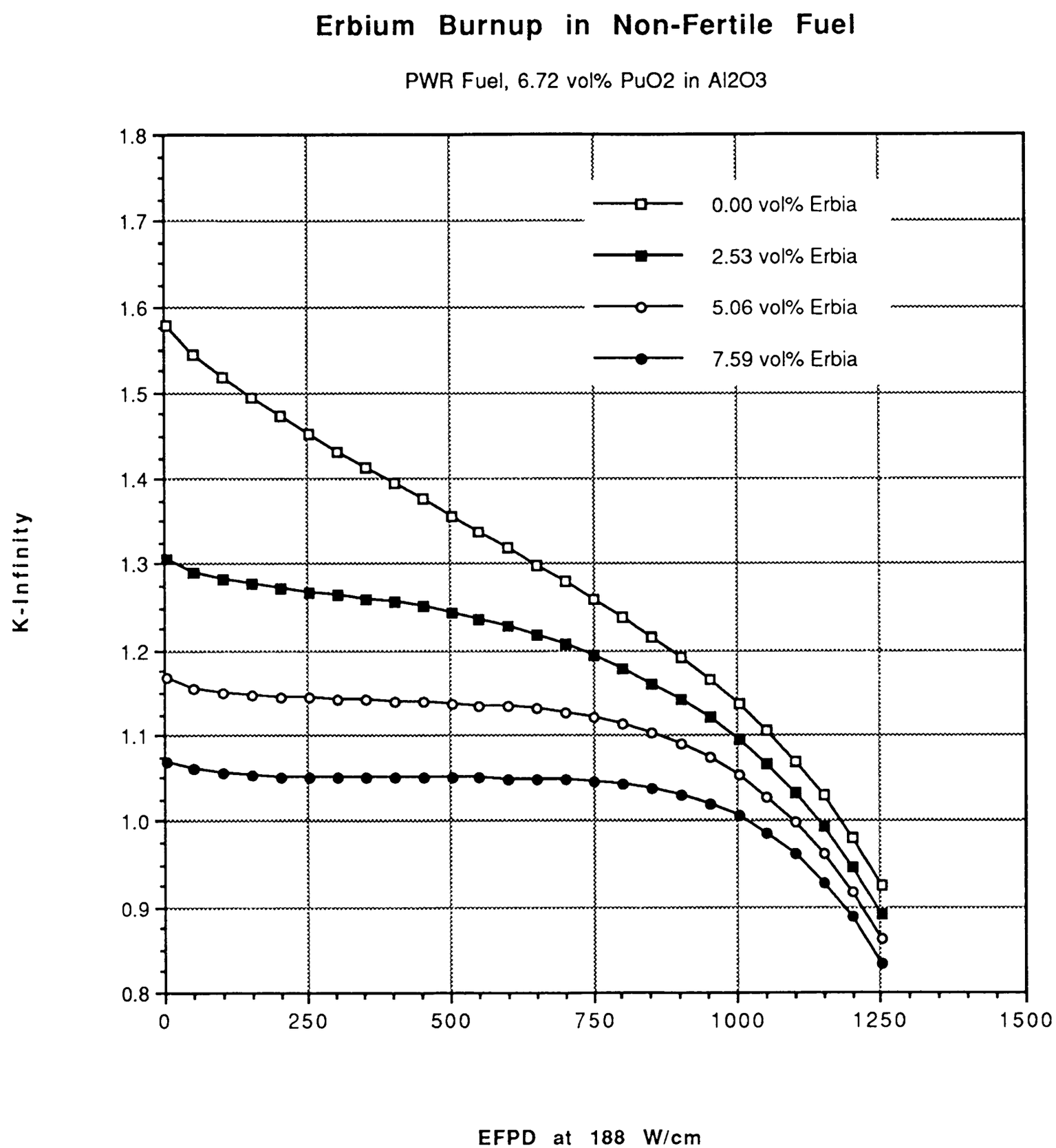
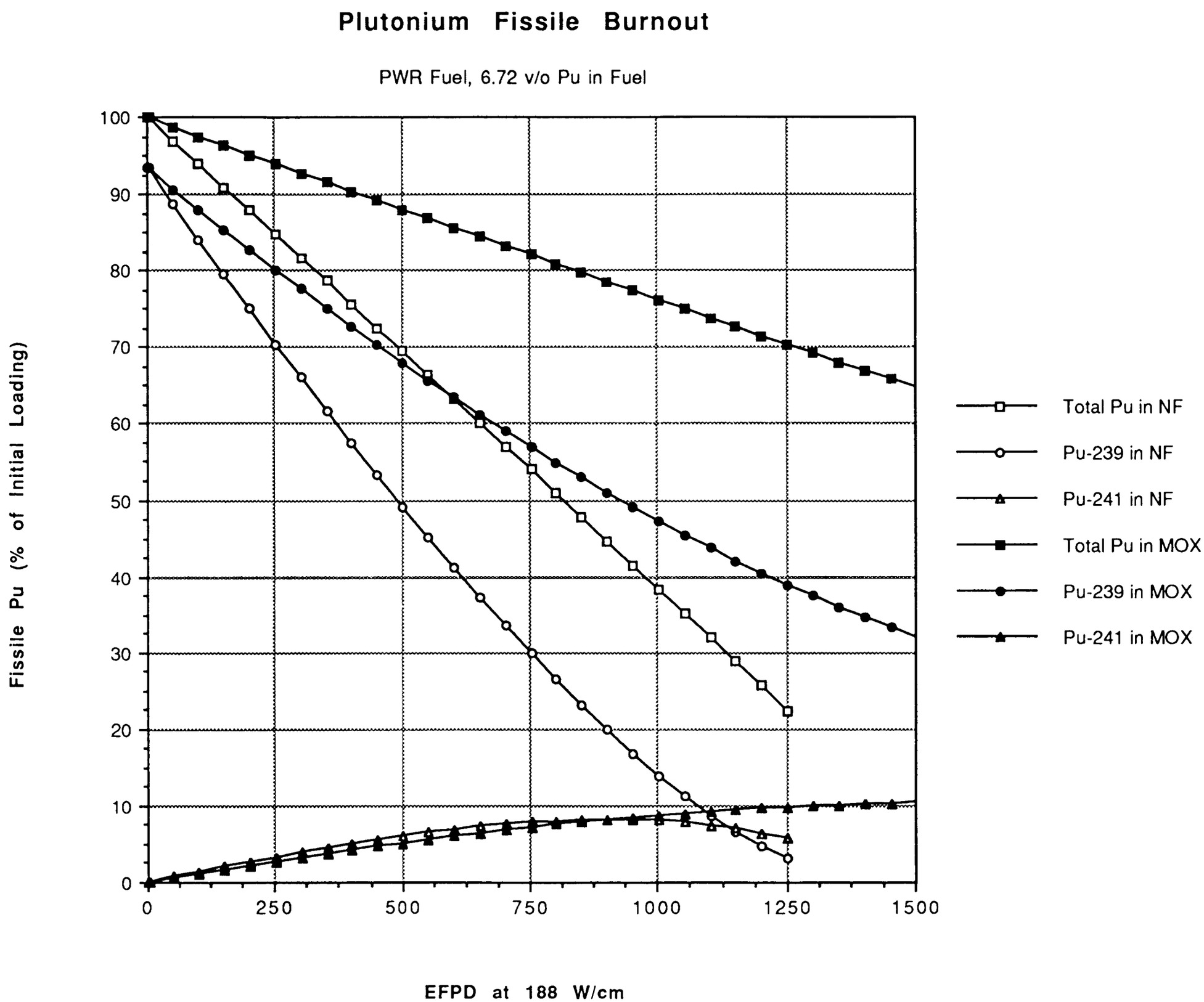
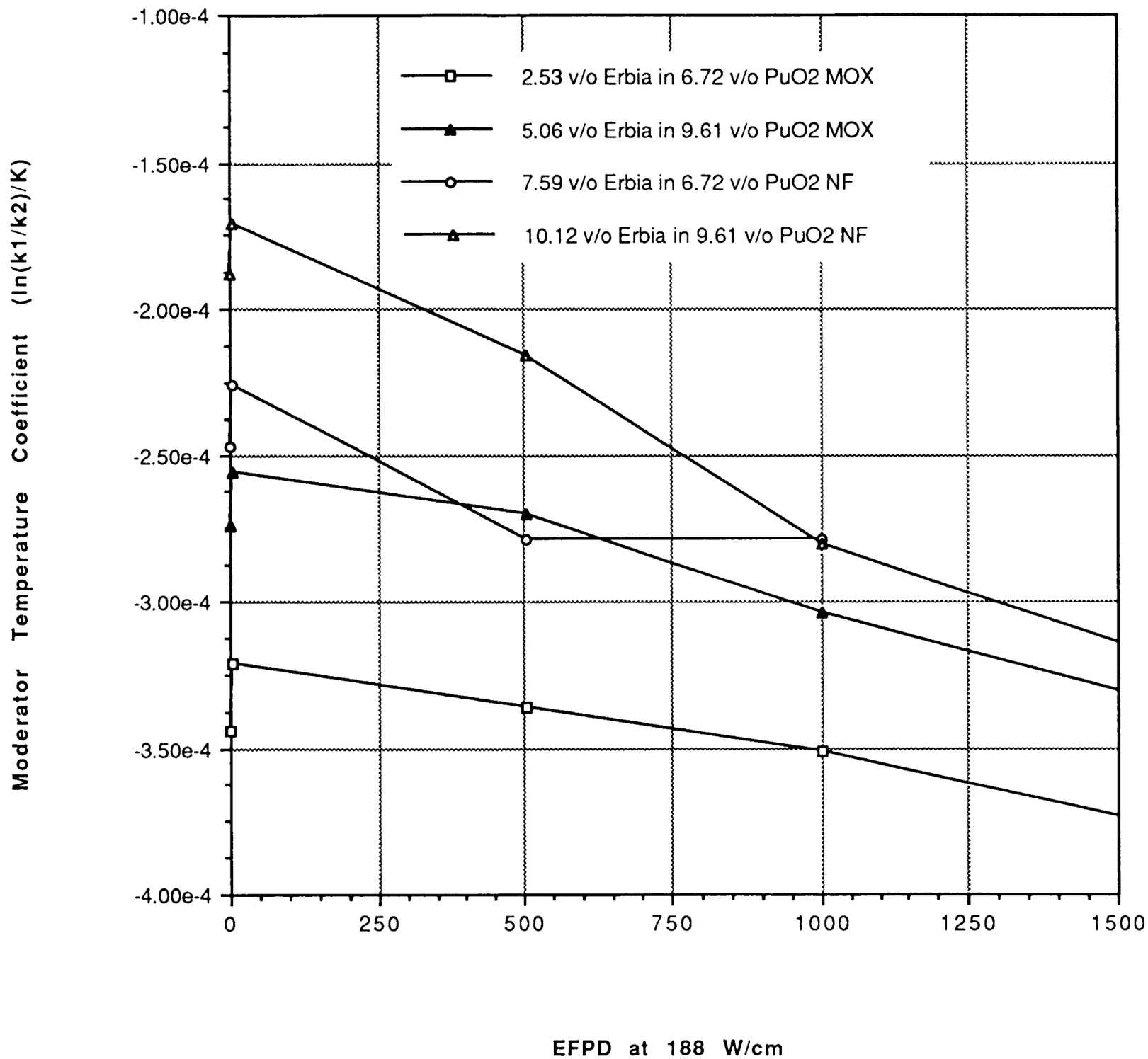
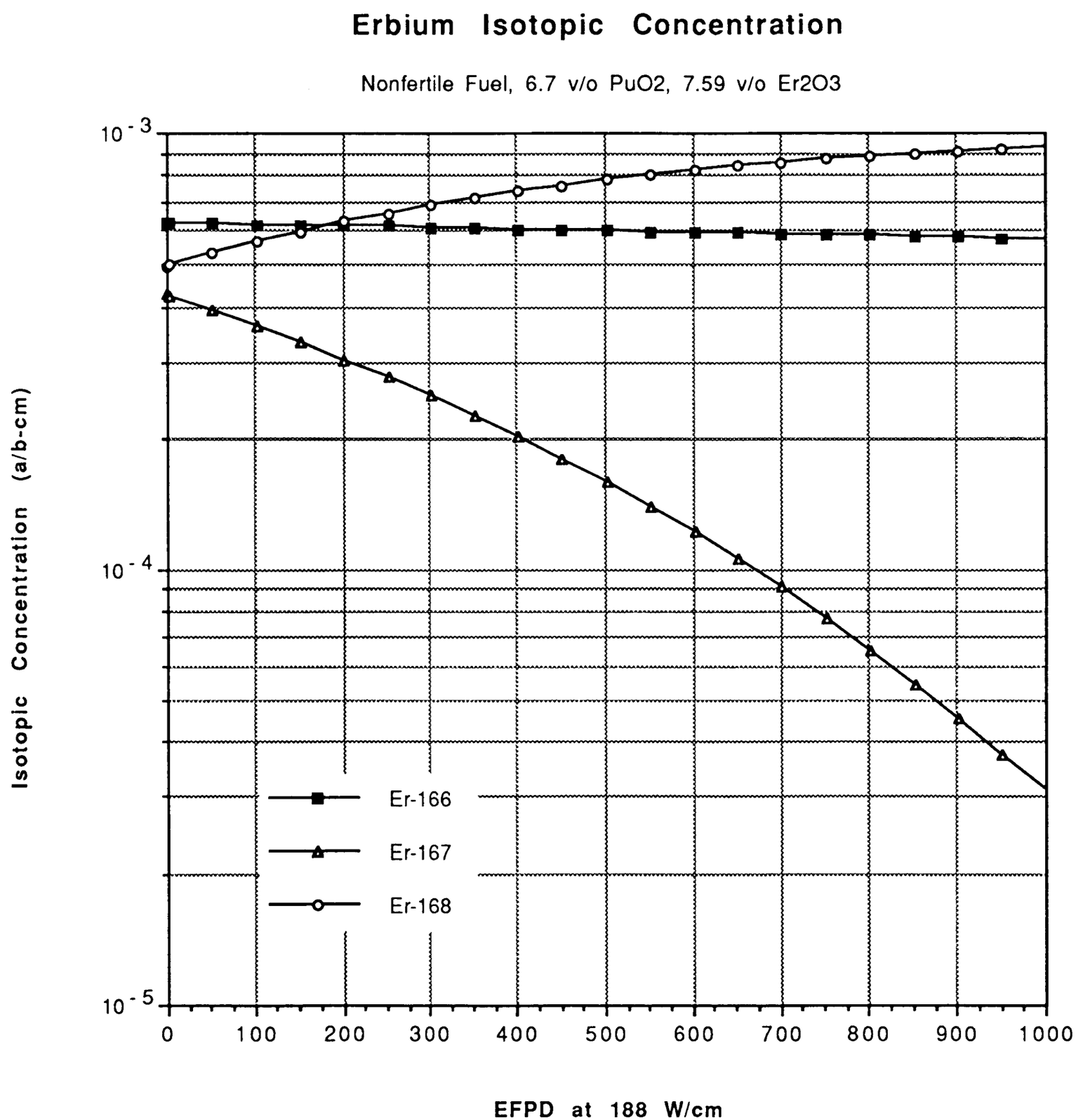

Erbium Burnup in MOX Fuel
PWR Fuel, 6.72 vol% PuO2 in UO2
K-Infinity
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0
250
500
750
1000
1250
1500
0.00 vol% Erbia
2.53 vol% Erbia
EFPD at 188 W/cm


Erbium Burnup in Non-Fertile Fuel
PWR Fuel, 6.72 vol% PuO2 in Al2O3
0.00 vol% Erbia
2.53 vol% Erbia
5.06 vol% Erbia
7.59 vol% Erbia
K-Infinity
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0
250
500
750
1000
1250
1500
EFPD at 188 W/cm


Plutonium Fissile Burnout
PWR Fuel, 6.72 v/o Pu in Fuel
Fissile Pu (% of Initial Loading)
100
90
80
70
60
50
40
30
20
10
0
0
250
500
750
1000
1250
1500
EFPD at 188 W/cm
Total Pu in NF
Pu-239 in NF
Pu-241 in NF
Total Pu in MOX
Pu-239 in MOX
Pu-241 in MOX

Moderator Temperature Coefficient in Pu Fuel




Erbium Isotopic Concentration
Nonfertile Fuel, 6.7 v/o PuO2, 7.59 v/o Er2O3
Isotopic Concentration (a/b-cm)
10 - 3
10 - 4
10 - 5
0
100
200
300
400
500
600
700
800
900
1000
EFPD at 188 W/cm
Er-166
Er-167
Er-168

SUMMARY AND CONCLUSIONS

- USE WEAPONS-GRADE Pu AS FUEL
  - EXISTING COMMERCIAL REACTOR USE FEASIBLE
  - MOX FUEL WELL DEVELOPED
  - NON-FERTILE FUEL OFFERS MAXIMUM ANNIHILATION
- NONPROLIFERATION
  - HIGHLY RADIOACTIVE FISSION PRODUCTS IN SPENT FUEL
  - PLUTONIUM DENATURED TO REACTOR-GRADE
  - 30 TO 80% OF Pu ANNIHILATED, ONCE THROUGH
  - GEOLOGIC DISPOSAL OF SPENT FUEL
- ECONOMICS
  - MAXIMIZE Pu LOADING AND EXPOSURE
  - SAVINGS FROM DISPLACED LEU
  - RECOVERS ENERGY AND ECONOMIC VALUE