Nuclear Fuel Design for SP -100

General Considerations

1.) Why not use a RTG for 100 kW_e power levels (figures)

2.) What are the general selection parameters(figure)

3.) Common forms of U^{235} (figure)

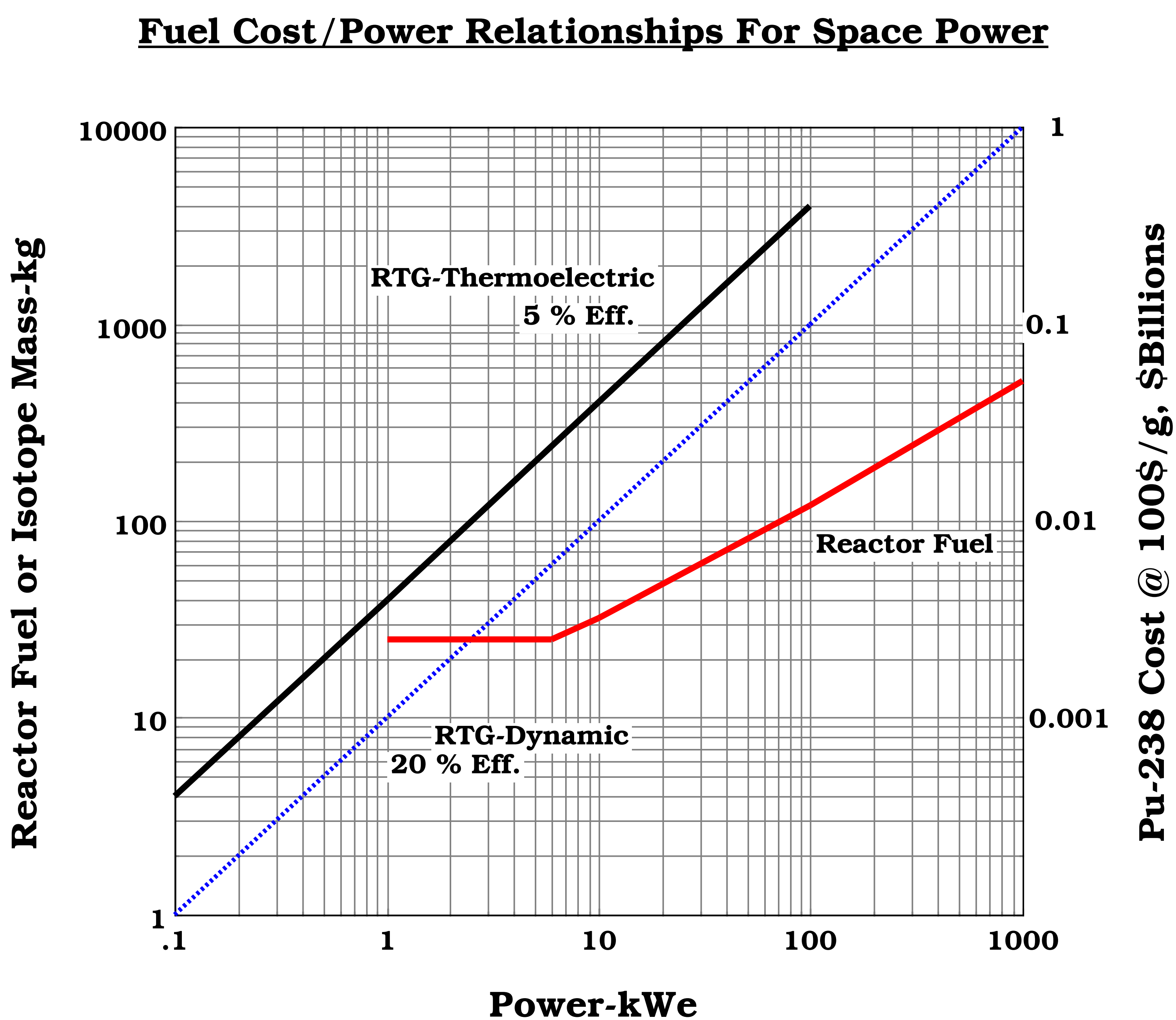
4.) Relevant data on space reactor fuels (2)

5.) Thermal effects (2 figures)

  A.) Fuel Temperature distributions
  B.) Vapor pressures

6.) Advantages and Disadvantages of fuels for space (7 figures)

  A.) UC (2)
  B.) UN
  C.) UO_2
  D.) Cermets
  E.) Coated particles (2)



Fuel Cost/Power Relationships For Space Power
Reactor Fuel or Isotope Mass-kg
10000
1000
100
10
1
Pu-238 Cost @ 100$/g, $Billions
1
0.1
0.01
0.001
RTG-Thermoelectric
5 % Eff.
Reactor Fuel
RTG-Dynamic
20 % Eff.
.1
1
10
100
1000
Power-kWe

Selection Factors For Space Reactor Fuel

- Chemical Stability at High Temperature
- Chemical Compatibility with Cladding
- Physical Stability
- High U Density
- Dimensional Stability under Irradiation

Fissionable Isotopes

-^{239}Pu-Launch Accident and Re-Entry Hazard

-^{233}U-^{232}U Buildup-Handling Difficulties (Isotope separation following reactor production prohibitively expensive)

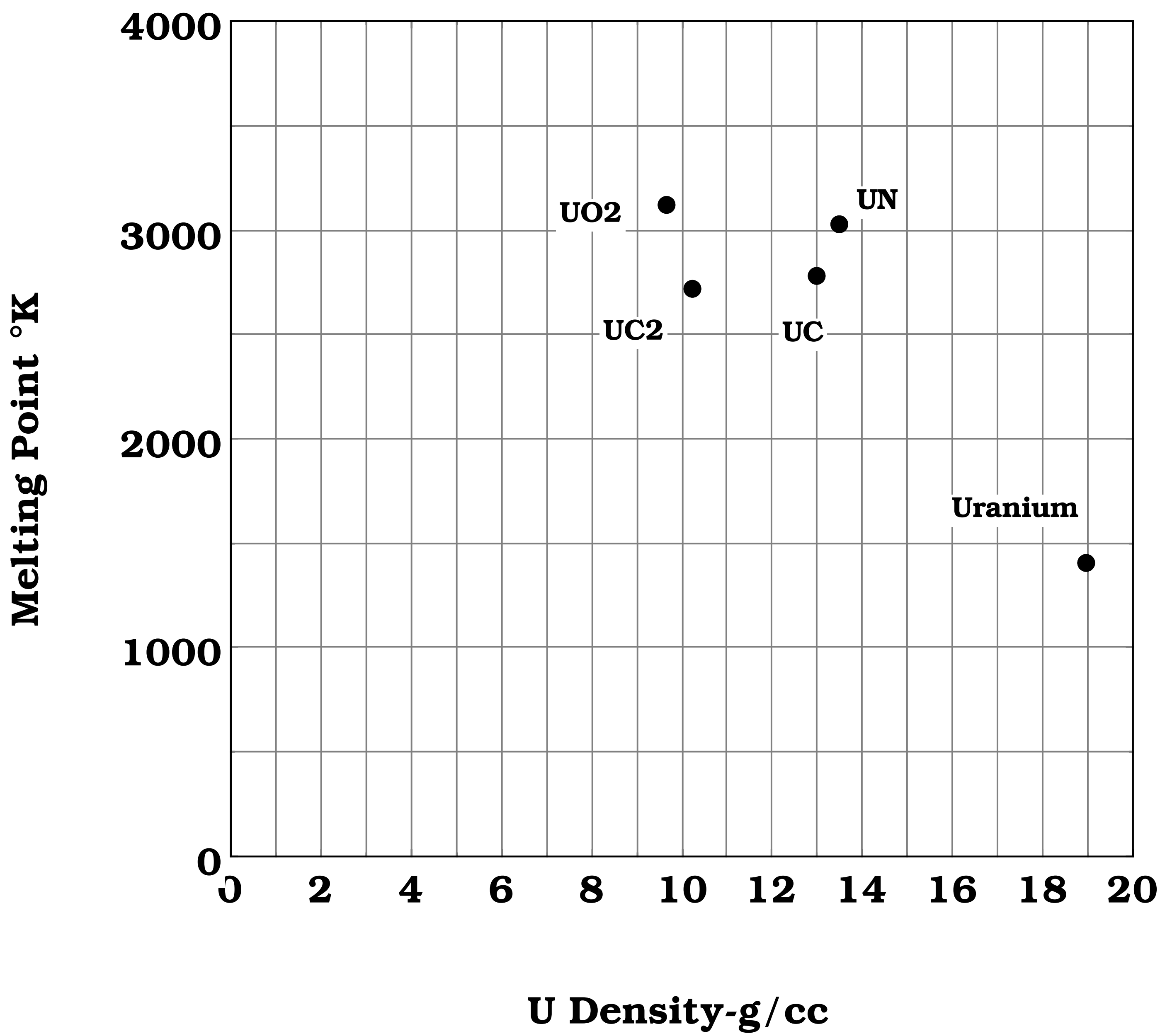
-^{235}U-Ultimate selection despite larger critical size

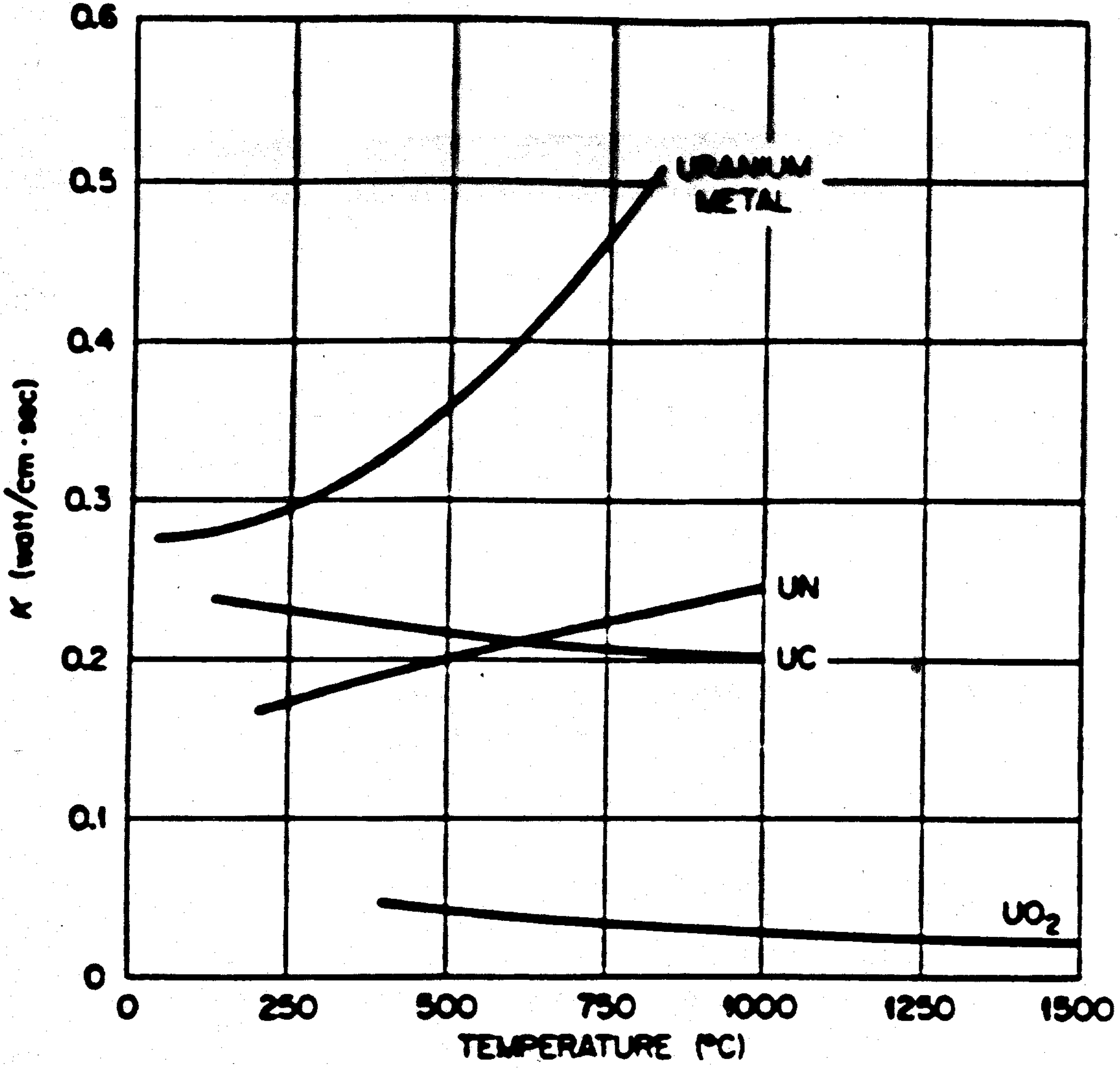
Common Forms of ^{235}U

- UZrH-Snap Reactor (thermal)
- U_3Mo-Cosmos-954, 1900
- SiC-C-UO_2, UC_2 Beads in Graphite-Rover, NERVA
- UC, UCZrC
- UO_2-Large data base for terrestrial reactors
- UN-SNAP-50

UO_2, UN cermets with W, WRe, Mo

Space Reactor Fuels



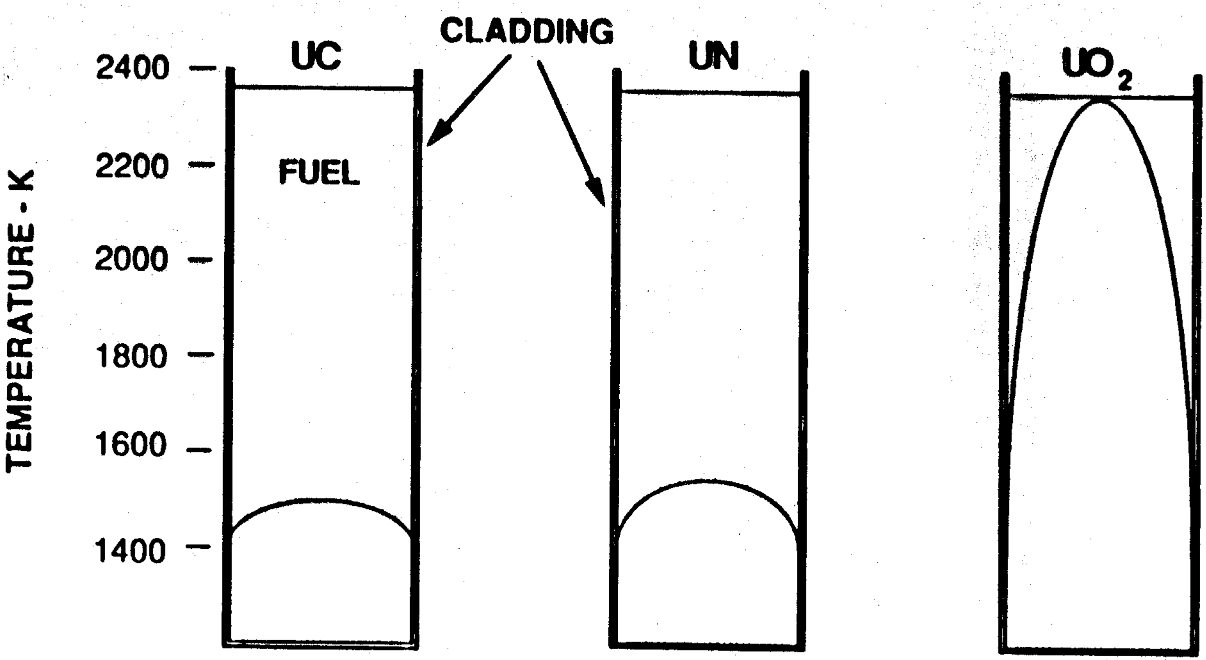


Thermal Conductivity of Reactor Fuel Materials.

COMPARATIVE FUEL TEMPERATURE DISTRIBUTION

ILLUSTRATIVE CASE:

POWER DENSITY: 200 W/cm ^{2}
FUEL ELEMENT OD: 1.3 cm
CLADDING TEMPERATURE: 1400 K
PERFECT FUEL/CLADDING THERMAL CONTACT



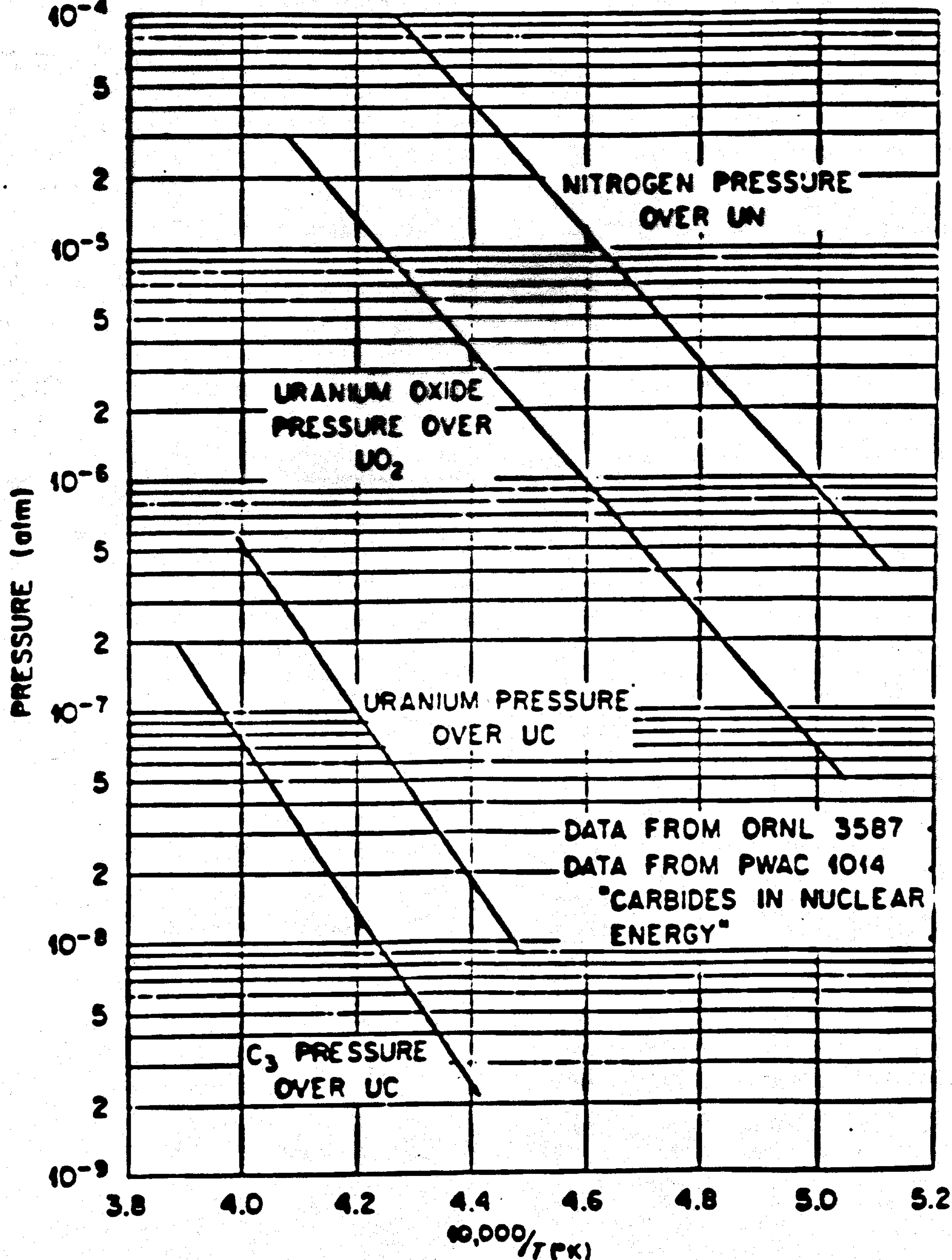
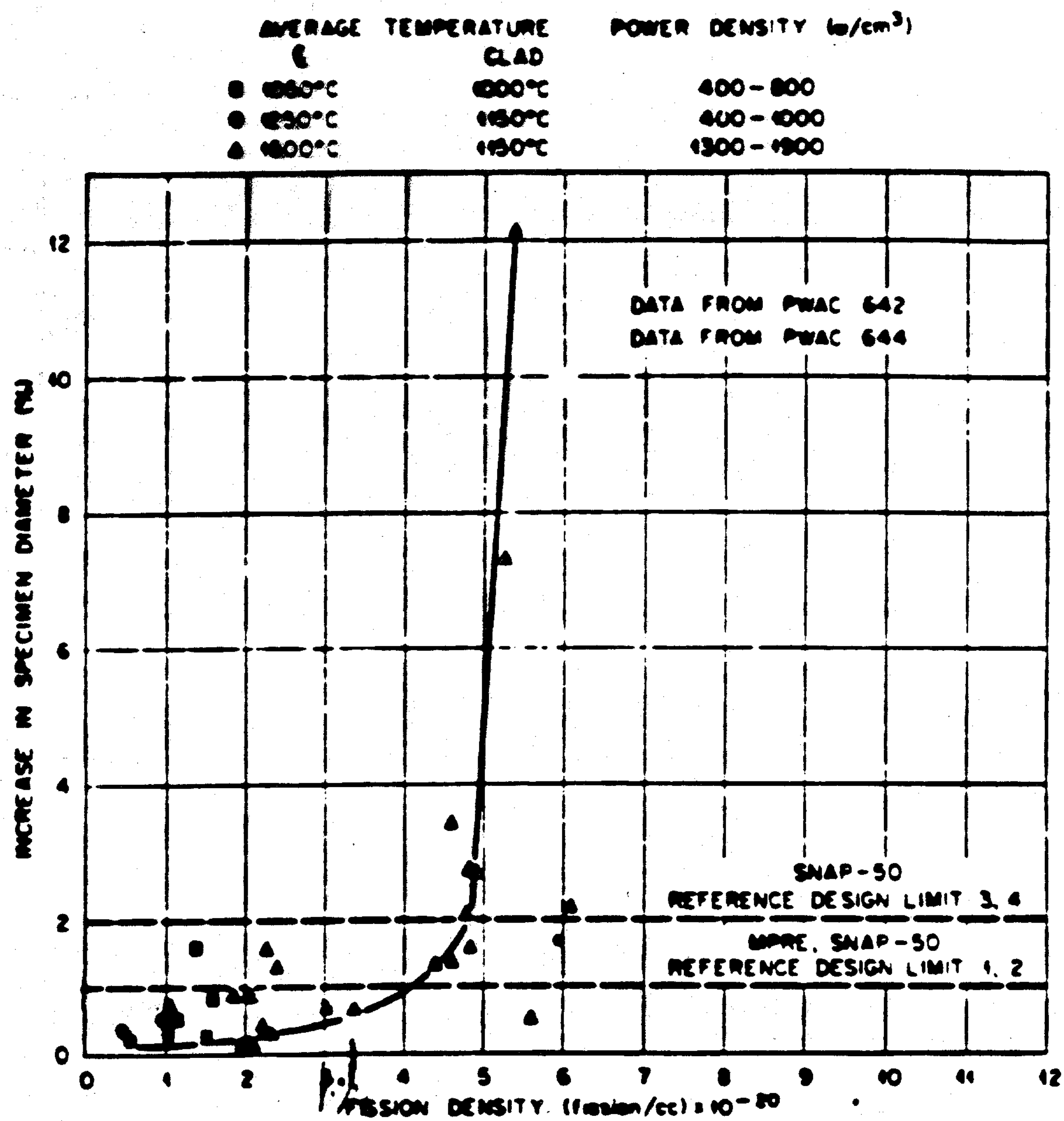


Fig. 20. Vapor Pressure of Fuels.

URANIUM CARBIDE

ADVANTAGES	DISADVANTAGES
LOW VAPORIZATION RATE	REACTION WITH Re, Mo, Nb
HIGH URANIUM DENSITY	HIGH SWELLING RATE
HIGH THERMAL CONDUCTIVITY	POSSIBLE BREAKAWAY SWELLING
	CONVERSION OF OPEN TO CLOSED POROSITY

UC FUEL PIN DIAMETRAL CHANGE



UC Fuel Pin Diametral Change.

BREAKAWAY SHOWN HERE MAY HAVE ESULTED FROM OFF-STOICHIOMETRIC CARBIDE

URANIUM NITRIDE

ADVANTAGES	DISADVANTAGES
HIGHEST URANIUM DENSITY (OF REFRACTORIES)	HIGH N_2 OVERPRESSURE
HIGH THERMAL CONDUCTIVITY	REACTION WITH Nb
COMPATIBILITY WITH LITHIUM (AS WELL AS W, Re)	

URANIUM DIOXIDE

ADVANTAGES	DISADVANTAGES
HIGH CHEMICAL STABILITY	LOW THERMAL CONDUCTIVITY
COMPARIBILITY WITH Mo, Re, W	LOWER FUEL DENSITY
VERY EXTENSIVE IRRADIATION TESTING HISTORY	HIGH VAPORIZATION RATE
	REACTION WITH LITHIUM
FUEL SWELLING SATURATION	

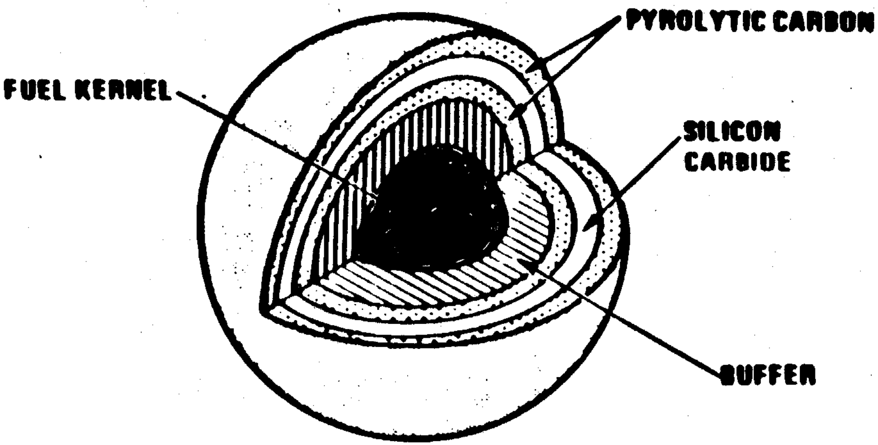
Mo, W, W25Re/UO_2,UN CERMET FUEL

ADVANTAGES	DISADVANTAGES
LOW FUEL SWELLING	LOW URANIUM DENSITY
HIGH THERMAL CONDUCTIVITY	FABRICATION INCONSISTENCY
EASY JOINING TO REFRACTORY METALS	

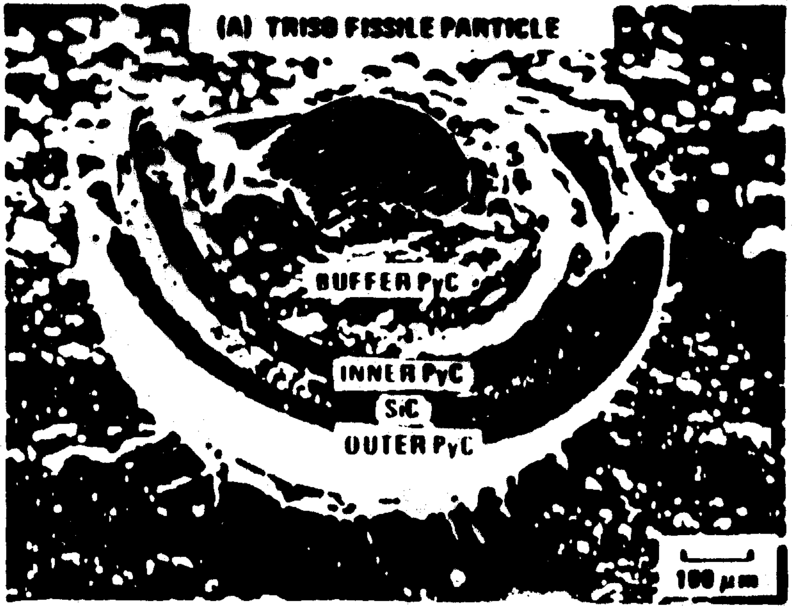
COATED PARTICLE FUELS

ADVANTAGES	DISADVANTAGES
POTENTIAL FISSION GAS RETENTION	LOW URANIUM DENSITY
POTENTIAL LOW SWELLING	REQUIRES FILLER FOR THERMAL CONDUCTIVITY
STOICHIOMETRIC CARBIDE COMPATIBLE WITH LITHIUM	ESSENTIALLY REQUIRES GAS COOLING
LOW PARASITIC NEUTRON ABSORPTION CROSS SECTION	

THE COATED PARTICLE CONCEPT



(a) SCHEMATIC OF TRISO-COATED
FUEL PARTICLE



(b) SEM MICROGRAPH OF A DELIBERATELY
FRACTURED TRISO-COATED FUEL PARTICLE

7.) Fuel Swelling (6)

- **A.) Dimensional under Irradiation**
- **B.) Swelling vs T (2)**
- **C.) Solid fission products**
- **D.) Gaseous fission products (2)**

8.) Fuel Rod design (Figure)

9.) Long term operation (Figure)

10.) Choice of UN (Figure)

DIMENSIONAL STABILITY UNDER IRRADIATION

FISSION GAS GENERATION IS THE MAJOR LIFETIME LIMITING FACTOR IN HIGH TEMPERATURE REACTORS. (0.3 ATOMS OF NOBLE GAS FORMED PER FISSION.)

SOLID FISSION PRODUCT FUEL EXPANSION IS A SECONDARY CAUSE OF FUEL EXPANSION. (1.5 - 1.7 ATOMS FORMED PER FISSION.)

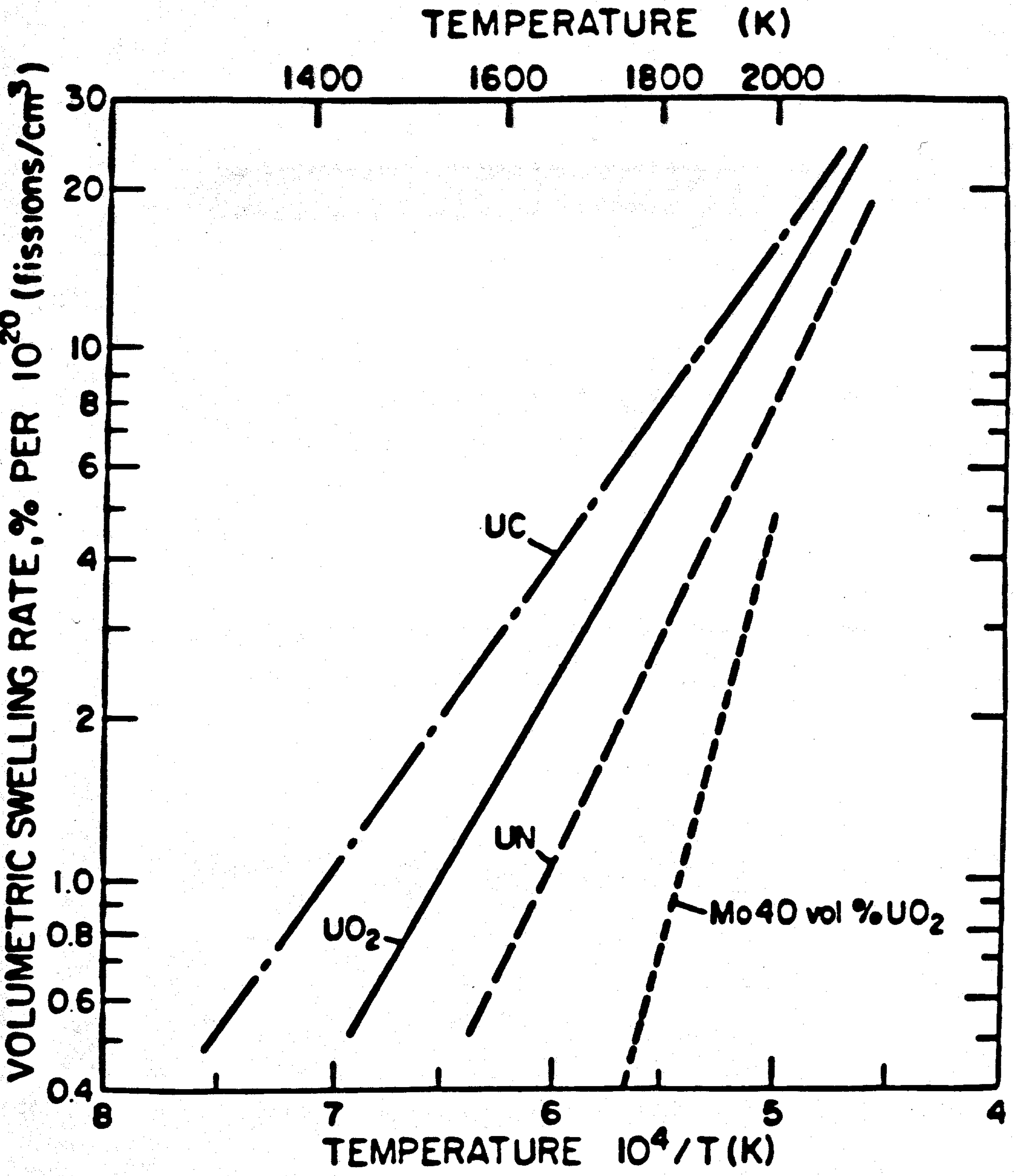
FISSION GAS EFFECTS:

- THE FRACTION ABLE TO ESCAPE FUEL MATRIX CAUSES PRESSURE BUILD UP IN FUEL ROD EXERTING STRESS ON THE CLADDING.

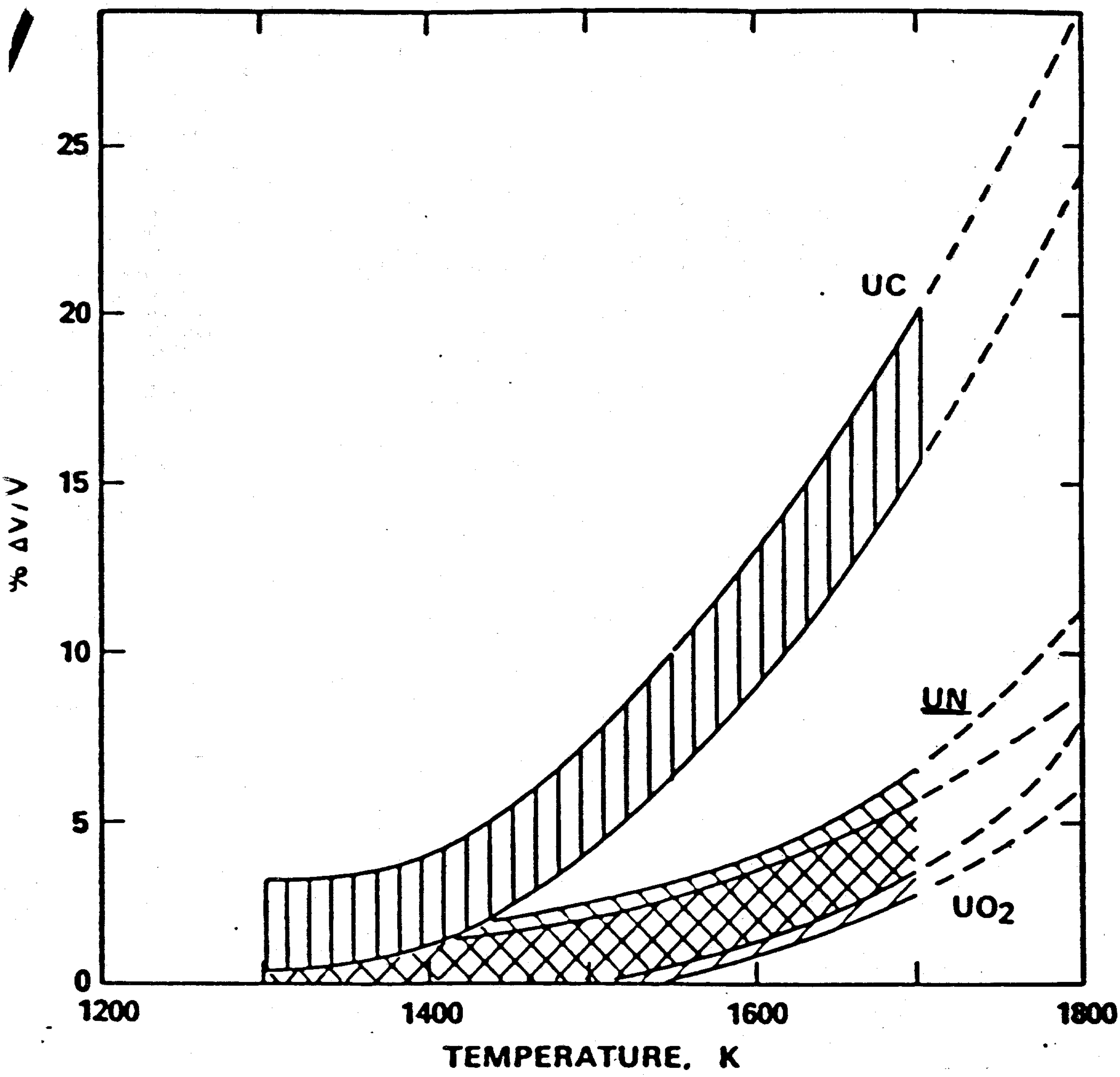
- THE FRACTION UNABLE TO ESCAPE FUEL MATRIX CAUSES FUEL TO EXPAND, EXERTING STRESS ON THE CLADDING.

FUEL SWELLING vs TEMPERATURE

W25Re CLAD FUEL SPECIMENS



MISLEADING REPRESENTATION
(SHOWS INITIAL BEHAVIOR ONLY)



% ΔV/V
0
5
10
15
20
25
1200
1400
1600
1800
TEMPERATURE, K
UC
UN
UO2

FUEL SWELLING MECHANISMS - SOLID FISSION PRODUCTS

FISSION PRODUCT ATOMS FORCE THEMSELVES INTO THE LATTICE STRUCTURE OF THE FUEL DURING THE FISSION EVENT.

APPROXIMATELY HALF OF THE "SOLID" FISSION PRODUCTS HAVE NO PLACE TO GO AND REMAIN INTERSTITIALLY IN THE FUEL LATTICE, CAUSING SWELLING.

"SOLID" FISSION PRODUCT SWELLING AMOUNTS TO 0.6 % $\Delta V/V$ PER 1 % BURNUP. IT IS LINEAR WITH BURNUP.

CESIUM AND RUBIDIUM, AND A FEW OTHER "SOLID" FISSION PRODUCTS CAN MIGRATE AND ESCAPE FAIRLY READILY AT HIGH TEMPERATURES, HENCE MAY NOT CONTRIBUTE TO THE LATTICE SWELLING.

FUEL SWELLING MECHANISMS - GASEOUS FISSION PRODUCTS

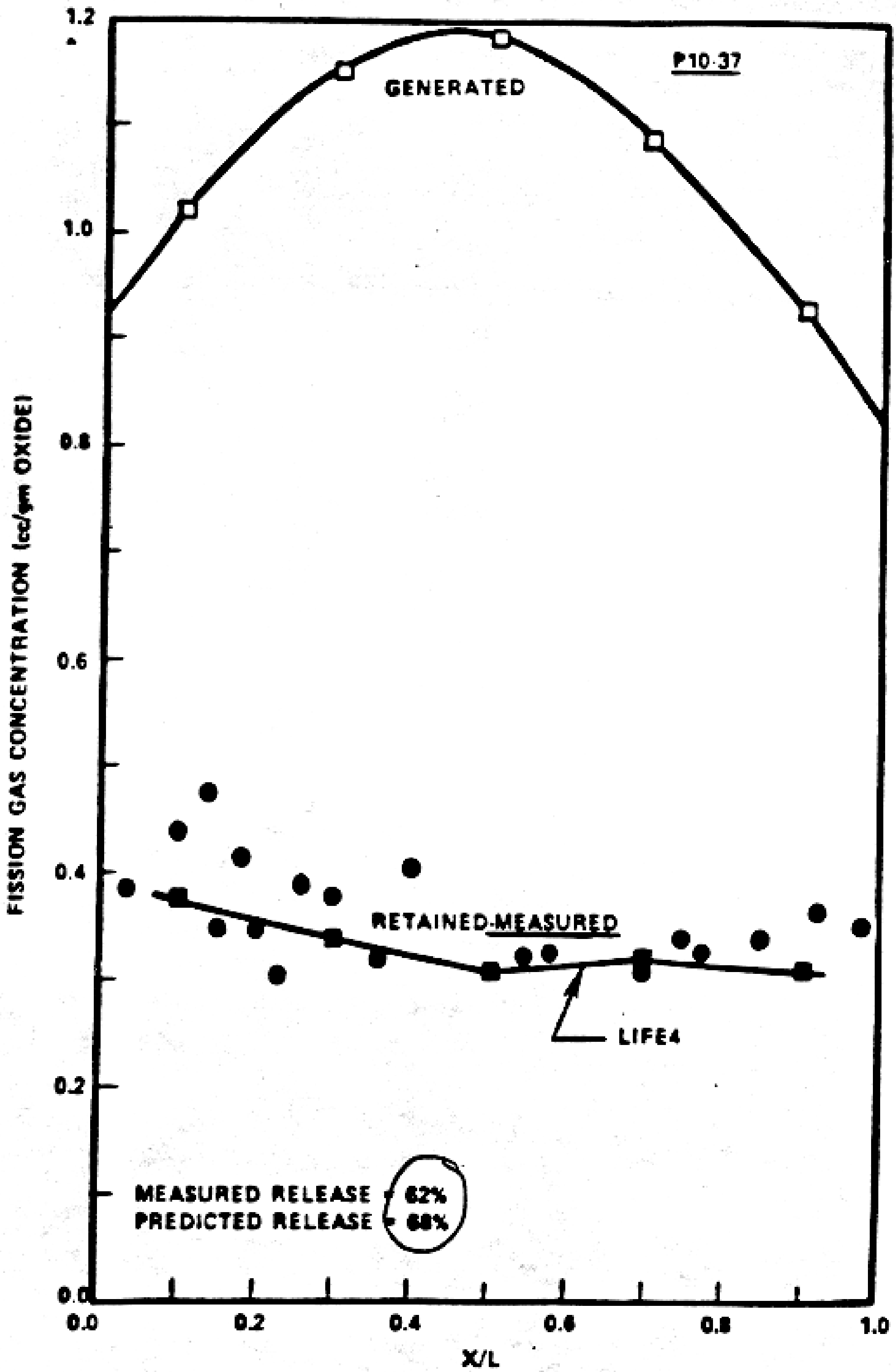
GASEOUS FISSION PRODUCTS (XENON, KRYPTON) PRECIPITATE ALONG FISSION TRACKS, FORMING SMALL BUBBLES.

BUBBLES FORMED IN THE FUEL GRAINS TEND TO BE LIMITED IN SIZE TO A FEW NANOMETERS (TENS OF ANGSTROMS) DIAMETER.

THIS LIMITATION IS CAUSED BY RE-SOLUTION, WHEREBY PASSING FISSION FRAGMENTS DRIVE THE GAS IN BUBBLES BACK INTO THE LATTICE AS INDIVIDUAL ATOMS.

BECAUSE OF THE RE-SOLUTION PROCESS, A SIGNIFICANT FRACTION OF THE FISSION GAS IS IN THE LATTICE AS INDIVIDUAL ATOMS. MOST OF THE GAS MOVEMENT OCCURS BY SINGLE-ATOM DIFFUSION.

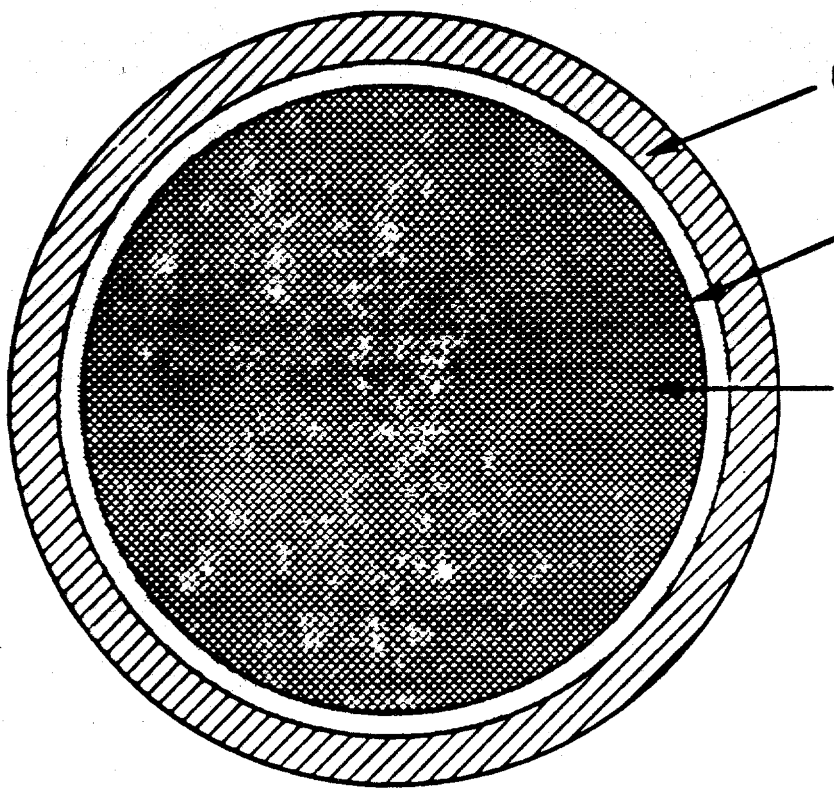
BECAUSE GRAIN BOUNDARIES ARE VERY EFFICIENT TRAPS FOR FISSION GAS, THE GAS ATOMS TEND TO FORM LARGE BUBBLES THERE. THIS IS THE PRIMARY CAUSE OF UO2 SWELLING BELOW 2000 K, AND POSSIBLY ABOVE 2000 K AS WELL.



FT-O-256

Figure 3.13. Comparison of Predicted and Measured Axial Profile of Retained Fission Gas in Pin P10-37, LIFE-4 (Rev 1)

FUEL ROD DESIGN



1.) TO ACCOMMODATE FUEL SWELLING A GAP IS LEFT BETWEEN THE FUEL PELLETS AND THE CLADDING.

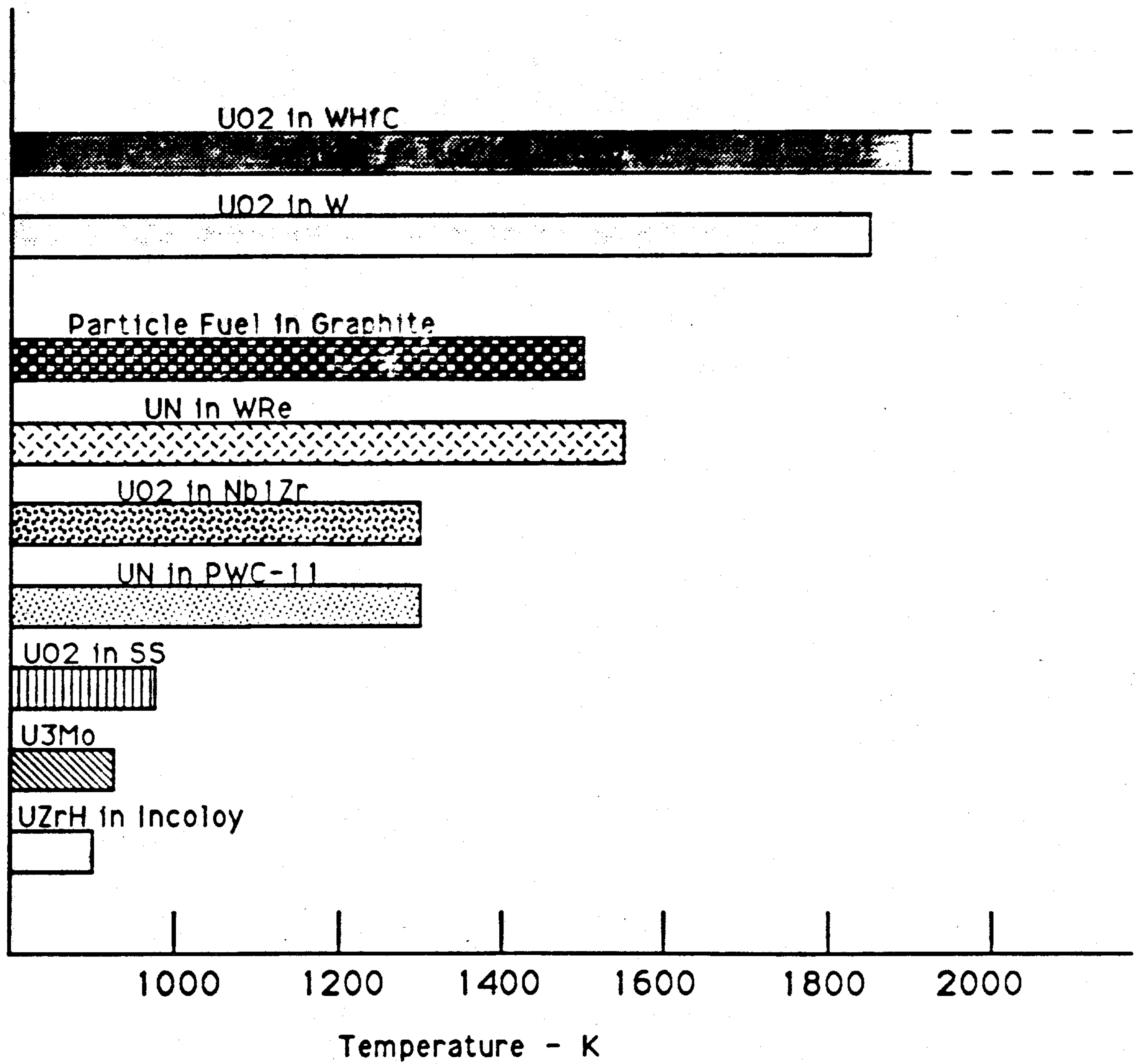
2.) THIS GAP CAUSES THE FUEL PELLET TO RUN MUCH HOTTER THE CLADDING.

3.) HELIUM IS ADDED TO THE GAP TO REDUCE THE FUEL/CLADDING ΔT.

4.) AS A RESULT OF IRRADIATION THE FUEL SWELLS AND REDUCES THE WIDTH OF THE FUEL/CLADDING GAP AND, HENCE, TENDS TO REDUCE THE ΔT.

5.) HOWEVER, FISSION GAS WITH POOR THERMAL CONDUCTIVITY (Xe, Kr) IS RELEASED FORM THE FUEL AND THIS TENDS TO INCREASE THE ΔT.

LONG TERM OPERATION CAPABILITY OF SPACE REACTOR FUELS (APPROXIMATE)



SP-100

- Oxides Unsuitable--Incompatibility with Lithium
- Question of Long Term Swelling for Carbides
- UN Selected as Reference Fuel

  Fuel Chemistry and Stoichiometry

  Fabricability

  Compatibility with Liner, Clad, and Coolant

  Potential for Loss of Nitrogen

  Solid Fission Product Transport

  Swelling and Fission Gas Release