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IRRADIATION EFFECTS ON FUELS FOR SPACE REACTORS

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ABSTRACT

Because of high-temperature/high-burnup requirements for efficient space reactor operation, fission gas induced fuel swelling and attendant gas release are important concerns in the evaluation of an optimum fuel choice and in-core design considerations. A review of irradiation induced swelling and gas release experience is presented here for the three principal fuels; UO_2, UC, and UN.

The primary advantage of UC and UN over UO_2 is higher thermal conductivity and attendant lower fuel temperature at equivalent pellet diameter and power density, while UO_2 offers the distinct benefit of well-known irradiation performance.

Irradiation test results indicate that at equivalent burnup, temperature, and porosity conditions, UC experiences higher swelling than UO_2 or UN. Fission gas swelling becomes important at fuel temperatures above ≈1320 K for UC, and at somewhat higher temperatures for UO_2 and UN. Evidence exists that at equivalent fuel temperatures and burnups, high density UO_2 and UN experience comparable swelling behavior; however, differences in thermal conductivity influence overall irradiation performance. The low conductivity of UO_2 results in higher thermal gradients which contribute to fuel microcracking and gas release. As a result UO_2 exhibits higher fractional gas release than UN, at least for burnups up to about 3%.

INTRODUCTION

Forthcoming missions of planetary exploration, earth surveillance, communications, and human presence in space require the development of a highly reliable energy source capable of providing large amounts of electrical power. Nuclear reactors offer many advantages for space applications due to their weight/power superiority and proven base technology. Nevertheless, because of long lifetime and high operating temperature requirements, potential fuel behavior problems arise with respect to thermal stability, fuel-cladding compatability, and fission gas induced swelling and release phenomena. The subject of this paper is the latter concern, where fission gas release and swelling effects are evaluated for the primary fuel candidates, namely UO_2, UC and UN.

Although the choice of reactor design will influence fuel requirements, the following criteria appear common to most reactor design concepts:

- <u>High Fuel Temperatures</u>: in the range of 1500-2000 K, so as to make possible high reject heat radiator temperatures;
- <u>High Fuel Burnup</u>: in the range of 3-10 atom percent, so as to accommodate a relatively long core lifetime of 7-10 years.

For such high-temperature/high-burnup conditions, significant fission gas induced fuel swelling and attendant gas release can be expected.

Swelling and gas release will not only impact the ultimate choice of fuel, but also as-manufactured stoichiometry, porosity, grain size, gap-thickness, gas plenum volume, etc. Swelling adversely affects fuel performance because it promotes fuel-cladding contact, which not only can cause cladding strain, but which can result in cladding contamination and alteration of mechanical properties that may shorten fuel element lifetime. Irradiation induced pore formation also decreases fuel conductivity, leading to temperatures higher than exhibited by fully dense fuel, at the same heating rate. High gas release requires either retention in a plenum which adds to reactor weight and overall dimensions, or venting of released gas to space, which complicates design considerations.

Table 1 presents an overview of properties affecting fuel performance. Although UO_2 offers the advantage of a large body of experience, its low thermal conductivity and fissile density can be a drawback where weight considerations and high temperatures are of primary importance. UC and UN in comparison offer distinct advantages with respect to thermal performance and weight characteristics. The principal drawbacks with regard to physical and chemical properties are that the carbides are more reactive with potential cladding materials and both UC and porous UN are subject to attack by water vapor in the air and hence have to be handled in protective gas environments. UN also has a relatively high vapor pressure. Because the vapor species is mainly N_2, free uranium formation will occur at high temperature unless a nitrogen overpressure is maintained.

Table I also presents a comparison of parameters affecting swelling/gas release performance, which is discussed in the following section.

OVERVIEW OF FISSION GAS BEHAVIOR

Fig. 1 illustrates the general nature of fission gas (≈25 percent of fission yield) behavior in polycrystalline fuel. Atoms of fission gas, particularly Xe and Kr, migrate to the grain boundaries of the fuel microstructure, either individually or in the form of small intragranular bubbles. At these boundaries they form larger intergranular bubbles. In as much as the gas density is lower than that of a solid, atoms residing in gas bubbles occupy more volume than the solid fissile atoms they replace. Bubble precipitation and growth thus lead to fuel swelling.

Pileup of bubbles at grain boundaries stresses the grain structure, resulting in grain boundary separation that eventually interlinks to form an interconnected network of pores. If such porosity is open to the fuel-cladding gap, fission gas is effectively vented to the pellet free surface. The fraction of gas released from the pellet gives rise to a cladding overpressure during its lifetime.

At high fuel temperature, the movement of pores formed by thermal cycling induced fuel cracking will occur by a fuel evaporation-condensation process in a temperature gradient. As discussed by Barnes (1963) and Olander (1976), such pores will migrate to the center of a cylindrical fuel body, sweeping up fission gas along the way and depositing it in a central void. This mechanism thus provides an additional means of releasing fission gases from the fuel microstructure. It is principally operative for UO_2 at temperatures above 2000 K.

Knowledge of fuel swelling/gas release behavior is of importance for designs that require high burnups, since the necessary margin required in the rod pressure to failure is reduced. The challenge to the designer is to ensure the maximum fuel rod reliability and to optimize gas retention/fuel swelling characterstics versus that for gas release and rod pressurization. It should be noted that such a competing tradeoff is not particularly restrictive if one has the option of venting gas to a large plenum or completely from the rod. Venting introduces severe complications in the design of a fuel pin reactor, however, and hence most space reactor designs call for a limited plenum volume and no gas-venting; thus, swelling and gas release phenomena are of primary concern.

Table I also lists some of the principal factors affecting fission gas behavior in polycrystalline fuel. Given the number of variables involved, the complexity of the problem becomes apparent; nevertheless, general trends have been determined from well established empirical findings and analysis of controlling phenomena. Such trends are as illustrated, where the symbol (↑) denotes a direct relationship between the variable under consideration and its effect on swelling/gas release, while the symbol (↓) denotes an inverse relationship. For example, the trend for increasing burnup is toward both increased swelling and gas release, while a larger grain size results in decreased swelling and gas release. In the following section specific findings with respect to UO_2, UC and UN fuels are reviewed.

FUEL PELLET SWELLING/GAS RELEASE EXPERIENCE

Swelling and gas release are complimentary processes. Retention of fission gases in the fuel matrix as burnup proceeds is usually accompanied by increased swelling. Conversely, fuel that releases a large fraction of its fission gas generally exhibits low swelling. However, some swelling almost always precedes gas release due to the buildup of intergranular bubbles with increased burnup. This induces matrix fuel swelling and stressing of the grain boundaries, causing grain boundary separation, interlinkage, and ultimately venting of gases from the fuel interior.

Although a large body of swelling/gas release data exists, this review centers primarily on a consideraton of UO_2, UC, and UN samples tested under similar irradiation conditions. Such an approach was deemed appropriate in order to obtain as accurate a ranking of UO_2, UC, and UN fuel swelling/gas release characteristics as possible, without the introduction of large differences in exposure conditions.

a. Battelle-Columbus Data

One of the more consistent sets of data with respect to similar UO_2, UC and UN test conditions is from the experiments of Hilbert et al (1971). Each cylindrical fuel specimen was clad with W-25 Re alloy having a diameter to thickness ratio of 12.5. The irradiation data was correlated to cladding surface temperatures. Fig. 2 presents a comparison of the high temperature swelling behavior for UN, UC, and UO_2 fuel samples, at burnups of ≈0.6 to 0.8 atom-percent. As indicated, UC experienced the greatest amount of swelling, while UN swelled the least. The data also indicates that at increased temperatures, differences in extent of swelling for the three fuel types is reduced. The lower limits of the curves in Fig. 2 represent the approximate points where a strong dependence of swelling on temperature begins, i.e., where fission gas induced swelling first becomes a factor. The cladding temperatures associated with this phenomenon are ~1320 K for UC, 1470 K for UO_2, and 1570 K for UN. As discussed by Hilbert et al (1971), at equivalent cladding temperatures the average temperature of UO_2 is ≈100 K higher than that of the carbide and nitride samples; thus, the UO_2 data would be shifted to the right accordingly. On a fuel temperature basis, the swelling rate of UO_2 would thus be nearly the same as that of UN. Clearly UC has a significantly higher swelling rate than either UO_2 or UN.

Fission gas release data for the UC and UN samples are compared in Table II. The data show that UC releases more gas than UN, and, as would be expected, highly porous fuel releases more gas than high density fuel. However, since UC swelled more than UN, it is apparent that higher gas release does not necessarily mean low swelling. To the contrary, the post-test microstructure suggest that a large proportion of the gas release was preceded by swelling. Although such parameters as initial porosity, stoichiometry, impurity content, and grain size were not well documented in the references cited and could have influenced fuel swelling/gas release conditions, the fact remains that for similarity in test conditions significant differences in swelling and gas release behavior were noted for the UC samples versus those for UO_2 or UN, at the low burnup conditions employed in these tests.

b. SNAP-50 Data

Under the SNAP program UC and UN fuels were investigated with respect to compatibility and irradiation characteristics. A tungsten lined Nb-1Zr cladding alloy was used, while W-Re alloy thermocouples measured fuel centerline and cladding surface temperatures. Details of the test conditions are described by DeCrescente et al. (1965) and Huegel (1965) and summarized in Table III.

Fig. 3 presents a comparison of the swelling and gas release data. As indicated, UN experienced significantly less swelling at an equivalent burnup than hyperstoichiometric UC. The superior swelling behavior of UN over UC, was primarily ascribed to a lower rate of bubble migration and agglomeration at grain boundaries in UN than UC.

Fig. 3 also compares fission gas release data. As indicated, the fractional release from UC at higher burnup levels (> 0.5 atom percent) is significantly greater than that observed for UN. For UN less gas reached the boundaries (more gas retained as intragranular bubbles) resulting in less buildup of intergranular bubbles, less stressing of grains, less swelling, and less attendant gas release. It was concluded that the UN crystal structure must be inherently more gas retentive than the UC structure, with UN having lower diffusivities for microbubble diffusion.

Although results must be qualified with respect to the important effects of as-fabricated properties (e.g. initial stoichiometry, porosity, grain size, cladding restraint, etc.), the fission gas data indicate that, in general, UN experiences superior gas retention and swelling behavior than UC under similar irradiation conditions. The remaining discussion therefore centers on a comparison of UO_2 and UN swelling/gas release characteristics.

c. Zimmermann et al Data

Zimmermann et al. (1975, 1978) performed irradiation experiments with UO_2 and UN annular pellets. In the oxide tests an alternating arrangement of UO_2 and Mo pellets ensured a low temperature gradient in the fuel. Because of the fabrication technique employed, the UN samples contained approximately 5-10 volume percent UO_2, generally in the form of inclusions at grain edges. Fuel temperatures in both experiments were measured via a thermocouple mounted in the mid-position between the inner and outer annular dimensions. Table IV presents pertinent fuel characteristics and irradiation conditions.

Fig. 4 presents the UO_2 swelling and gas release data as a function of burnup and temperature. The burnup dependence shows a linear increase in swelling at low and medium burnup values. However, at elevated burnup levels, the swelling rate diminishes, particularly for higher irradiation temperatures, which can be interpreted as due to the saturation of fission gas retention. Fig. 4 also illustrates fission gas release results, showing the release fraction increasing with both temperature and burnup The release fraction increases markedly with burnup in the region of one atom-percent.

Zimmerman's irradiation tests of annular UN fuel pellets were conducted to three burnup levels of 10, 20, and 30 MWd/kg-U[a]. The effects of swelling

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a. As a rule-of-thumb 10^4 megawatt-days of thermal energy released per metric ton (10^3 kg) of heavy metal corresponds to 1.0 atom-percent burnup; i.e., 10 MWd/kg-U = 1.0 atom-percent burnup.

were assessed via measurement of the change in fuel volume from its as-fabricated condition. Fig. 5 presents the change in sample volume as a function of burnup for a mean fuel temperature of ≈1520 K. The volume change, effect of sintering, and estimated fission gas induced swelling are plotted. As discussed by Zimmermann (1975), a decrease in initial volume due to radiation-induced sintering was noted, which concludes at a burnup of ≈10 MWd/kg-U. The effect of sintering and the associated enlargement of the fuel-clad gap explains the observed drop in heat transfer coefficient noted at the beginning of irradiation. Subtracting out the effect of sintering from the measured value of volume change, Zimmermann obtained the fission gas swelling curve as indicated. Below 20 MWd/kg-U the swelling rate is about one percent per 10 MWd/kg-U, while above 20 MWd/kg-U approximately 5.5 percent per 10 MWd/kg-U. It should be noted however, that the contamination of the UN samples with UO_2 may have influenced initial sintering and subsequent swelling characteristics.

A comparison of the UO_2 and UN swelling and gas release data is presented in Table IV. For the same mean fuel temperatures (≈1520 K) the data indicate similar volumetric swelling at low burnup levels. The UN sample however was more gas retentive than UO_2. Although caution must be used in extrapolation of this limited data, such a comparison illustrates that at equivalent fuel temperatures, the swelling of UO_2 and UN may be similar, which also corresponds to the trend observed by Hilbert et al (1971). One can interpret such results as indicating that at equivalent burnup and temperature conditions the UO_2 must release more gas from the fuel matrix than UN, for a similar increase in volumetric swelling. Considering the combined advantages of limited swelling and gas release, UN may exhibit somewhat better irradiation performance characteristics than high density UO_2. The one caution in this interpretation is the rather sudden increase in swelling and gas release occurring for UN between 2% and 3% burnup (Fig. 5). This behavior is similar to the breakaway swelling observed for UC at about 2% burnup for a cladding temperature of 1425 K (Weaver and Scott, 1965).

In a recent study by Rest (1983), the UO_2 fission gas release and swelling data of Zimmermann were analyzed using the FASTGRASS code, which is a mechanistic model for the prediction of fission gas and volatile behavior in stoichometric UO_2 fuel. The code calculates gas production from fissioning nuclei, bubble nucleation and re-solution, bubble migration, bubble coalescence, gas-bubble/channel formation of grain faces, interlinked porosity on grain edges, microcracking, gas release and swelling for steady-state and transient thermal conditions.

In Fig. 6, the FASTGRASS calculated UO_2 swelling, due to retained fission gas, as a function of irradiation temperature is compared with the experimental results obtained by Zimmermann (1978). In general, the predicted swelling agrees quite well with the data trends. The results show a very strong temperature dependence of the swelling rate at low burnups. With increased burnup, the swelling rate and the temperature dependence diminish, which can be attributed to the predicted interlinked grain boundary porosity and attendant gas venting from the fuel matrix. A comparison of gas release results is presented in Fig. 7. Grain diameters between 1 and 10 microns were used for the code calculations, for average fuel temperatures between 1250 and 2000 K. Good agreement is evident within the range of probable grain size. Such agreement indicates to the present reviewers, that consideration should be given to the use of the FASTGRASS code for a preliminary evaluation of

UO_2 fission gas release and swelling under SP-100 fuel conditions. Besides the Zimmermann data, Bowles and Gluyas (1975) also studied UO_2 and UN swelling/gas release phenomena under similar irradiation conditions. Their results are reviewed next.

d. Bowles and Gluyas Data

Bowles and Gluyas (1975) compared the irradiation performance of low and high density UN with high density UO_2 for space reactor applications. The variables studied were UN density (85 and 95 percent dense), fuel type (UN and UO_2), and cladding alloy (Ta-8W-2Hf and Nb-1Zr)[a]. The reason for varying initial UN density was to assess the effect of interconnected-open porosity (low density fuel) versus closed porosity (high density fuel) on fission gas release and swelling phenomena. Pertinent initial conditions and swelling/gas release results are presented in Table V. The data indicate that low-density/high-porosity UN experiences less swelling than high density UO_2, although at these burnup levels (i.e., $\leq$ 3-atom-percent) high density UN exhibits markedly higher swelling than UO_2, at equivalent density/porosity conditions.

Limited fission gas release data are given in Table V. The fission gas release from the 95 percent dense UO_2 was six to eight times greater than the gas released from the 85 percent dense UN sample.

Metallographic examination of the UO_2 pellets indicated severe pellet cracking and weakening of the grain boundaries due to fission gas bubble pileup at grain interfaces. In comparing the 95 and 85 percent dense UN fuel samples, it was found that the fission gas induced diametral increase was more readily

a. The alloy, Ta-8W-2Hf, (where the numbers refer to the weight percent of constituents added to the base metal), is sometimes referred to as T-111.

accommodated in the high-porosity/low-density specimen, as would be expected. The greater fission gas release fraction of the low-density UN may be a factor in this difference. Another factor may be the lower creep strength of the porous fuel, ameliorating its potential to strain the cladding. (The volumetric increase of these low density UN specimens may have been as much as 5%.) Of the three types of fuel, the 85 percent dense UN exhibited superior diametral stability and gas release characteristics.

e. Interdata Comparison

In the previous sections swelling and gas release data were compared for different fuels irradiated under similar test conditions. Here such data are presented in composite graphs to illustrate UO_2 versus UN irradiation performance for a wide range of test conditions. Fig. 8 illustrates swelling data from a number of sources. Several important features are first noted upon inspection of this figure, notably that all high burnup data for high density UO_2 are from Zimmermann, while no data are indicated for UN at burnup levels in excess of 3-atom-percent. Nevertheless, the fact remains that one cannot definitively conclude, based upon available data, an overriding superiority in swelling characteristics for UN over UO_2. Indeed at all burnup levels the UO_2 data generally show somewhat better swelling performance than UN, at equivalent fuel temperatures. However, it is noted that because of a lower thermal conductance, UO_2 will exhibit higher fuel temperatures at an equivalent power rating than UN, which will induce somewhat greater swelling in UO_2 over that for UN, at least at low burnups.

The practical effect of this observation is the tilt it gives towards using small diameter (and hence lower temperature drop) fuel rods with UO_2 or using molybdenum or tungsten fins for augmenting the thermal conductivity of the UO_2 when the resulting fuel volume fraction reduction can be tolerated.

These conclusions are based on comparative irradiation testing between UN and UO_2 where the specimen geometry and irradiation conditions were rather closely equivalent. In the one instance where lower density UO_2--fabricated with the use of pore formers--was irradiated under relatively isothermal, as well as unrestrained, conditions, the conclusions are substantially different. The lowermost curve in Fig. 8 shows the swelling observed for 93% dense UO_2 irradiated in the form of 1-mm diameter spheres to burnups of approximately 2%, 4%, and 6% at an average fuel temperature of 1770 K (Kauffmann, et al., 1980). The shape of the curve suggests that above 2% burnup fuel sintering forces counterbalanced residual fission gas swelling forces. As a result the swelling at 1770 K and 6% burnup was just slightly more than 1%.

Fig. 9 illustrates a comparison of gas release behavior between UN and UO_2, where again it is noted that the data for UN are limited to burnup levels less than 3-atom-percent. Comparing the low burnup data, it can be seen that for equivalent fuel temperatures, the UN data indicate less gas release than from UO_2. Unfortunately the UN data are too limited to extrapolate to high burnup conditions. However, the trend is toward high fractional gas release for burnups greater than 3%.

COATED PARTICLE FUELS

An alternative type of fuel configuration is the coated particle concept used successfully in gas cooled reactor design. In this concept the idea is to retain the fission gases in an impervious shell of high strength carbide. To date most irradiation experience has been with UC_2 or UO_2 kernels of fuel coated with a succession of graphite and SiC layers. For these particles the ratio of fuel volume to total particle volume has been low--on the order of 10%--so that they are of little interest for high performance space reactor design. However, a small amount of data consists for UO_2 kernels coated with sufficiently thin pyrocarbon and ZrC so that fuel volume fractions of 68 to 72% were obtained (Bullock and Kaae, 1982). This data suggests that, for burnups on the order of 5% and coated particles surface temperatures of 1475 K, it may be possible to contain the fission gases within the particle. If such containment could be obtained with similarly coated UC particles it could eliminate the need for either a fission gas plenum or venting of the fuel rods and do so with relatively little penalty in fuel density compared to UO_2 fuel.

FUEL SWELLING EFFECTS IN THE IN-CORE THERMIONIC CONVERTERS

The fuel form for in-core thermionic reactors consists of relatively thin-walled cylindrical refractory metal cups filled with nuclear fuel. These cups are the fueled emitters which, when heated in cesium vapor to temperatures above about 1700 K by the fission process, produce the electron emission current upon which the thermionic conversion process is based. For reactor power levels of 100 kW_e the optimum fuel emitter diameter is somewhat above two centimeters and the average emitter temperature is on the order of 1750-1800 K. The need for good electron emission properties and for fuel and clad stability at these temperatures has led to the selection of chemically vapor deposited tungsten as the cladding (high strength and excellent emission properties) and to UO_2 as the fuel. UC has been tested for this application but has been found to cause deterioration of the tungsten emission properties with time and has been observed to exhibit breakaway swelling at about 0.2% burnup at 1860 K (Fitzpatrick, Yates and Schwarzen, 1973). This behavior is shown in Fig. 10 for both 1940 K and 1860 K. The initial density of this fuel was about 75% of theoretical. Associated with the sudden diametral increase of the tungsten cladding and fuel was a very pronounced fall-off of the surface area of the interconnected porosity, caused either by a coarsening of the initial porosity or a change from open to closed porosity.

Irradiation tests of tungsten clad UO_2 also show diametral increase. In this case it is roughly linear with burnup and amounts to about 4.3% increase in diameter for each 1% burnup in 28-mm diameter specimens with 1.0-mm tungsten cladding at 1780 K. Doubling the cladding thickness reduced the rate of diametral increase to approximately 2.4% per 1% burnup. A diametral increase of about 2% will cause the fueled emitter to short out to the collector that surrounds it in the typical thermionic fuel element design. It should be emphasized, however, that these dimensional increase rates represent initial values for data limited to about 0.3% burnup and it is likely that a linear extrapolation of these results will overpredict swelling at higher burnup values due to saturation-of-swelling effects. The lack of high-burnup experience for thermionic fuels, however, makes lifetime prediction tenuous.

The high disassociation pressure of UN (see Table I) at thermionic emitter temperatures as well as unfavorable high temperature irradiation data in W25Re cladding (severe cladding-fuel reaction and swelling) (Keller, 1970) has discouraged the use of this fuel for the thermionic application. A further discussion of thermionic fuel element design and irradiation performance can be found in the GA (1973) and Yang (1972) papers cited in the Reference list.

SUMMARY/CONCLUSIONS

From the foregoing comparison of irradiation data, the following conclusions are drawn with respect to fission gas induced swelling and attendant gas release behavior.

Swelling Phenomena

- The predominant factors affecting fuel swelling are burnup level and temperature, where an increase in both results in increased swelling.
- Fission gas induced fuel swelling is caused primarily by the growth of intergranular bubbles entrapped at grain boundaries prior to the development of interlinked grain boundary porosity. Once such interlinked porosity has developed, fission gas release via 'tunneling' to the pellet exterior occurs, resulting in a saturation of swelling.
- For equivalent burnup, temperature, and fabricated porosity conditions, UC fuel experiences significantly more swelling than either UO_2 or UN. Enhanced swelling caused by fission gas has been observed for temperatures above about 1350K for UC and at somewhat higher temperatures for UO_2 and UN.
- Fuel stoichiometry condition and impurity content can have a pronounced effect on swelling. Other factors being equal, hyperstoichiometric (nitrogen-rich) UN exhibits less swelling than hypostoichiometric (nitrogen-deficient) UN, which is also true for UC. However, in general hyperstoichiometric UO_{2+x} experiences greater swelling than oxygen deficient UO_2, due to enhanced gas diffusivities in oxygen-rich UO_2.
- Although evidence exists that at equivalent fuel temperatures and burnup levels, UO_2 and UN experience comparable swelling behavior, differences in thermal conductivity influence overall irradiation performance. The low conductivity of UO_2 results in higher thermal gradients which contribute to

fuel microcracking and gas release. As a result UO_2 exhibits higher gas release fraction than UN, at least for burnups up to about 3%.

Gas Release Phenomena

- The three predominant factors affecting fission gas release are porosity, burnup, and fuel temperature. Interconnected porosity in the fuel enhances gas release as do higher temperature and burnup conditions.
- The effect of as-manufactured fuel porosity is two-fold. Closed porosity can serve as a collection vessel for fission gas so that fuel of this type can actually be more gas retentive than fully dense fuel where gas collects at grain boundaries and generates its own, eventually interconnected, porosity. Duplicating this self-generated interconnected porosity in the initial fuel may produce a fuel that has inherently high gas release properties and consequently low swelling characteristics.
- Microcracking, due to fission gas pileup at grain boundaries and elevated temperatures, exerts a strong influence on gas release. Because UO_2 exhibits lower thermal performance, microcracking and attendant enhanced gas release can be expected to somewhat greater UO_2 than UN, other factors being equal.
- Venting of released fission gas into space may be a viable alternative to plenum containment. This is readily accomplished for reactor designs in the fuel surrounding the coolant channels, but introduces considerable design complexity for fuel pin type reactors. In addition, condensation of non-noble gas volatile fission products such as iodine, cesium, strontium and tellurium and/or their associated compounds (e.g., CsI and various tellurides) can introduce potential fission product induced corrosion and plugging of vent lines.

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LIST OF FIGURES

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TABLE I

Comparison of UO_2, UC, and UN properties and parameters affecting fission gas induced fuel swelling and gas release behavior.

Properties:

Property	UO_2	UC	UN
Theoretical density, g/cm^3	10.97	13.63	14.32
Uranium density, g/cm^3	9.67	12.97	13.52
Melting Point, K	3120	2660	3030
Thermal conductivity at 1300 K, w/cm-K	0.03	0.25	0.23
Crystal Structure	Cubic-CaF_2	Cubic-NaCl	Cubic-NaCl
	a = 5.47 Å	a = 4.96 Å	a = 4.89 Å
Vapor Pressure, Pa (Stoichiometric Compound)			
1600 K	1.5×10^{-6}	$\sim 10^{-9}$	2×10^{-5}
1800 K	2.0×10^{-4}	$\sim 2 \times 10^{-7}$	2×10^{-3}

Swelling/Gas Release Trends:

Variable	Fuel Swelling	Fission Gas Release
Increased Microcracking	(↓)	(↑)
Increased Burnup	(↑)	(↑)
Increased Temperature	(↑)	(↑)
Increased Dislocation Density	(↓)	(↓)
Increased Grain Size	(↓)	(↓)
Increased Porosity	(↓)	(↑↓)[a]

(↑) Denotes direct proportionality
(↓) Denotes inverse proportionality
a. Medium initial porosity traps gas bubbles in fuel matrix, high initial porosity vents gas to pellet surface.

TABLE II

Hilbert et al fission gas release data for fuel samples irradiated to a burnup level of $2(10^{20})$ fissions/cm^3 at a cladding surface temperature of ≈2000K

	Percent Gas Release	
Fuel	High-Density Fuel (98-99 TD)	Porous Fuel (60-70 TD)
UN	<5 percent	≈20 percent
UC	≈40 percent	≈90 percent

To convert MW-d/ton-u into fiss/cm^3, the burnup in MW-d/ton-U is multiplied by $2.68(10^{15})$ and the uranium density (g/cm^3) of the fuel. Thus, $2(20^{20})$ fiss/cm^3 ≈$0.6(10^4)$ MW-d/ton-U ≈0.6 atom-percent burnup.

TABLE III

Fuel and irradiation parameters for the SNAP-50 UN and UC comparative study of fuel swelling and gas release characteristics

Property	UC	UN
Fuel Density, percent TD	80-97	90-96.4
U-235 enrichment, percent	9.6-11.6	10-93
Rod OD, cm	0.75	0.75-0.79
Fuel stoichiometry	0.94-1.14	not specified
Burnup, atom-percent	0.31-1.84	0.31-1.94
Clad surface Temp., K	1340-1530	1240-1520
Fuel center Temp., K	1480-1870	1370-1840

TABLE IV

Zimmermann UO_2 and UN fuel characteristics and irradiation data at a fuel mean temperature ≈1500K

Test Conditions:

Property	Unrestrained UO_2 Samples	Unrestrained UN Samples
Fuel density, percent TD	98	95
U-235 enrichment, percent	15	8
Mean grain diameter, μm	10	15
Fuel stoichiometry	2.00 <O/U <2.005	5-10 vol.-percent UO_2
Pellet annular diameters, mm	5.1/2.2	9.87/2.9
Pellet height, mm	1	4.5-8.5
Burnup, percent U	0.4-12	1.0-3.0
Mean fuel temperature, K	1300 - 2020	1450-2070

Irradiation Results:

Burnup, atom percent	Volume Swelling, percent UO_2	Volume Swelling, percent UN	Gas Release, percent UO_2	Gas Release, percent UN
1	1	1	10	0.4
2	3	2	27	0.1
3	5	7	40	29

TABLE V

Bowles and Gluyas UO_2 and UN characteristics and irradiation data

Test Conditions:

Property	UO_2	UN
Cladding	Nb-Zr/T-111	T-111
Cladding liner	Tungsten (W)	Tungsten (W)
U-235 enrichment, percent	8.0-10.0	10.96-19.86
Fuel Density, percent TD	95	85/95
Pellet OD, cm	0.78	0.78
Burnup, atom-percent	1.67-2.04	2.64-2.87

Swelling Data (at cladding surface temperature ≈1260 K):

Clad	Fuel Density, percent	Burnup, atom-percent	Cladding Diametral Change, percent
T-111	85-UN	2.87	0.2
T-111	85-UN	2.83	0.3
T-111	85-UN	2.79	0.2
T-111	85-UN	2.72	0.4
T-111	95-UN	2.74	1.5 (Cracked Cladding)
T-111	95-UN	2.64	3.7 (Cracked Cladding)
Nb-Zr	95-UO_2	1.67	0.5
T-111	95-UO_2	1.76	0.5
Nb-Zr	95-UO_2	2.04	1.0

Gas Release Data:

Clad	Fuel Density, percent	Fission Gas Release, percent
T-111	85-UN	4.3
T-111	95-UO_2	34.9
Nb-Zr	95-UO_2	26.4

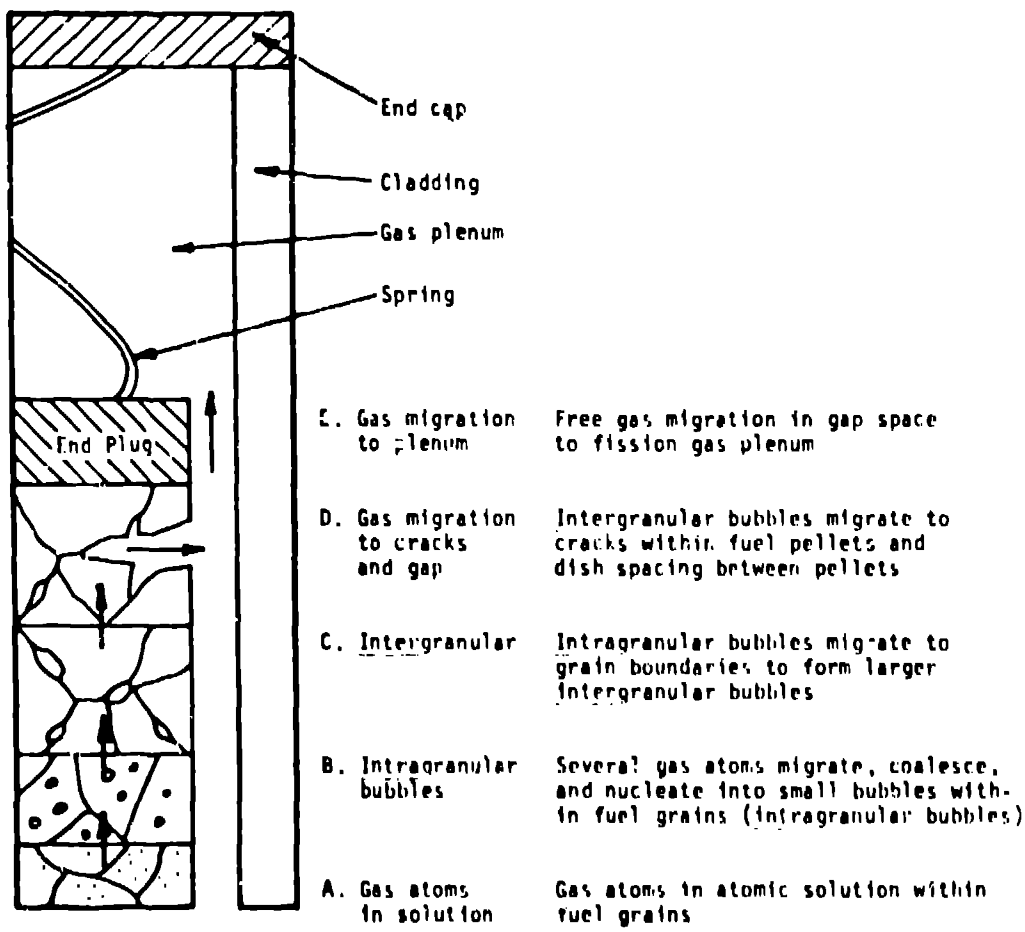

Fig. 1. Illustration of fission gas behavior in solid fuel.

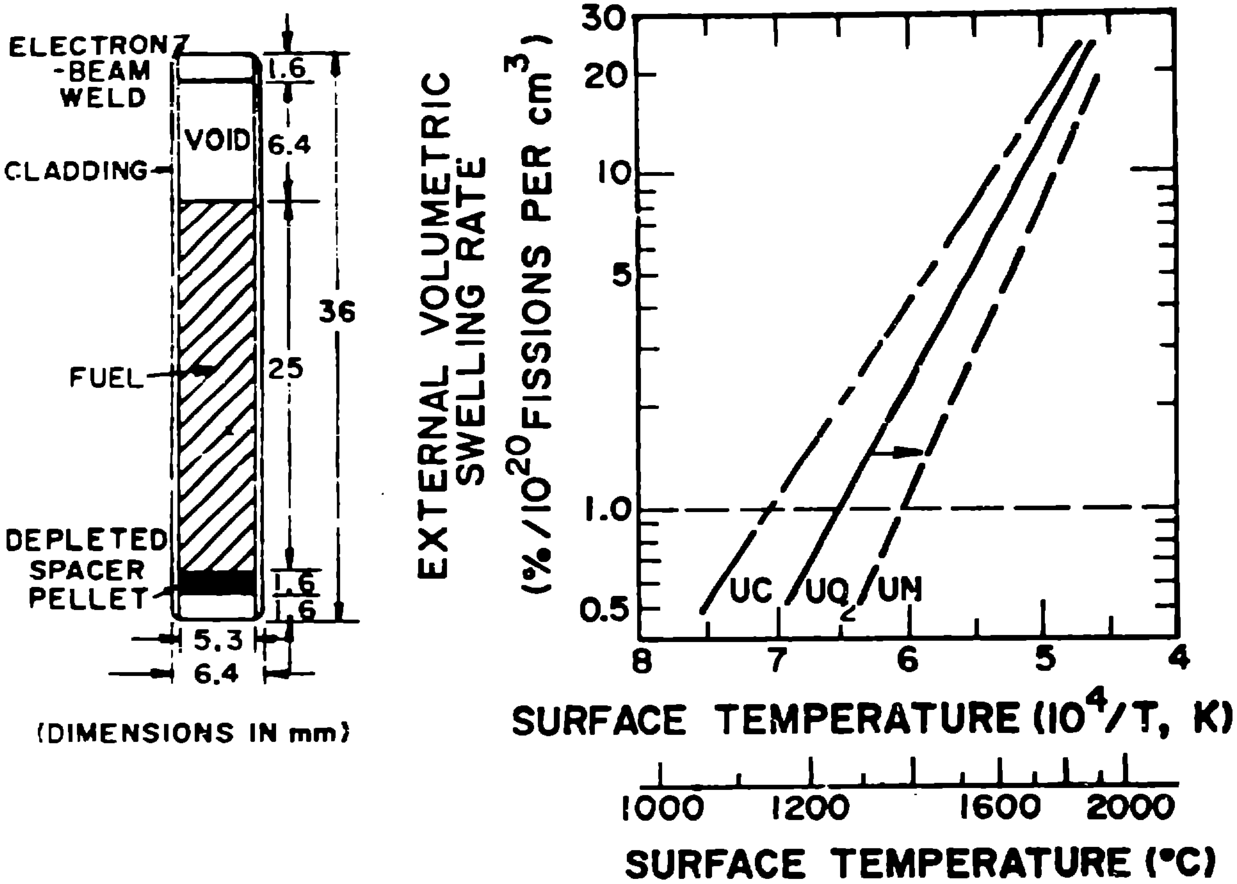

Fig. 2. Hilbert et al., irradiation geometry and associated swelling data as a function of cladding surface temperature, at a burnup of 2.0 (10^{20}) fiss/cm^3 (i.e., ≅ 0.6 atom-% for UN and UC, ≅ 0.77 atom-% for UO_2). The arrow on the UO_2 curve indicates the amount of relative curve shift that occurs if average fuel temperature is used instead of fuel surface temperature.

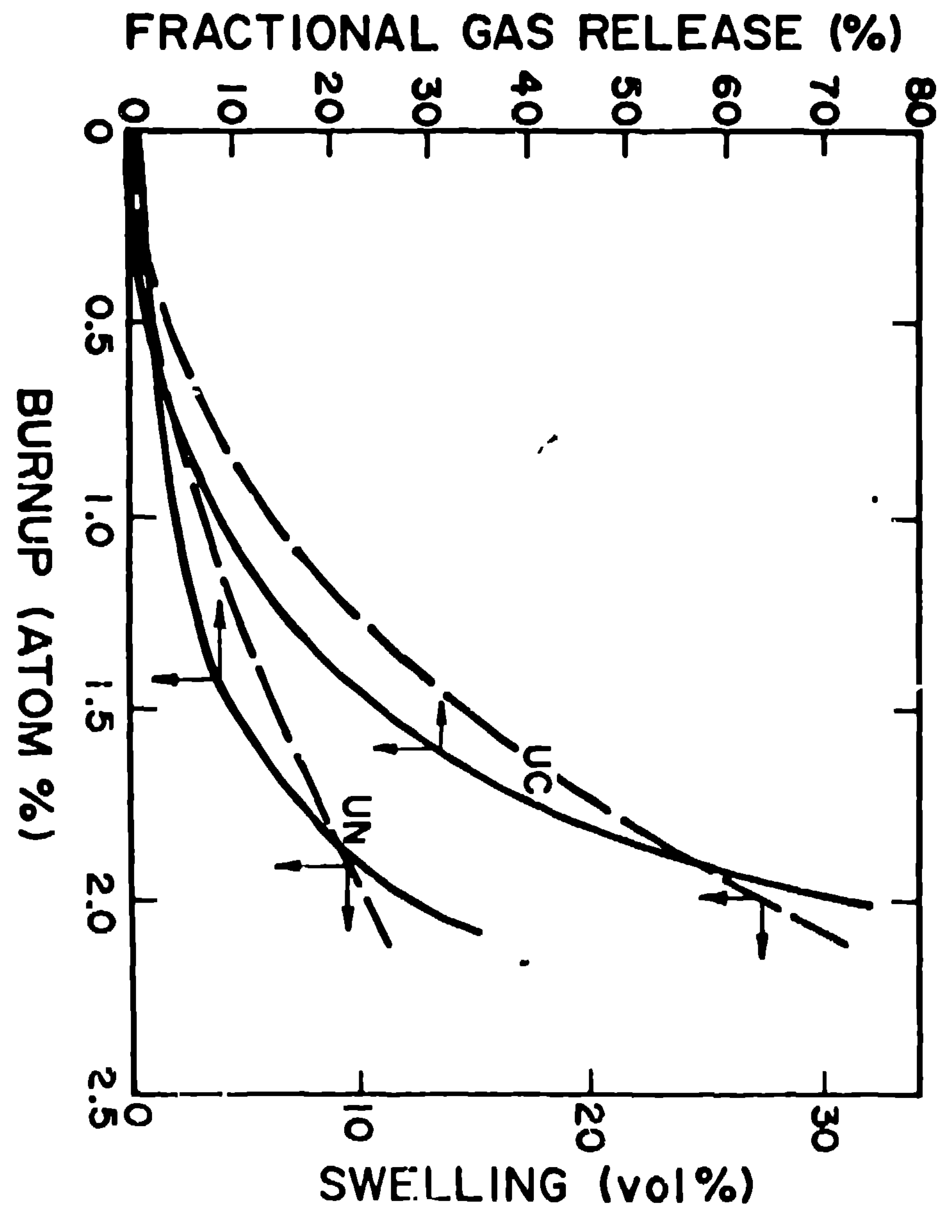

Fig. 3. Comparison of SNAP-50 UN and UC swelling and gas release data at a fuel centerline temperature of ≈ 1670 K.

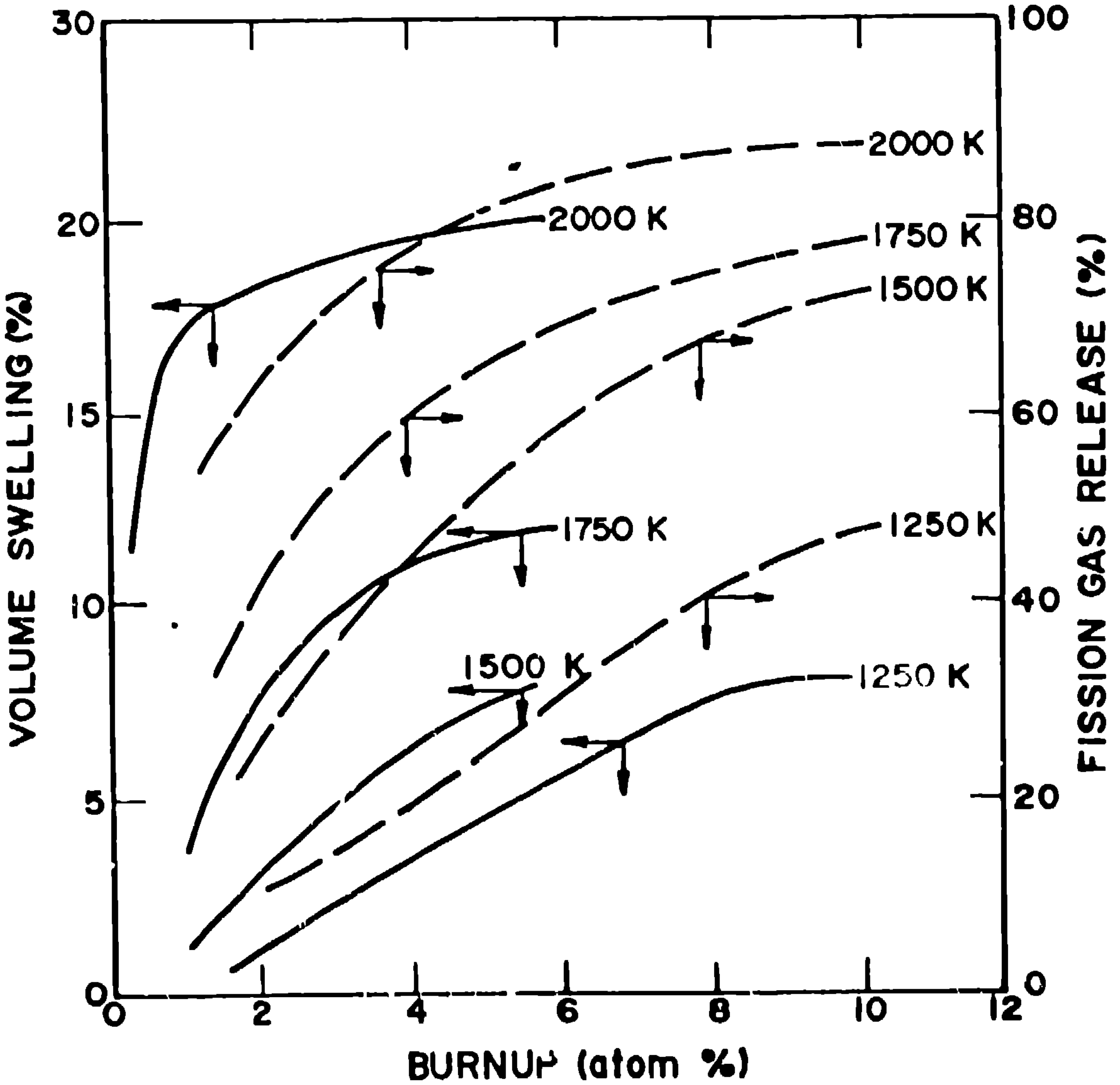

Fig. 4. Zimmerman data of UO_2 volumetric swelling and fractional gas release as a function of burnup and fuel mean temperature (full density ≈ 98% TD).

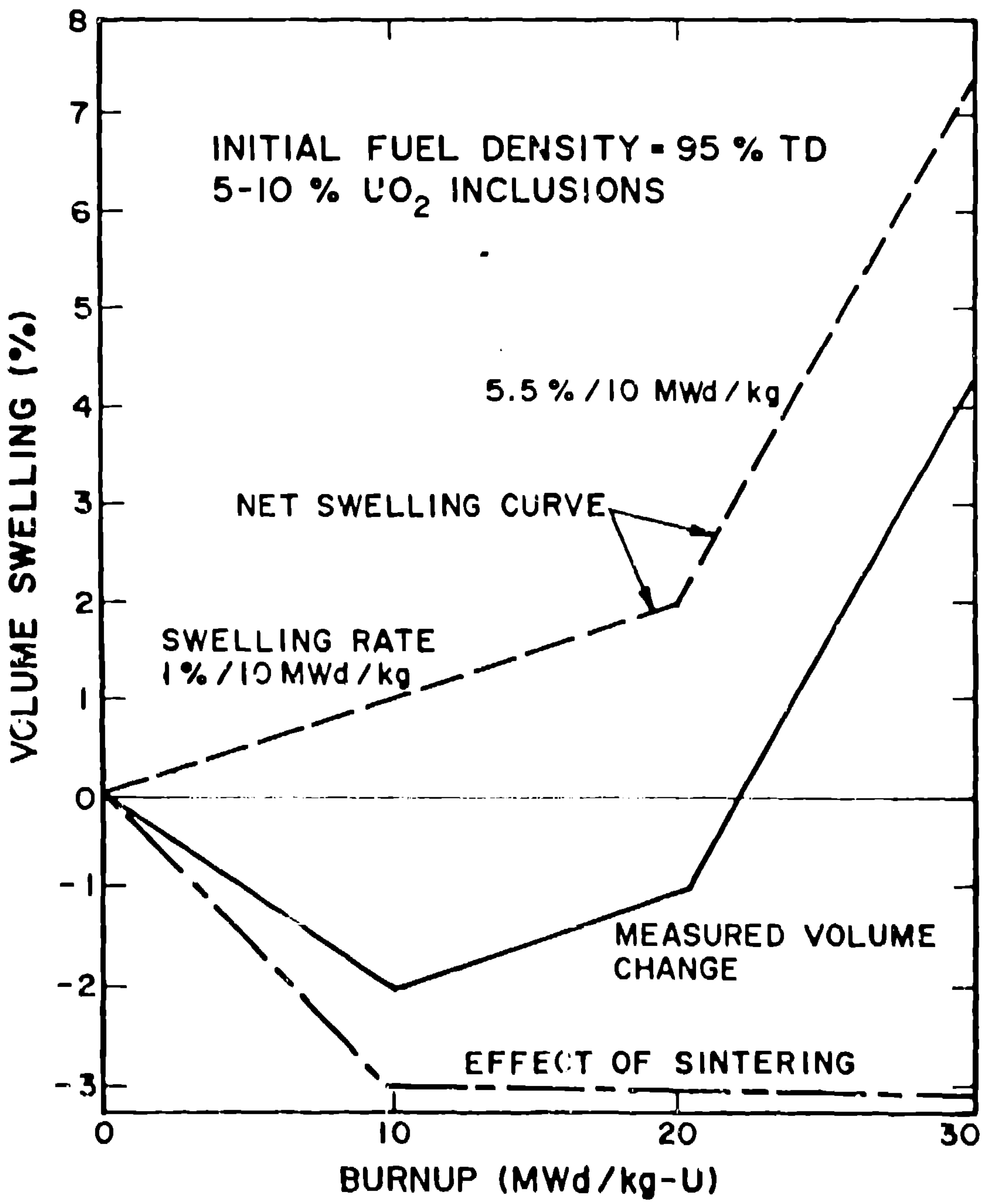

Fig. 5. Zimmerman et al. data of volume change of nitride fuel as a function of burnup at a mean fuel temperature of ≈1520 K.

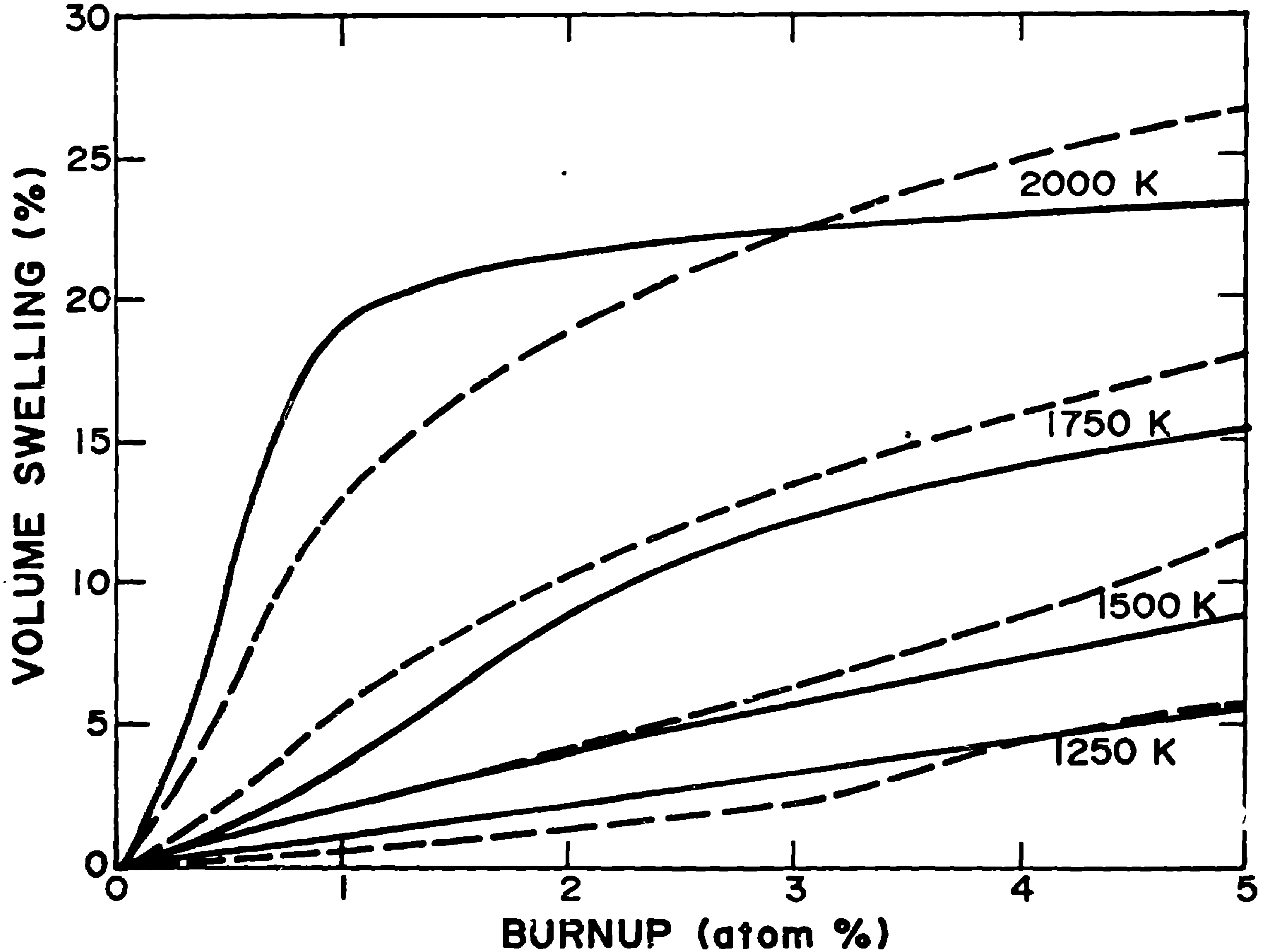

Fig. 6. Predicted swelling of UO_2 (dotted curves) as a function of fuel temperature and burnup compared with the data of Zimmerman (solid curves).

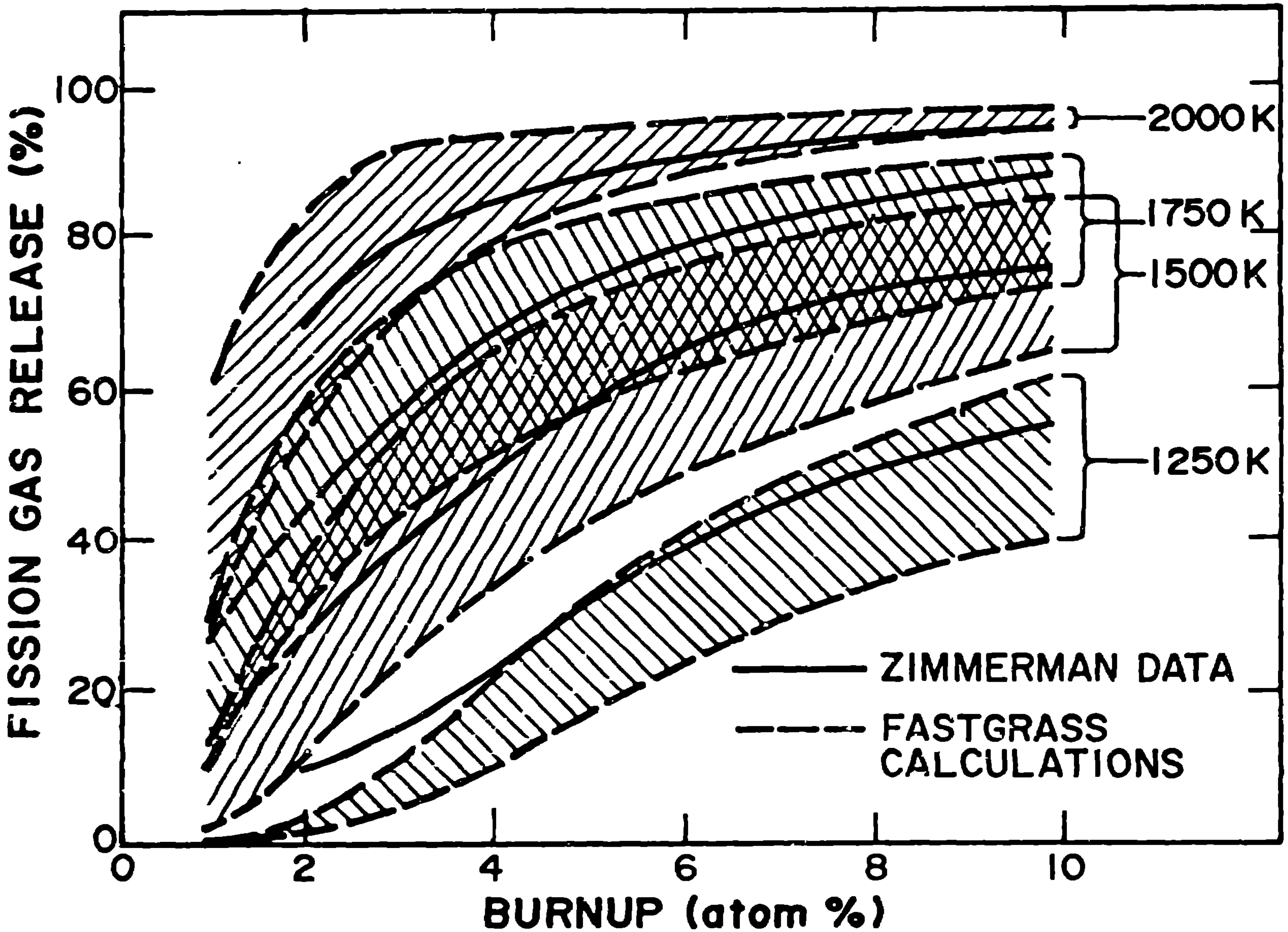

Fig. 7. FASTGRASS predicted fractional fission gas release from UO_2 at 1250, 1500, 1750, and 2000 K (dotted curves) compared with the data of Zimmerman (solid curves).

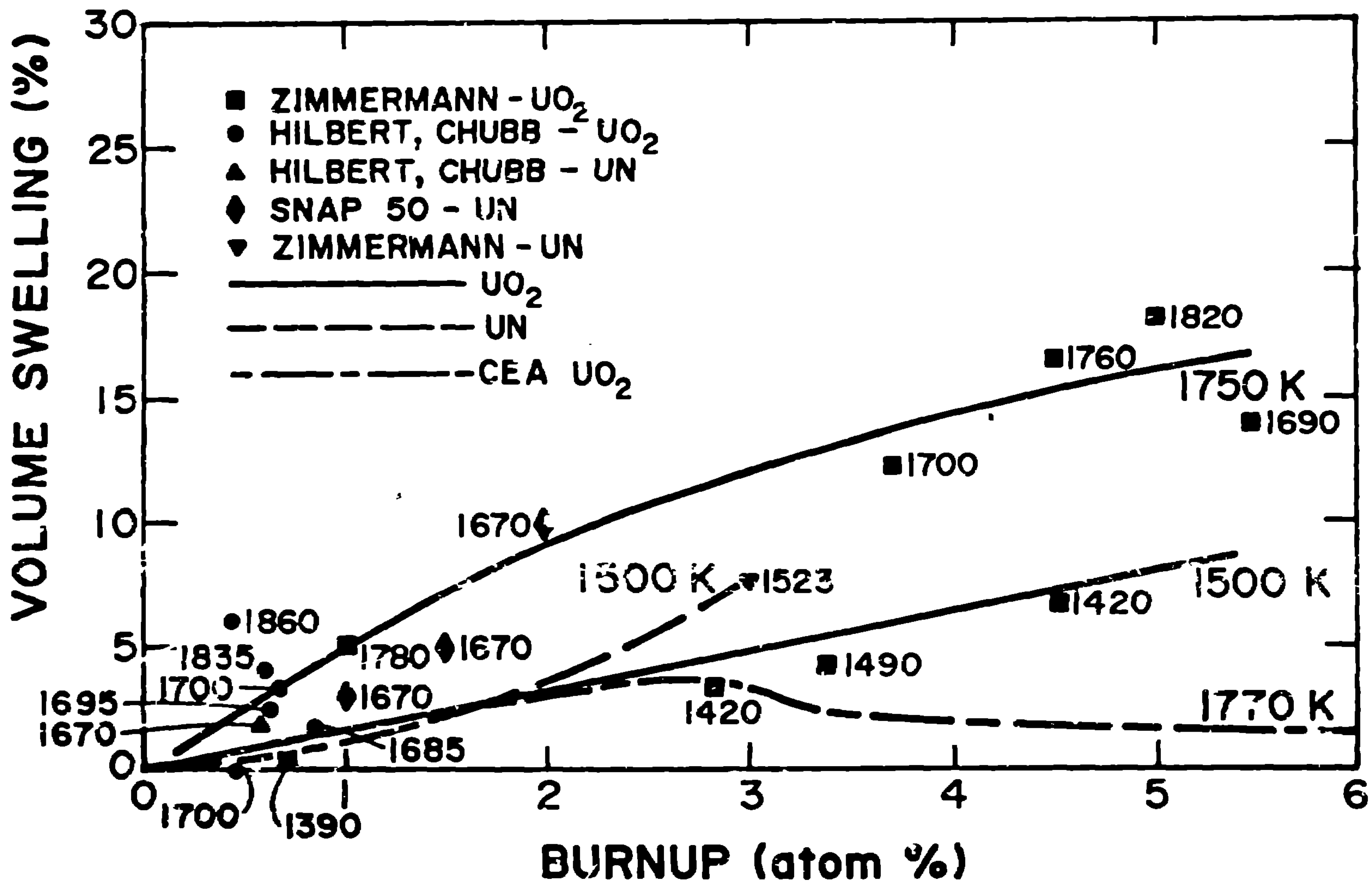

Fig. 8. Fuel swelling characteristics for various UN and UO_2 data as a function of burnup and fuel temrerature.

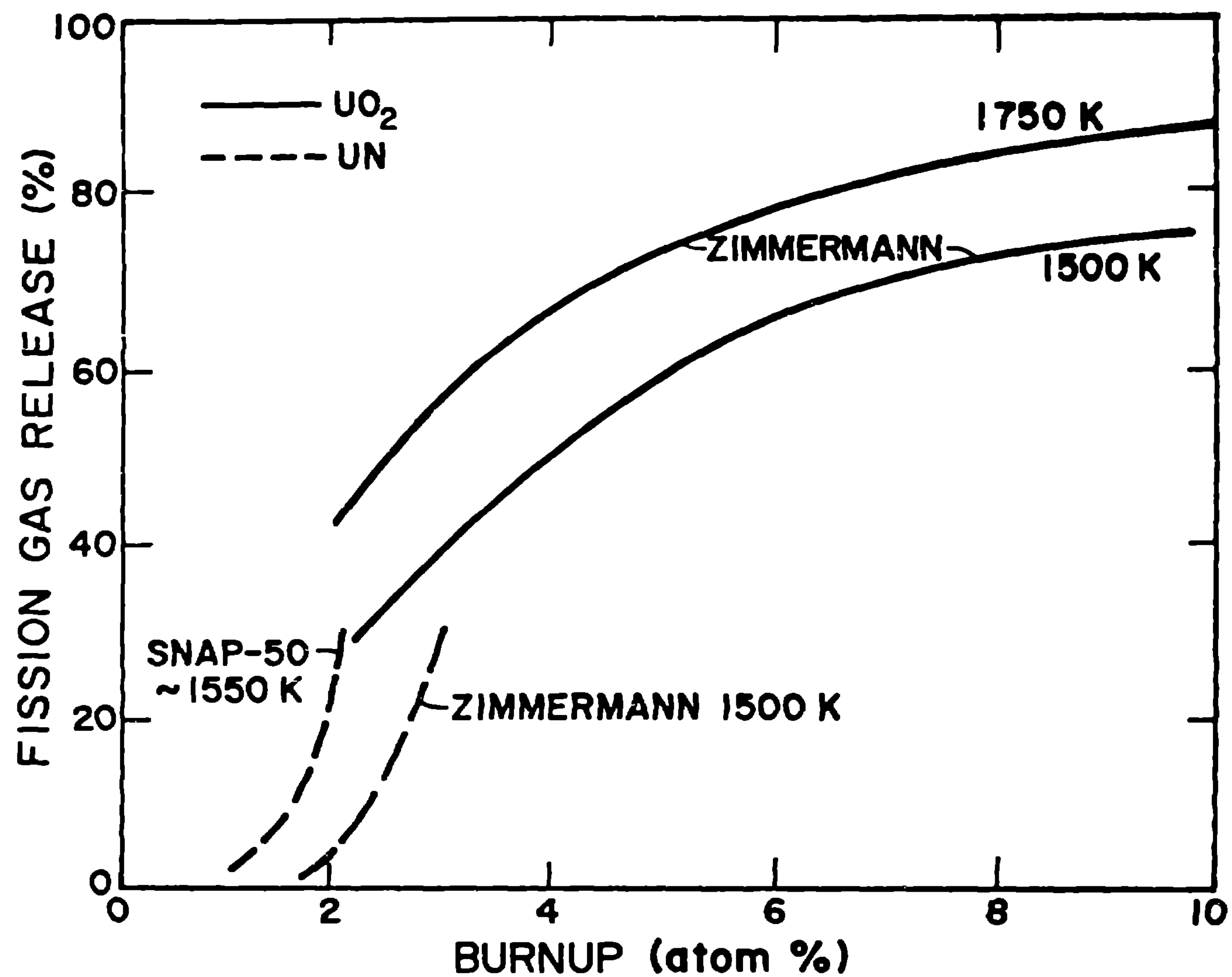

Fig. 9. Fission gas release characteristics for various UN and UO_2 data as a function of burnup and fuel mean temperature.

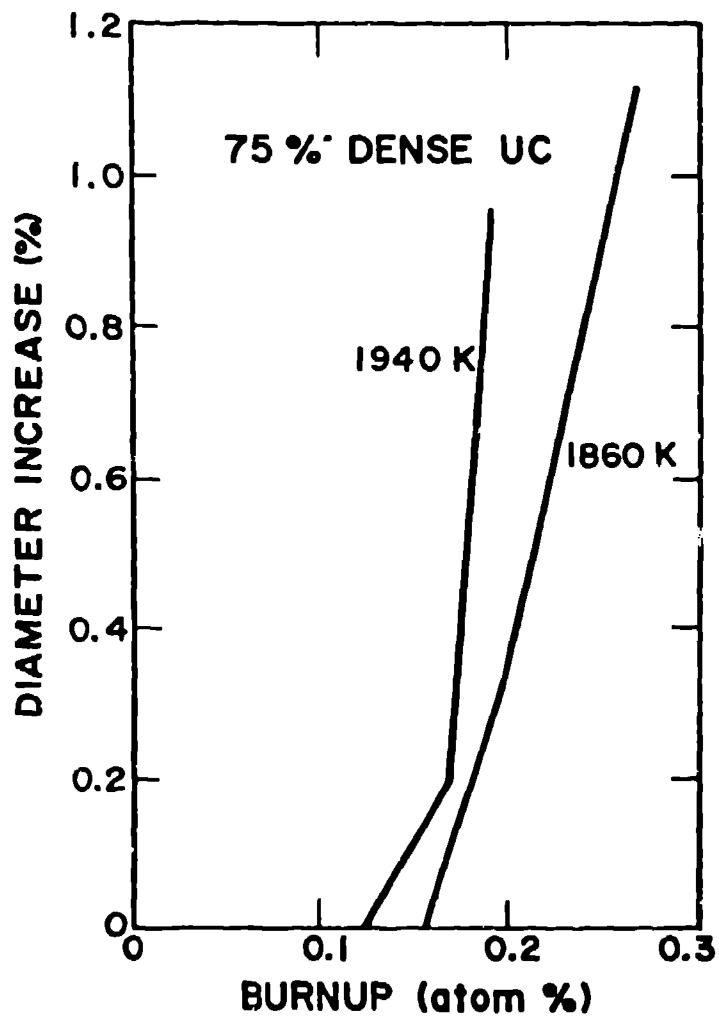

Fig. 10. Diametral increase of tungsten clad 75% dense UC versus burnup.