

Equation of State and Specific Heats of U–C–F Gas Mixtures at High Temperatures and Pressures

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ABSTRACT

Thermodynamic properties of a (U–C–F–e) gas mixture in a gas-core fission reactor have been investigated, especially the equation of state and the specific heats. A cooled graphite wall is maintained at a fixed temperature of 2000 K. The wall is in chemical equilibrium with the gas mixture. Depending on the energy produced, the gas temperature varies between 2000 and 10,000 K. The pressure will increase from about 3 to 100 bar as a result of dissociation and temperature increase. The free electron concentration at 10,000 K is between 4 and 8%, depending on the pressure. Below 5000 K, this concentration is negligible. The value of C_p varies by a factor of 4, owing to dissociation processes. At 2000 K, $C_p/C_v \approx 1.1$ and at 10,000 K ≈ 1.5 . The influence of uncertainties in basic data has been discussed.

Index Entries: Equation of state; specific heat of gas mixtures; gas mixtures, thermodynamic properties of; gas-core fission reactor; high temperature gas properties; uranium-fluorides; carbon-fluorides; dissociative systems.

INTRODUCTION

The basic principles and operating conditions of a gas-core fission reactor, consisting of a graphite vessel and containing uranium fluorides as a fuel, have been treated previously (1,2). It was shown that such a

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reactor, based on an energy production of $50 \text{ MW}_{\text{th}}$, can be operated at a pressure of 2.5 MPa, a wall temperature of about 2000 K, and a total charge of 28 kg U (30% enriched). In the center of the reactor, the temperature rises to about 12,000 K.

The possibility of the application of such a reactor for energy extraction, by means of a "Nuclear Diesel Engine," has been discussed by one of us (3). For a correct description of the cyclic processes happening in such a fast running engine, one has to know the equation of state and the specific heats of the gaseous mixture as a function of temperature and pressure.

From previous work (4,5), we know that our gaseous system is rather complicated. It involves ~ 50 species of a great physical and chemical variety. From the point of view of molecular composition, we have a mixture of polyatomic gases (up to 12 atoms). The amount of various species present in the equilibrium composition at different temperatures and pressures was calculated by applying Eriksson's computer program "SOLGASMIX" (6), which is based on the minimization of the free energy of the system. The basic data to be inserted in the program are the standard entropies, the heats of formation, and the $c_p(T)$ values of the various species. We considered a temperature range of 2000–10,000 K and pressure ranges from 0.1–10 MPa. Recently, many improved thermodynamic data became available (7). Therefore, the calculated equilibrium compositions in our present work differ from those published earlier (4,5).

At temperatures up to 2500 K, the main species present are UF_5 , UF_4 , and CF_4 . With increasing temperature, these molecules dissociate into lower valent fluorides. Dissociation processes are pressure dependent, i.e., at higher pressures, equilibrium compositions are shifted to higher temperatures. These dissociation processes will affect the equation of state, as well as the specific heats of our system. A summary of various equations of state and their industrial applications has recently been given by T. I Barry (8). The properties of a mixture can always be written in terms of an ideal contribution, which is a function of temperature only, and a residual or "excess" contribution, depending on the temperature, pressure, and composition of the gas mixture.

The purpose of this work was to provide an explicit expression relating pressure, volume, and temperature data for our dissociating system and investigate the influence of these dissociation processes on the specific heats of our system. They produce the "residual contributions" mentioned above. For the calculation of the specific heats, we considered three total pressures, namely 0.1, 2.5, and 10 MPa, for the same temperature range. These three pressures were chosen because of the wide range of possible operating conditions of the gas-core fission reactor (1,3,9). Clearly, a higher pressure involves higher temperatures and more possibilities for energy extraction. On the other hand, lower pressures are preferable from the point of view of construction materials.

Values of c_p and c_p/c_v were calculated by applying standard thermodynamic relations. We find that, in the temperature regions where UF_5 , CF_4 , and UF_4 dissociate, the residual contributions multiply the ideal c_p value by a factor of 4 to 5. The ratio c_p/c_v increases from a value of ~ 1.1 at 2000 K (polyatomic gas) to ~ 1.5 at 10,000 K.

PHENOMENOLOGICAL ASPECTS

The Initial Composition of the Gaseous U–C–F Mixture

One of the characteristics of this reactor is that the wall is part of the chemical system. This means that the graphite wall is in thermodynamic chemical equilibrium with the gaseous mixture. For a fixed amount of uranium and fluorine, the amount of carbon in the "boundary gas layer" depends on the temperature of the reactor wall and the operating pressure inside the reactor. This amount of carbon can be found by calculating the equilibrium composition of a system consisting of gaseous and condensed U–C–F components. The gaseous system will be discussed in details below. The *condensed components* included in our calculations were: C-graphite; UF_n , $n = 0, 3, 4, 5$, and 6; and UC, $UC_{1.9}$, and U_2C_3 .

In Table 1 we give some typical quantities of carbon in the boundary gas layer, in equilibrium with the graphite wall and for various temperatures and pressures.

Since the primary purpose of this work was to investigate the thermodynamic behavior of the gaseous U–C–F system as a function of pressure and temperature, we did all our calculations for a constant overall, mean molar ratio F:U:C = 4.00:0.70:0.18. From Table 1, we see that this specific ratio corresponds to chemical equilibrium at a graphite wall at 2000 K and 2.5 MPa. *These are the assumed operating conditions of our reactor* (4). Different wall temperatures or gas pressures will cause corrosion of the walls or deposition of carbon, as discussed in a recent publication (23). Table 1 gives some indications in this direction.

Influence of Temperature and Pressure on the Dissociation and Ionization Processes

Applying the computer program SOLGASMIX, we calculated equilibrium compositions in the temperature range 2000–10,000 K and the pressure range 0.1–10 MPa (1–100 bars). In these calculations, we included 49 gaseous species, which are given in Table 2. Equilibrium compositions at pressures of 0.1 and 10 MPa are given in Figs. 1 and 2. For 2.5 MPa, these compositions have been given elsewhere (10). We present the mol fractions of the various species as a function of temperature. Figure 1 gives the main dissociating species for both pressures, whereas Figs. 2a and b show some minor species.

Table 1

Equilibrium amounts of carbon in the boundary gas layer for various wall temperatures and operating pressures. The fixed amounts of uranium and fluorine were 0.70 moles U and 2.00 moles F₂.

Temperature K	Pressure MPa	Carbon Moles
1700	0.1	0.17
1800	0.1	0.19
2000	0.1	0.21
1900	2.5	0.17
2000	2.5	0.18
2100	2.5	0.19
2200	10	0.18
2300	10	0.19
2500	10	0.22

Table 2

Species included in the calculation of the equilibrium compositions of the gaseous system U-C-F-e-ions

C _n	n = 1, ...7	CF _n ⁺	n = 0, ...3
F _n	n = 1,2		
CF _n	n = 1, ...4	C ₂ ⁺	
C ₂ F _n	n = 1, ...6	C ⁻ , C ₂ ⁻ , F ⁻	
UF _n	n = 0, ...6	UF _n ⁺	n = 0, ...5
UC ₂		UF _n ⁻	n = 1, ...6
U ₂ F ₁₀		e ⁻	

From these equilibrium calculations, we find the total number of moles and the corresponding volume occupied by the gas mixture at every temperature and pressure on the assumption of ideal gas behavior. Results are given in Table 3 and Fig. 3. The total number of moles increases especially: for 0.1 MPa, between 2400 and 3000 K, where the dissociation of UF₅ and CF₄ takes place, and between 4000 and 6000 K, where UF₄ and lower valent uranium and carbon fluorides dissociate; and for 10 MPa, between 3000 and 4400 K, and between 5500 and 8500 K, because of the same reasons.

The dissociation processes result in a large amount of monatomic fluorine gas, as shown explicitly in Table 4. Ionization of monatomic

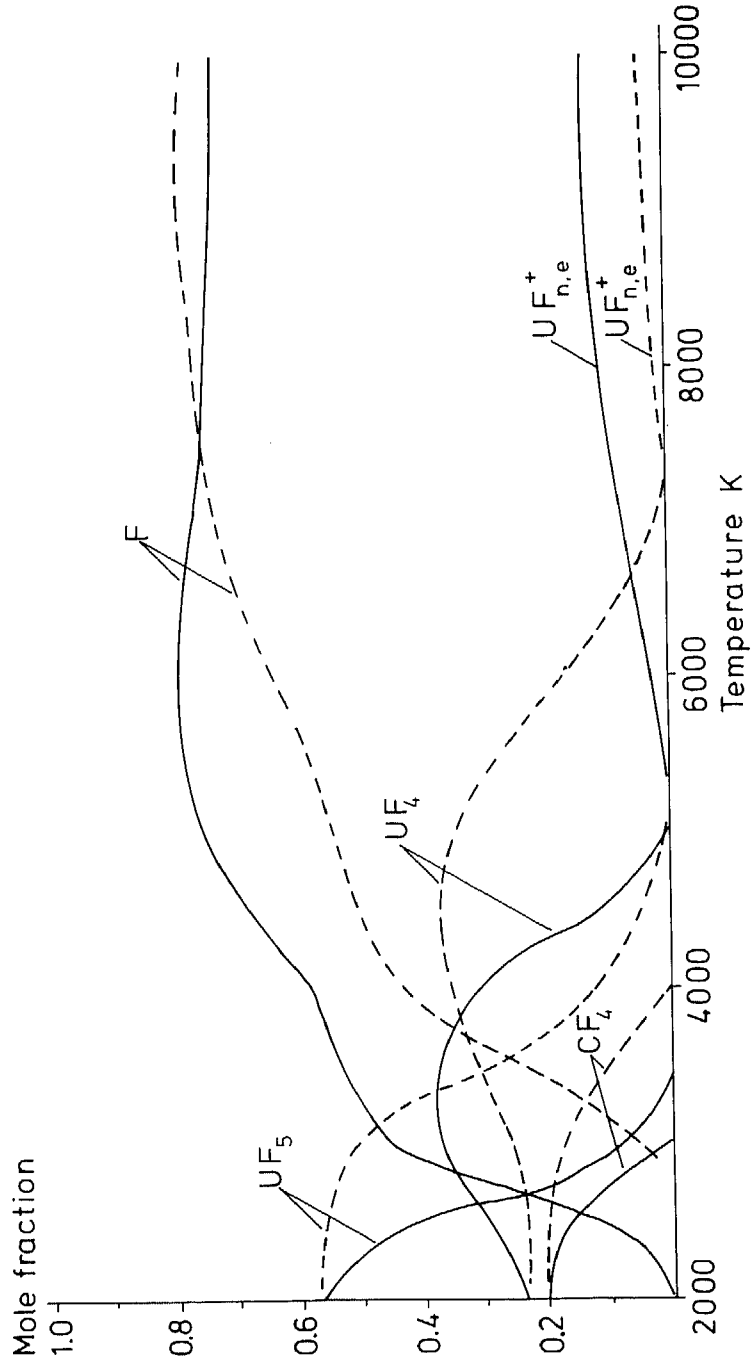


Fig. 1. Equilibrium compositions of the gaseous system U-C-F-e-ions. Major components. Number of mols available: F:U:C are 4:00:0.70:0.18. ——— P = 0.1 MPa; - - - - P = 10 MPa.

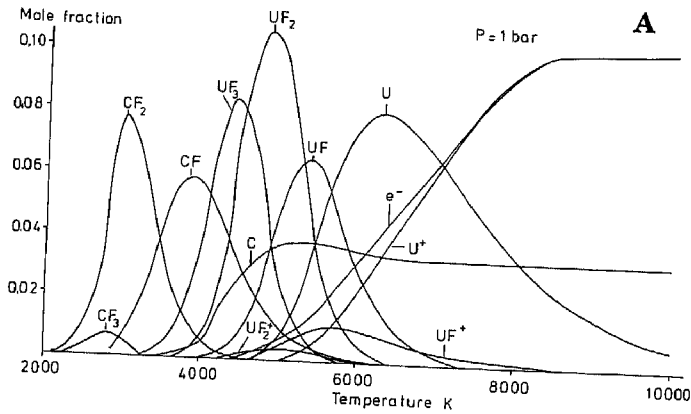
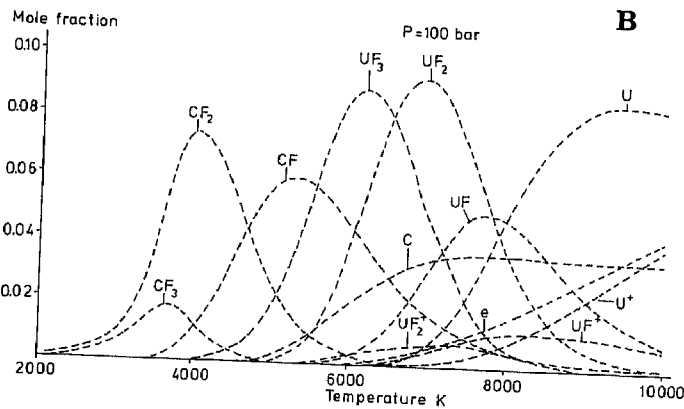


Fig. 2. (a) Equilibrium compositions of the gaseous system U-C-F-e-ions. Main minor components. $P = 0.1$ MPa.



(b) Equilibrium compositions of the gaseous system U-C-F-e-ions. Main minor components. $P = 10$ MPa.

uranium gas starts above 5000 K for 0.1 MPa and above 7000 K for 10 MPa. However, because of the enormous increase in the amount of free fluorine, the relative contribution of the free electrons to the total number of mols is small, below 10,000 K. This becomes quite different in the trajectory between 10,000 and 15,000 K, where the degree of ionization of

Table 3
Total number of moles as a function of temperature and pressure

Temperature K	Pressure in MPa						
	0.10	0.25	0.50	1.00	2.50	5.0	10.0
2000	0.879	0.878	0.877	0.877	0.876	0.875	0.873
3000	1.563	1.367	1.219	1.102	0.998	0.949	0.917
4000	2.011	1.909	1.850	1.795	1.708	1.619	1.494
5000	3.553	3.046	2.649	2.326	2.062	1.947	1.862
6000	4.761	4.396	4.031	3.639	3.099	2.691	2.354
7000	5.173	5.016	4.862	4.638	4.182	3.752	3.308
8000	5.376	5.253	5.148	5.031	4.827	4.580	4.209
9000	5.488	5.402	5.315	5.216	5.072	4.942	4.758
10000	5.547	5.492	5.429	5.347	5.218	5.111	4.991

uranium and carbon atoms tends to be 100%. From Figs. 2a and b, we see that, in the temperature ranges of ~ 4000 – 6500 K ($P = 0.1$ MPa) and ~ 5500 – $10,000$ K ($P = 10$ MPa), the concentration of positive ions is higher than the concentration of free electrons owing to the formation of negative ions. Formation of F^- is enhanced at higher pressures. All negative ions are thermally destroyed between 8000 and $10,000$ K.

Figure 4 demonstrates the pressure dependence of the total number of mol. This dependence is strongest about 3000 – 6000 K, where the dissociation processes occur. At 2000 K, there is hardly any pressure dependence since all uranium- and carbon-fluorides are still stable. Above 8000 K, the dependence is also small because most binary molecules have dissociated.

We have noticed during our calculations that the concentrations of dimers, like C_2F_2 , U_2F_{10} , and also of the group C_3 , C_4 , C_5 , and so on, increase if pressures increase. But their mol fractions stay below 0.001 for temperatures between 2000 and 6000 K. Our gaseous system is very complicated. Dissociation processes of various components depend, each in their own way, on temperature and pressure. Therefore, a "normal" equation of state, like the ideal gas law, cannot be applied without taking into account the influences of chemical processes.

A NUMERICAL EQUATION OF STATE

The total number of mol in Table 3 reflects the degree of dissociation and ionization at various temperatures and pressures. This total number of mols $n(P,T)$, implies a volume, V , to be calculated by

$$P \cdot V = n(P,T) \cdot R \cdot T \quad (1)$$

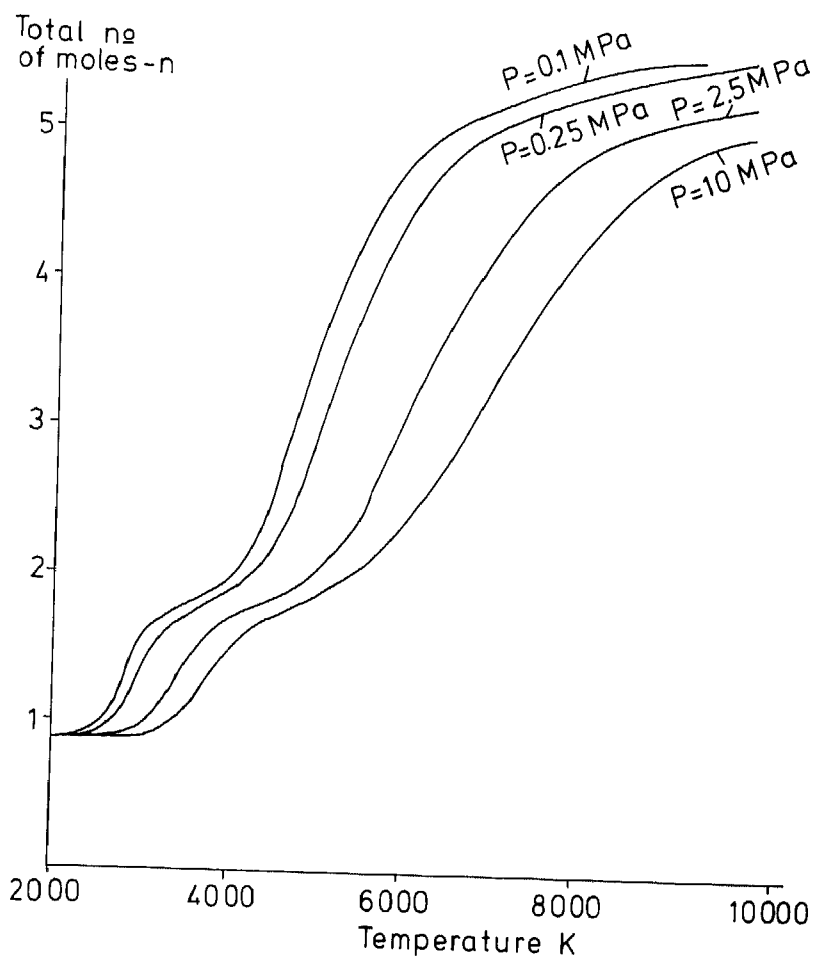


Fig. 3. Total number of mols as a function of temperature. Parameter: pressure in MPa. Number of mols available: F:U:C = 4.00:0.70:0.18.

In Fig. 5, we present the pressure, P , as a function of the volume, V , with the temperature, T , as a parameter. Per definition, the compressibility factor for a real gas is given by

$$C = (P \cdot v)/(R \cdot T) \quad (2)$$

where v is the molar volume of the gas at the temperature, T (see Smith (11)). In a gas mixture, we have $V = v \sum_i n_i$. An increase in temperature, at constant pressure, results in extra dissociation. This effect causes a larger volume than expected from the ideal gas law. One can normalize the factor C , relative to an ideal gas, by

$$C_{\text{norm.}} = n(P, T)/n(P_i, T_i) \quad (3)$$

where $n(P_i, T_i)$ are the total number of mols at the initial conditions of

Table 4
Equilibrium amounts of higher valent carbon and uranium fluorides and of fluorine
for certain temperatures and pressure

Temperature in K	Total pressure in MPa	Species in moles			
		UF ₅	UF ₄	CF ₄	F
2000	0.1	0.49	0.21	0.18	0.00
3000	0.1	0.12	0.58	0.02	0.69
4000	0.1	0.00	0.61	0.00	1.15
6000	0.1	0.00	0.00	0.00	3.72
.....					
2000	10	0.49	0.20	0.17	0.00
3000	10	0.47	0.22	0.16	0.04
4000	10	0.18	0.51	0.02	0.62
5000	10	0.03	0.64	0.00	0.99
8000	10	0.00	0.00	0.00	3.23

pressure and temperature (2.5 MPa; 2000 K). In Fig. 3, the total number of mols, n , has been plotted as a function of T , with P as parameter. With the values of n taken from this figure, one can demonstrate that C_{norm} varies between 1 and 6.

In case of compression of our gas mixture from a large volume, V_2 , to a smaller volume, V_1 , keeping the temperature, T , constant, we will observe an increase in pressure that is less than for an ideal gas. Then, we say that the gas is more compressible than an ideal gas.

$$(P_1/P_2)_{mixture} = \frac{n_1(P_1, T)}{n_2(P_2, T)} \cdot \left(\frac{V_2}{V_1} \right) \quad (4)$$

where $\frac{n_1}{n_2} < 1$ owing to recombination. In order to get a mathematical expression for the equation of state, we try

$$\log_{10} P = a \log_{10} V + b, \text{ or} \quad (5)$$

$$P \cdot V^{-a(T)} = 10^{b(T)} \quad (6)$$

The values for P and V from Fig. 5 have been plotted in Fig. 6, according to Eq. (5). For every temperature, we see a straight line. The coefficients "a" and "b" are temperature dependent. In order to find the numerical values of these coefficients for every temperature, we have introduced values of P and V , as obtained from SOLGASMIX, into a *least-squares fit* computer program (12). This program could finally reproduce the input data from Fig. 5 within 7%. The highest deviations are where dissociation processes are most active.

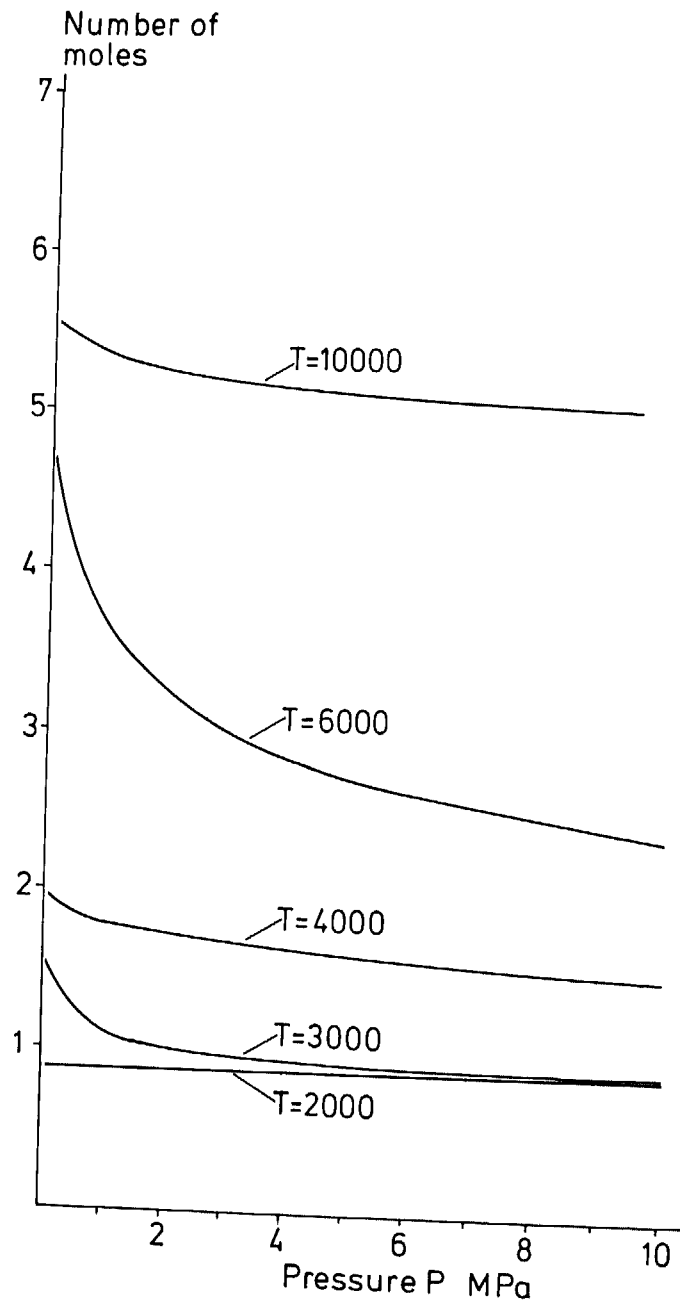


Fig. 4. Total number of moles as a function of the pressure. Parameter: temperature in K. Number of moles available: F:U:C = 4.00:0.70:0.18.

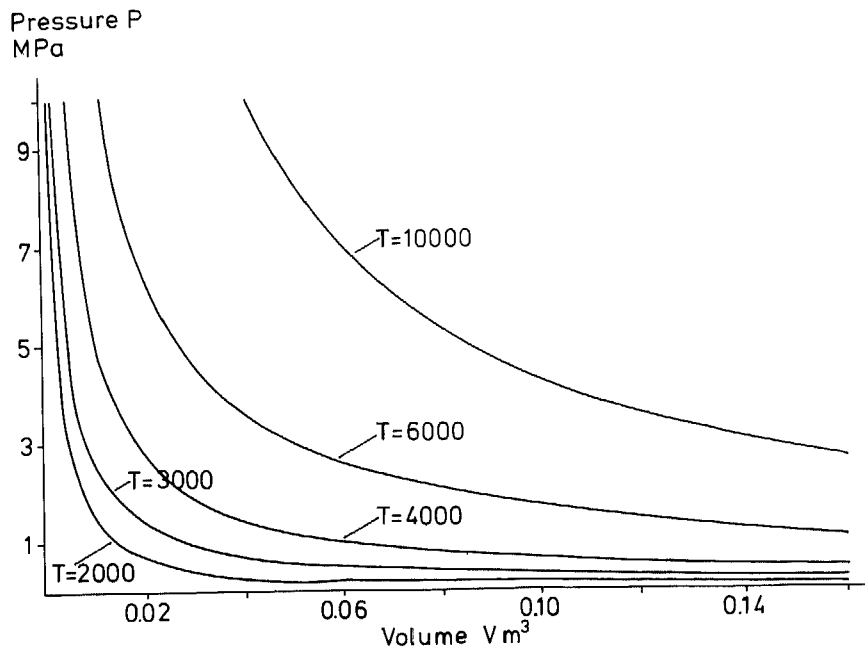


Fig. 5. A (P,V) diagram for the gaseous system U-C-F-e-ions for a given quantity of material, taking into account dissociation and ionization.

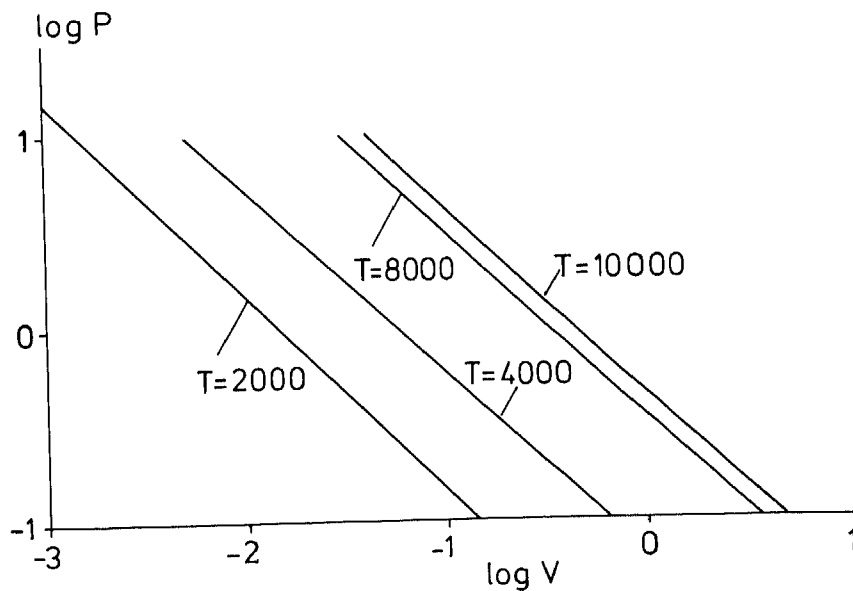


Fig. 6. $\log P$ as a function of $\log V$; P = pressure in MPa; V = volume in m^3 . Parameter: temperature in K. System: U-C-F-e-ions. Number of mols available: F:U:C = 4.00:0.70:0.18.

We calculated a and b in the temperature range 2000–10,000 K, using small temperature intervals of 200 K. Some selected values are in Table 5. We notice that $|a| < 1$ because of molecular recombination processes. For an ideal gas $|a| = 1$. In Fig. 7a, we see the values of "a" as a function of temperature. In Fig. 7b, it is the same for "b." These values have been curve-fitted by the computer program "Cricket graph" (13). The resulting equations are

For the temperature range:

$$2000 \text{ K} \leq T < 4200 \text{ K (with } T = 10^3 T')$$

$$a(T) = -3.3576 + 6.69339 T' - 6.452637(T')^2 + 2.801388(T')^3 - 0.5611048(T')^4 + 0.042220499(T')^5 \quad (7a)$$

$$b(T) = 0.0287 + 0.4469T' + 1.925646(T')^2 - 1.3965195(T')^3 + 0.35629045(T')^4 - 0.03104086(T')^5 \quad (7b)$$

For the temperature range:

$$4200 \text{ K} \leq T \leq 10,000 \text{ K (with } T = 10^3 T')$$

$$a(T) = 2.1393 - 3.19189T' + 1.169843(T')^2 - 0.19514(T')^3 + 0.0151843(T')^4 - 4.48793 \cdot 10^{-4}(T')^5 \quad (8a)$$

$$b(T) = -3.17545 + 5.66073T' - 2.067737(T')^2 + 0.3552273(T')^3 - 0.02841493(T')^4 + 8.58538 \cdot 10^{-4}(T')^5 \quad (8b)$$

The values of a and b , given in Table 5, and the set of equations, (7a) to (8b), can be used to calculate the (P, V) diagram of a cyclic process in the pressure range 1–100 bars, for temperatures between 2000 and 10,000 K (accuracy within 7%).

Normalization Procedure

The coefficients a and b of Eq. (6) have been calculated for a total quantity of 0.876 mols of gas, for a fixed ratio F:U:C = 4.00:0.70:0.18, corresponding to chemical equilibrium in a U–C–F gas mixture in direct contact with a graphite wall (2000 K, 2.5 MPa). These conditions were chosen for historical reasons and are not relevant to the equation of state. Of course, one can also multiply this quantity 0.876 with a factor, m , to get any other quantity of gas, keeping the ratio F:U:C the same. But then we should keep in mind that: coefficient a depends only on the chemical composition of the gaseous mixture and is *independent of m* ; and coefficient b has to be replaced by $b' = b - a \log m$ which follows directly from $V' = mV$ and $P(V'/m)^{-a} = 10^b$. The equation of state of the new system, with $(m \cdot 0.876)$ mols, is then given by $P(V')^{-a} = 10^{b'}$

Table 5

The coefficients "a" and "b" of the equation " $\log P = a \log V + b$ " as a function of temperature, adjusted to the pressure range of 1 to 100 bar and for a ratio F : U : C = 4.00 : 0.70 : 0.18. V is in liters.

Temperature in K	a	b
2000	- 0.998	2.16
3000	- 0.899	2.31
4000	- 0.941	2.67
5000	- 0.880	2.76
6000	- 0.859	2.93
7000	- 0.904	3.18
8000	- 0.959	3.42
9000	- 0.969	3.51
10000	- 0.976	3.58

SPECIFIC HEATS OF THE (U-C-F-e) GAS MIXTURE

The procedure, applied before the ratio c_p/c_v can be calculated, consists of two steps: (1) calculation of the mean values of c_p for the gaseous mixtures, corresponding to the various equilibrium compositions, and (2) calculation of the difference $c_p - c_v$. Values of c_p/c_v have to be calculated in the temperature range of 2000 to 10,000 K for pressures of 0.1, 2.5, and 10 MPa.

Some Theoretical Considerations

The difference in heat capacities at constant pressure and at constant volume for any real system is given by

$$C_p - C_v = T \left(\frac{\partial P}{\partial T} \right)_v \left(\frac{\partial V}{\partial T} \right)_P \quad (9)$$

where V = volume of the system at temperature T and pressure P , C_p = heat capacity of the system at constant pressure P and C_v = heat capacity of the system at constant volume V (See K. Denbigh (14)).

Equation (9) can be written in the form

$$C_p - C_v = TV \alpha^2/\beta \quad (10)$$

where the expansion coefficient, α , is defined by

$$\alpha = \frac{1}{V} \left(\frac{\partial V}{\partial T} \right)_P \quad (11)$$

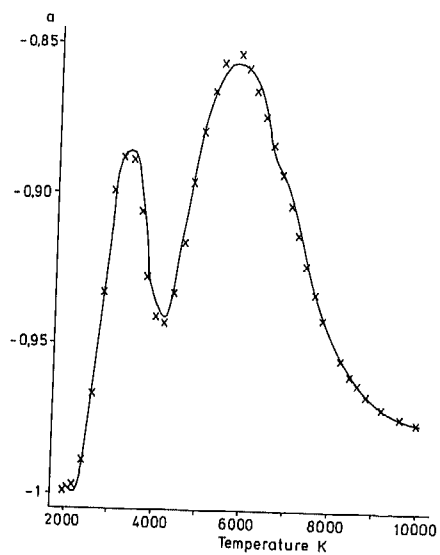


Fig. 7 (a). The coefficient "a" of Eq. (5) as a function of temperature. x calculated points; - interpolated line (eqs. (7a, 8a)).

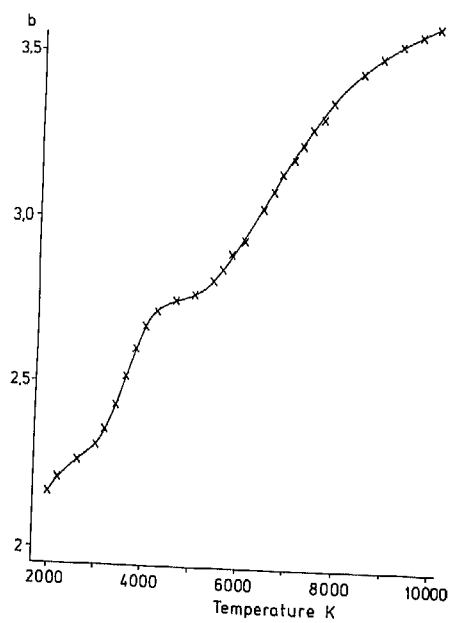


Fig. 7 (b). The coefficient "b" of Eq. (5) as a function of temperature. x calculated points; - interpolated line (eqs. (7b, 8b)).

For an ideal gas system $\alpha = 1/T$.

The isothermal compressibility factor, β , is defined by

$$\beta = - \frac{1}{V} \left(\frac{\partial V}{\partial T} \right)_T \quad (12)$$

For an ideal gas $\beta = -1/P$.

This factor indicates the fractional change of volume with pressure at a constant temperature. Combining eqs. (10-12), one obtains

$$C_p - C_v = \frac{T \left(\frac{\partial V}{\partial T} \right)_P^2}{-\left(\frac{\partial V}{\partial P} \right)_T} \quad (13)$$

This relation gives the exact thermodynamic difference between the heat capacities at constant pressure and constant volume for any real system.

Considering eq. (1) for our gaseous mixture (U-C-F-e-ions), values of $(\partial V/\partial T)_P$ and $(\partial V/\partial P)_T$ can be obtained in terms of the number of mols, $n(P,T)$, as follows

$$\left(\frac{\partial V}{\partial T} \right)_P = \frac{R}{P} \left[n(P,T) + T \left(\frac{\partial n}{\partial T} \right)_P \right] \quad (14)$$

$$\left(\frac{\partial V}{\partial P} \right)_T = \frac{RT}{P} \left[- \frac{n(P,T)}{P} + \left(\frac{\partial n}{\partial P} \right)_T \right] \quad (15)$$

Considering eqs. (1) and (13), it can be shown that the difference in the molar-specific heats, i.e., $c_p - c_v$, can be calculated by dividing Eq. (13) by $n(P,T)$, i.e.,

$$c_p - c_v = - \frac{T \left(\frac{\partial V}{\partial T} \right)_P^2}{n(P,T) \left(\frac{\partial V}{\partial P} \right)_T} \quad (16)$$

Calculation of c_p

Because of the dissociation processes involved, values of c_p have to be calculated according to the relation

$$c_p(P,T) = \sum_{i=1}^N f_i(P,T) \cdot c_{p,i}(T) + c_{p,diss}(P,T) \quad (17)$$

where f_i = the equilibrium mol fraction of species i (see Figs. 1 and 2), $c_{p,i}(T)$ = the specific heat of species i at a temperature T , and

$c_{p,diss}(P,T)$ = the extra energy needed for dissociation and an increase in temperature with one degree Kelvin. This specific heat for our gas mixture can be calculated from the equilibrium compositions and the individual molar enthalpies of each species i , according to the relation

$$c_p(P,T) = \frac{\sum_{i=1}^N n_i(P,T_2)H_i(T_2) - \sum_{i=1}^N n_i(P,T_1)H_i(T_1)}{[\bar{n}_{tot}(P)](T_2 - T_1)} \quad (18)$$

where n_i = number of mols of species i and H_i = molar enthalpy of species i

$$2\bar{n}_{tot}(P) = n_{tot}(P,T_2) + n_{tot}(P,T_1)$$

The molar enthalpy of each species has been calculated by SOLGASMIX, according to the general relation

$$H_i(T) = \int_{298}^T c_{p,i}(T)dT + \Delta H_{f,i,298.15}^{\circ} \quad (19)$$

By considering the different equilibrium compositions at temperatures T_2 and T_1 , we took the extra energy needed for dissociation into account. In Fig. 8, we give values of c_p as a function of temperature for pressures of 1, 25, and 100 bar. In order to demonstrate the influence of dissociation on the specific heat values, we have also presented in these figures a curve representing the molar mean specific heat $\bar{c}_p(T)$, which is given by the first term of Eq. (17). The specific heats of the main dissociating species, including the specific heats of fluorine and uranium monatomic gas, are given in Figs. 9a and b.

Calculation of $c_p - c_v$ and c_p/c_v

Values of $c_p - c_v$ were calculated from eqs. (13–15). In order to find reliable values of $(\partial n/\partial T)_P$, equilibrium compositions were calculated in the temperature range 2000–10,000 K, at intervals of 200 K, for constant pressures of 1, 25, and 100 bar. In order to obtain values of $(\partial n/\partial P)_T$ a bandwidth of 10% of the corresponding pressure was considered. This means that, for every temperature, we calculated equilibrium compositions at the pressures 0.9, 1.0, and 1.1 bar; 22.5, 25.0, and 27.5 bar; and 90, 100 and 110 bar. Values of $c_p - c_v$, in units of R , are given in Fig. 10. From the results of Eqs. (16) and (17), values of c_p/c_v can be calculated. They are also given in Fig. 10.

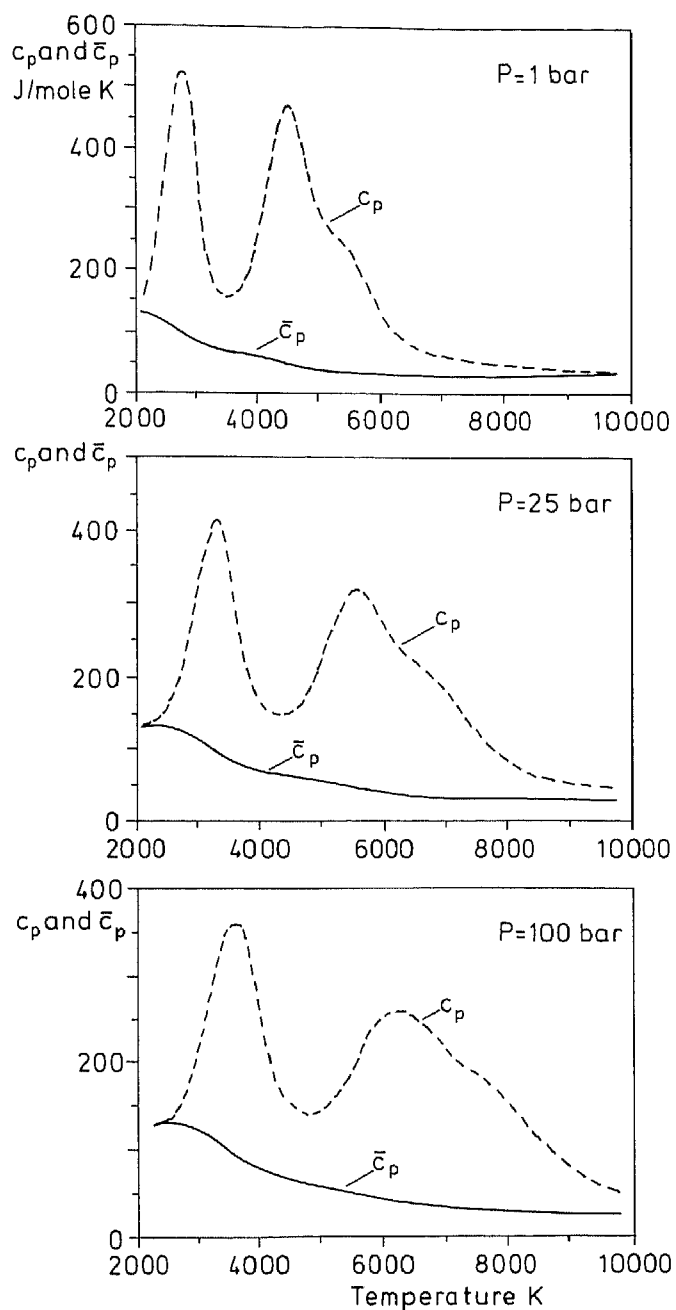


Fig. 8 Total specific heat c_p and molar specific heat \bar{c}_p of the gaseous system U-C-F-e-ions as a function of temperature. The difference between both curves, for each temperature, is called the "residual" or "excess" contribution.

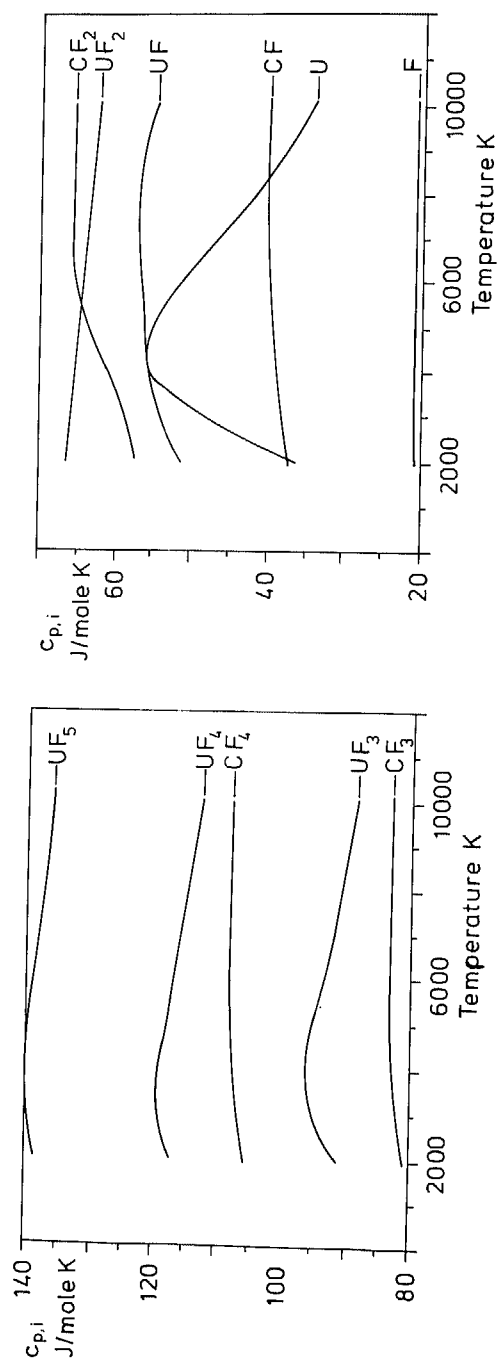


Fig. 9. (a) The individual specific heats of the main higher valent fluorides as a function of temperature (7).
 (b) The individual specific heats of uranium, fluorine, and the main lower valent fluorides as a function of temperature (7).

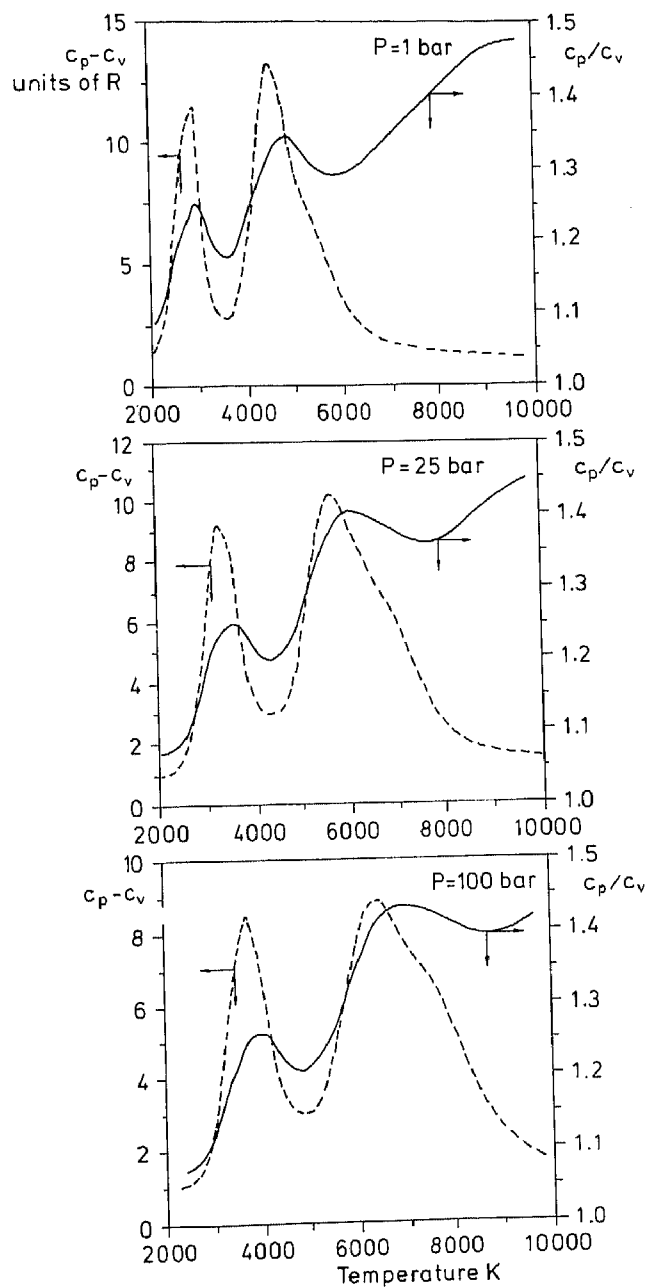


Fig. 10. Values of $c_p - c_v$ and c_p/c_v (system U-C-F-e-ions), as a function of temperature, for the pressures of 1, 25, and 100 bar.

EXPANSIVITY AND COMPRESSIBILITY OF OUR MIXTURE

In Tables 6a and 6b, we give some values of the expansion coefficient, α , and the compressibility factor, β , as calculated for our gaseous mixture, according to Eqs. (11) and (12). Values of

$$\left(\frac{\partial V}{\partial T} \right)_P \text{ and } \left(\frac{\partial V}{\partial P} \right)_T$$

were computed for the temperature and pressure intervals given above. We see that the influence of the temperature on the dissociation processes is much bigger than the influence of the pressure. This is in agreement with Figs. 3 and 4.

DISSOCIATION ENERGIES

The dissociation energies of the uranium and carbon fluorides can be calculated from the enthalpies of the corresponding species, according to the relationship

$$D_{XF_n}(T) = H_{XF_{n-1}}(T) + H_F(T) - H_{XF_n}(T)$$

for $X = U, n = 1, \dots, 6$ or

$X = C, n = 1, \dots, 4.$

Some values have been given in Table 7 and are compared with experimental data given in the literature for 298.15 K.

DISCUSSION

Accuracy of the Thermodynamic Data

The fundamental thermodynamic data used by us were recently assessed by the National Data Bank in Harwell (7). They differed slightly from the data we used in previous papers (5). The influence on the chemical composition of our gas mixture in free contact with the graphite wall was impressive, however. Therefore, we did a thorough analysis about the influence of the officially indicated uncertainties in the newest British data on the calculated abundance of the main components in the boundary gas layer. The results are in Table 8. A list of basic data, plus their official uncertainties, for the 50 components in our gaseous system can be obtained from the authors or the Data Bank in Harwell (7).

High Pressure Regime

At a pressure of 100 bar and a wall temperature of 2000 K, changes in the composition, as indicated in Table 8, might have remarkable consequences.

Table 6a
The expansion coefficient α (in 10^3 K^{-1}) of our gas mixture for various temperatures and pressures

Pressure in bars	Temperature in K			
	3000	5000	7000	9000
1	0.98	0.63	0.19	0.13
25	0.84	0.49	0.37	0.15
100	0.56	0.36	0.43	0.18
α ideal gas	0.33	0.20	0.14	0.11

Table 6b
The compressibility factor β (in bar^{-1}) of our gas mixture for various temperatures and pressure

Pressure in bars	β ideal gas	Temperature in K			
		3000	5000	7000	9000
1	1	1.11	1.15	1.03	1.01
25	0.04	0.043	0.044	0.046	0.041
100	0.01	0.0104	0.0106	0.0119	0.0107

Table 7
Dissociation energies in eV per molecule* of uranium and carbon fluorides at various temperatures

Species	Experimental values at 298 K	Temperature K			
		2000	4000	6000	8000
$\text{UF}_6 \rightarrow \text{UF}_5 + \text{F}$	2.85 [15]	3.21	3.26	-	-
$\text{UF}_5 \rightarrow \text{UF}_4 + \text{F}$	4.47 [15]	4.15	4.15	4.14	4.11
$\text{UF}_4 \rightarrow \text{UF}_3 + \text{F}$	6.48 [15]	6.38	6.32	6.27	6.22
$\text{UF}_3 \rightarrow \text{UF}_2 + \text{F}$	6.53 [15]	6.27	6.10	5.91	5.77
$\text{UF}_2 \rightarrow \text{UF} + \text{F}$	5.96 [15]	5.96	6.14	6.39	6.64
$\text{UF} \rightarrow \text{U} + \text{F}$	6.88 [15]	6.82	7.14	7.54	7.74
$\text{CF}_4 \rightarrow \text{CF}_3 + \text{F}$	5.65 [16]	5.60	5.53	5.44	5.37
$\text{CF}_3 \rightarrow \text{CF}_2 + \text{F}$	3.82 [16]	3.85	3.80	3.84	3.90
$\text{CF}_2 \rightarrow \text{CF} + \text{F}$	5.22 [16]	5.29	5.29	5.23	5.01
$\text{CF} \rightarrow \text{C} + \text{F}$	5.73 [16]	5.85	5.94	6.02	6.10

*1 eV/mol corresponds with $9.64 \cdot 10^4 \text{ J/mol}$.

Table 8
Estimated uncertainties in the composition
as a result of officially indicated uncertainties in the basic thermodynamic data [7]

Species	Heat of formation $\Delta H_{f,298.15}^{\circ}$ kJ.mol ⁻¹	Gibbs Free Energy $\left(\frac{G-H_{298}}{T}\right)_{5000\text{ K}}$ J.mol ⁻¹ .K ⁻¹	Pressure 100 bar			
			Temperature 2000 K		Temperature 4000 K	
			mole* fraction	mole fraction** range	mole* fraction	mole fraction** range
UF ₅	-1920±30	-631±25	~ 0.60	0.50-0.70	0.12	0.06-0.24
UF ₄	-1600±20	-571±15	~ 0.20	0.27-0.13	0.34	0.38-0.28
CF ₄	- 933±1	-433±7	0.18	0.21-0.16	0.02	0.02-0.01
F	- 79±1.5	-199±0.02	0.01	0.01-0.01	0.42	0.44-0.37
Other fractions			0.01	0.01-0.01	0.10	0.10-0.10
Total number of moles			0.88	0.89-0.87	1.49	1.60-1.38

Species	Heat of formation $\Delta H_{f,298.15}^{\circ}$ kJ.mol ⁻¹	Gibbs Free Energy $\left(\frac{G-H_{298}}{T}\right)_{5000\text{ K}}$ J.mol ⁻¹ .K ⁻¹	Pressure 1 bar			
			Temperature 2000 K		Temperature 4000 K	
			mole* fraction	mole fraction** range	mole* fraction	mole fraction** range
UF ₅	-1920±30	-631±25	~ 0.56	0.54-0.66	0.00	
UF ₄	-1600±20	-571±15	~ 0.24	0.25-0.15	0.30	0.35-0.25
CF ₄	- 933±1	-433±7	0.18	0.20-0.17	0.00	
F	- 79±1.5	-199±0.02	0.01	0.01-0.01	0.57	
Other fractions			0.01	0.00-0.01	0.13	
Total number of moles			0.88	0.89-0.87	2.01	2.16-1.85

*Calculated for the heat of formations given in the second column for a U-C-F gas mixture in chemical equilibrium with a graphite wall at 2000 K.

**Assessed on the basis of several calculations considering the official uncertainties in ΔH and $(G-H)/T$ for the main components.

Condensation

The partial pressure of UF₄ will be between 13 and 27 bar, according to Table 8. But at about 20 bar, UF₄ starts to condense on the wall. This means that the partial pressure of UF₄ never can rise above the vapor pressure at 2000 K. Depending on the basic data about UF₄ and UF₅, the maximum total pressure will adjust to this limitation. If a higher total pressure is required, one has to raise the wall temperature.

Wall Corrosion

If the UF₅ content decreases according to Table 8, this will automatically increase the content of UF₄ and CF₄. The extra carbon is taken from the wall. See our recent publication on corrosion (23).

Total Number of Mols

In the boundary wall layer, the changes in the total number of mols are negligible. But at higher temperature, away from the wall, the polyatomic fluorine compounds will decompose. For carbon-fluorides, this happens already between 2500 and 3500 K and for uranium-fluorides about 6000 K. At 4000 K, we estimate an uncertainty in the total number of mols, owing to the uncertainties in the basic data, of less than 10%. For any chemical reaction, the reaction rate is directly proportional to the concentration of the components. This law also holds for the production of nuclear energy. This means that there is a present-day uncertainty of 10% in the required total gas pressure in a Gas Core Fission Reactor for a set energy production per unit volume.

Chemical Composition

For certain purposes, the chemical composition of the boundary gas layer, at a mean temperature of say 3500 K, will be important. This will especially be the case if this gas mixture is used for the creation of an energetically inverted layer for lasing purposes.

The influence of the spread in composition (Table 8) on the specific heat ratio c_p/c_v is of the order of 1%.

Medium Pressure Regime

The second half of Table 8 illustrates the influence of the uncertainties in the basic data, in case of a total pressure of 1 bar. We notice the following: variations in chemical composition owing to uncertainties in the heat of formation of UF_5 or UF_4 very much resemble the 100 bar case and the total number of mols at 1 bar, 4000 K is 30% larger than at 100 bar, 4000 K. The uncertainty in this number is about 10%. Figures 1, 2a, and 2b illustrate the influence of the pressure on the chemical equilibrium. At a level of 4000 K, 1 bar, UF_5 and CF_4 have degraded into lower valent fluorides, and the amount of free fluorine increases relative to 4000 K, 100 bar, with a factor two, for a fixed initial number of mols at 2000 K.

Low Pressure Regime

During the last 10 years, we see a growing interest in rarefied gaseous systems in the pressure range 10^{-4} – 10^{-2} bar and at temperatures between 600 and 3000 K. This interest originates from the possibility of etching and material deposition in systems that have resemblance with our U–C–F gaseous system. Sometimes, U is replaced by W or Mo and C by Si (see Pauleau (25) and Nordine (26)). In that case, the applications are in the industry of semiconductors. We did no calculations in this pressure range.

The Equation of State

The coefficients a and b in Eqs. (5) and (6) were calculated for a mean molar ratio in the reactor gas of F:U:C = 4.00:0.70:0.18. Any other composition of the reactor gas will influence the dissociation processes and, therefore, the a and b values. For an ideal gas, $a = -1$. The values of a in Table 5 and Fig. 7 are a measure for the ideality of the gas. The two extremes at 3200 and 5500 K represent deviations from the ideal gas law between 10 and 15%. They correspond with the dissociation of CF_m and UF_n compounds, respectively.

All these dissociation processes are pressure dependent. To get a set of a and b numbers of wide use, we adjusted them to a pressure range of 1 to 100 bar, which of course means the introduction of a mean value with a spread about the real value. To investigate this spread, we calculated $-a$ and b for pressure ranges of only 10%, with the following results: for 0.9–1.1 bar: the extremes in $-a$ from Fig. 7a move to lower temperatures, to 3000 resp. 4600 K, with values of $-a$ of 0.90 resp. 0.83; for 90–110 bar: the opposite effect is observed. The extremes move to 3600 resp. 6000 K, at values of $-a$ of 0.86 resp. 0.85; and for both narrow pressure ranges, the deviations in b , relative to the values in Table 5 and Fig. 7b, are less than 3%, with a single exception at 6000 K, 1 bar, where it amounts to 5%. The conclusion is that eq. (6) is satisfactory for most work within an accuracy of 7%.

Deviations from the Ideal Gas Law

Nonideal behavior of plasmas, from a point of view of quantum statistics, has been discussed by Kraeft et al. (20) and Ebeling et al. (21). They work with chemically-idealized systems, like hydrogen or only noble gases, like Schram et al. (18).

The extreme deviations from ideality, which we observed owing to dissociation (up to 15%), allow us to neglect these phenomena. Classical deviations from ideality are estimated as follows

1. *The fugacity coefficients, based on critical data.* The critical temperatures for CF_4 and UF_6 (or UF_5) are about 228 and 500 K, respectively. The critical pressures are 37 and about 50 bar. At 2000 K, 25 bar, the reduced values for temperature and pressure lead to a fugacity coefficient $1.00 < f/p < 1.03$ (See (10), Chapter VII, Appendix). For temperatures of 4000 K or higher, the gas mixture, dominated by F-gas, behaves like a noble gas. At these temperatures, all f/p values are equal to 1.00.
2. *Deviations owing to ionization.* Owing to the large content of electronegative gases, the concentration of free electrons below 6000 K is negligible. But from our calculations, we know that this concentration is $1.7 \cdot 10^{24} \text{ m}^{-3}$ at 10,000 K, 25 bar. Then $(n_{\text{gas}} + n_{\text{ions}})/n_{\text{electrons}} = 12$ in the bulk of the hot plasma.

Following Debye and Hückels theory (24) for the mean molar activity coefficient, γ_e , of the electron gas, we find $\gamma_e = 0.75$. The deviations of the Gibbs free energy, from the overall Gibbs free energy of the gaseous mixture at 10,000 K, 25 bar, is only 0.3% owing to the presence of charged species. The influence of this deviation on the real concentration of the electrons has to be investigated in the future.

The Specific Heats for Individual Species

In Fig. 9, we give the specific heats of the main individual species in our gaseous mixture. A broad peak appears in the specific heat of the monoatomic uranium gas, owing to the influence of the higher electronic levels of the uranium atom on the partition function. For a Boltzmann distribution, the population of the levels above 620 cm^{-1} increases from 5 to 40%, going from 2000 to 3000 K (17). Above 4000 K, the internal energy of the uranium atom hardly increases, resulting in a decrease of the specific heat. The same influence is visible in Table 7, where the dissociation energies of UF and UF₂ increase if the temperature rises from 2000 to 8000 K.

The Specific Heats of Mixtures

Recently De Haas and Schram, using Hsu and Pfender's relations, found that the specific heat of monoatomic argon gas increases with a factor 50 between 10,000 and 15,000 K because of the internal energy of the argon atom finally emerging into ionization (18,22). The same effect, but on a much larger energy scale, occurs in our gas mixture for CF_n, resp. UF_m compounds. But instead of ionizing, they dissociate. In both cases, the extra energy needed for the splitting of the compound molecule is manifested by a peak in the specific heat as a function of the temperature (Fig. 8). This peak becomes lower and broader with increasing pressure. At low temperatures, in both cases, the specific heat of the gas has its ideal-gas value. For monoatomic argon gas, this is $5/2 R$ below 8000 K. In our work, we see for higher pressures (25–100 bar) at 2000 K for a mixture of UF₅, UF₄, and CF₄, a value of $c_p/c_v = 1.1$. This is in good agreement with the statistical relation, for bigger molecules, in an ideal gas

$$c_p/c_v = 1 + 2/f$$

where f is the number of degrees of freedom ($f \approx 3n$, where n is the number of atoms in the molecule). Experimental data obtained in shock-wave experiments in UF₆ gas show the same c_p/c_v value (19).

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