

HYDROGEN-GENERATING REACTIONS IN LWR SEVERE ACCIDENTS
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INTRODUCTION

Considerations of hypothetical accidents in light water reactors focus on the loss of effective water cooling to the core which leads to some degree of core damage. If the core is deprived of cooling water for a sufficient time, there can be significant overheating of the Zircaloy cladding, the stainless steel structures and the uranium dioxide fuel within the core. All of these materials have some tendency to react chemically with water and steam to generate hydrogen gas when they are badly overheated. The hydrogen gas generated during an overheating event is a potential threat to the containment integrity for specific plant designs. Because of this, it is important to determine the quantity of hydrogen generated for a range of accident scenarios.

The available data on the reactions of Zircalloys, stainless steels, uranium metal and uranium dioxide with steam at temperatures above about 1000°C and the reactions of core melts during concrete penetration have been reviewed and assessed for the IDCOR Program. The uranium metal is included because small quantities can be formed from the high temperature interaction between Zircaloy and uranium dioxide and because the uranium data adds insight into the nature of the reactions of core materials with steam.

Thermodynamic analyses and comparisons of reaction rate data have been made. The reactions of the metals have been considered according to the two principal phases of severe core damage sequences: the in-core oxidation and the oxidation which occurs on quenching of hot debris in liquid water either within the reactor vessel or within the containment building. The thermodynamic analyses were based on Ref. 1.

One of the purposes of this assessment was to develop fully the information generated in the early studies of oxidation processes, particularly the extensive program carried out at ANL from about 1960 to 1968. Considerable information on the important oxidation processes were generated during the lifetime of the program. Most of the results of the ANL program were documented in Ref. 2. It is of interest to relate these results to the more detailed understanding of the processes developed in recent studies.

REACTIONS OF ZIRCONIUM AND ITS ALLOYS

From a thermodynamic point of view, Zircaloy alloys will react completely in steam even in the presence of a large initial excess of hydrogen. The reaction produces zirconium dioxide and hydrogen. The heat of reaction is 6300 J/g Zr just below the melting point and 6530 J/g just above the melting point.

In-core Oxidation

Isothermal Studies

Early studies included those of Bostrom(3), Lemmon(4) and Baker and Just(5). Baker and Just derived a parabolic rate equation based on an analysis of a series of experiments in which submerged zirconium wires were heated by condenser discharge. Experimental temperatures ranged from slightly below to well above the zirconium melting temperature of 1850°C. The rate law was obtained by fitting an equation to the rate at the melting point and to the Bostrom and Lemmon data in the 1000-1300°C temperature range.

More recent studies have established that there is a step change in the rate at 1580°C corresponding to a phase transition in the oxide(6). The reaction rate is believed to be controlled by the diffusion of oxygen anions through an outer oxide film, through an inner layer of α-zirconium and into the bulk, β-phase of the metal. The diffusion rate through the outer oxide layer increases sharply as the temperature increases from the 1000 to 1580°C stability range of the tetragonal oxide into the stability range of cubic oxide above 1580°C.

A number of studies have been performed in the 1000 to 1580°C temperature range. Table 1 shows a comparison of the rate law parameters and includes

Table 1
Parabolic Rate Laws for Zircalloys in the
1000-1580°C Range

Investigator	Rate Constant (mg Zr/cm ²) ² /s at		Pre-exponential Factor x 10 ⁻⁶	Activation Energy kJ/mole
	1580°C	1000°C		
Suzuki(7)	60.2	0.39	3.80	170.3
Leistikow(7)	58.5	0.31	5.86	177.4
Brown(7)	58.3	0.38	3.64	170.1
Cathcart(8)	57.2	0.41	2.94	167.1
Lemmon(4)	45.9	0.68	0.47	142.2
Westerman(9)	42.2	0.58	0.52	145.2
Klepfer(10)	40.0	0.64	0.36	140.2
Ballinger(11)	35.9	0.58	0.31	139.6
Urbanic(6)	33.9	0.54	0.30	139.8

a listing of the rates predicted at 1000°C and at 1580°C. The comprehensive study by Cathcart and his associates(8) resulted in the following parabolic rate law:

$$w^2 = 2.94 \times 10^6 t \exp(-167,100/RT) \quad (1)$$

where w = mg Zr reacted per sq cm
t = time, s
R = gas constant, J/mole K
T = temperature, K

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Equation (1) appears to describe accurately the reaction in the important temperature range from 1580°C downward to about 1000°C. Ocken(7) pointed out that the investigations could be classified into two categories. Those which used external heating had the higher activation energies, of the order of 170 kJ/mole, while those using internal heating had activation energies of the order of 140 kJ/mole. He recommended use of the results based on internal heating because of the similarity to the reactor accident situation.

The experimental data at 1580°C and above are more scattered than those at lower temperatures. A major reason for this is the strong self-heating tendency, particularly when actual cladding tubes are used which have a relatively high surface to volume ratio. For example, a sample self-heated from 1700°C to 2800°C on contact with steam in one study(12) and in another study a temperature increase of 500°C from 1500°C was predicted(13). The available data above 1580°C indicate that the Baker-Just equation describes the results in a reasonable, although somewhat conservative manner(14). It is expected that ongoing studies in the US and in Germany will result in a refined rate law in the near future.

Most of the studies noted above have employed an excess of steam to avoid any possibility of steam starvation. The Baker-Just study(5) called attention to the likely limitation of the rate of gaseous diffusion of steam through the evolving hydrogen. This limitation becomes important at high temperatures when the solid-state reaction rate (parabolic rate law) becomes very rapid. Chung's experiments(15,16) at low temperature showed a definite but not a large effect on reaction rate caused by the presence of an excess of hydrogen. Two possible kinetic limitations were considered responsible. One of these is a decrease in the level of adsorbed oxygen on the surface of the oxidizing metal such that the reaction becomes controlled at the surface rather than by diffusion through the oxide-containing layers. The other, more important, limitation is caused by an inhibition of the solid-state diffusion rate caused by the presence of significant quantities of hydrogen in the growing oxide film. The inhibiting effect of hydrogen was verified by the comparison of experiments performed in helium with those in hydrogen. Some of the experiments at high temperatures which showed a very large reduction in reaction rate were not checked by helium comparisons and could possibly have resulted from a gaseous diffusion limitation.

Chung's experiments have added an important new dimension to the isothermal, in-core oxidation problem. However, more isothermal experiments at high temperature are required. Experiments under well-defined hydrodynamic conditions which include hydrogen-helium comparisons would be especially valuable.

Non-isothermal Studies

Non-isothermal experiments have provided a high degree of understanding of how actual fuel pin structures respond to overheating sequences. Early studies indicated that the extent of reaction could be predicted by integration of the parabolic rate law over the transient temperature(17). They showed that there was little or no fuel-cladding interaction if the temperature was limited to about 1700°C. Also, it was shown that the Zircaloy

did not run or drip from the UO₂ pellets at temperatures as high as 2140°C because of the containment provided by the partly oxidized outer shell. Conditions for cladding integrity following water quenching were established in a preliminary way.

Recent studies have evaluated the effects of the complex oxygen partitioning between the outer oxide layer, the α phase and the β -metallic core. Cronenberg and El-Genk(18) have reviewed the available information on oxygen diffusion in the phases of interest. Hagen and Malauschek(19) reported the development of bundles of fuel rod simulators which used UO₂ ring-shaped pellets with a central tungsten rod electrode. The rods were clad with Zircaloy-4 and arranged in a 3 x 3 bundle. The experiments showed that the meltdown behavior was influenced by interactions between components of the fuel elements and by the degree of oxidation caused by Zircaloy-steam reaction. The UO₂ begins to be dissolved by the melting of Zircaloy at 1850°C. Oxidation reduces the meltdown. As the temperature rises, the oxide surrounds the rod as a tight layer, the thickness of which increases with decreasing heating rate in the presence of sufficient steam. Thin oxide layers develop holes and cracks immediately which become rinsed down with the melt. Thicker oxide layers form a stable shell which encloses the melt. At 1900°C, holes form and the melt begins to pour out. For a fully oxidized cladding tube, no meltdown occurs up to about 2500°C. There is a strong tendency for the melt to stick between the rods forming a lump of molten material at the lower end of the melting region. With lack of steam, oxidation occurs preferentially in the lower region of the bundle. The nature of the interaction of Zircaloy-4 with UO₂ has been established(20,21). The results show that solid Zircaloy reacts with UO₂ if there is good contact between the two solids. The Zircaloy reduces the UO₂ to form α -Zr(O) and uranium metal. The uranium metal forms a U,Zr alloy which is liquid above 1200°C. The sequence of reaction layers is UO₂, α -Zr(O) + (U,Zr), (U,Zr), α -Zr(O) and Zr-4. Rates of layer formation are parabolic between 1000 and 1700°C. The rate is controlled by the diffusion of oxygen into the cladding. The oxygen content of the cladding increases to a maximum value of 6 w/o. The reaction between solid UO₂ and liquid Zircaloy accelerates as oxygen in the Zircaloy increases the wettability between UO₂ and liquid Zircaloy(21).

One important aspect of the interaction process which is not fully understood is the thermal effect of the fuel-cladding interaction(16). Large uncertainties in analyses of core heating result from the unknown magnitude of the energy change associated with the pseudoeutectic liquefaction process. Another uncertainty is the reaction rate law for the reaction products. The principal product is the partly oxidized metallic species (U,Zr,O) for which there are apparently no oxidation rate data.

Oxidation during Quenching

Out-of-pile Experiments

Molten Zircaloy quenching in water was achieved under controlled conditions by a condenser discharge method(5). One-inch lengths of either 30- or 60-mil zirconium or Zircaloy-3 wires were heated within a few hundred μ s under water. Tests were performed in room temperature water and in saturated water at pressures ranging from 10 to 1500 psia.

The electrical energy input was used to estimate the initial temperature and fractional melting using enthalpy data and assuming that no heat losses occurred during heating. The extent of reaction was calculated on the basis of the quantity of hydrogen generated.

The experimental results showed that the reaction depended strongly on the effective particle sizes generated by the rapid heating. At temperatures below melting, the wires remained intact. As the energy input increased from fully solid at the melting temperature to fully molten at the melting temperature, the metal changed from an intact wire to a distorted wire to a few large particles mixed with a few small ones. As the temperature increased above melting, the average particle size decreased continuously. This is shown in Fig. 1 where the extent of reaction is plotted as a function of mean diameter.

The results in room temperature water indicate that the reaction was relatively slow and limited to less than 25% unless the particle diameter was smaller than about 0.6 mm. In heated and saturated water, the reaction was limited to about 30% unless the mean particle size was less than about 1.2 mm. It should be noted that there was no apparent difference in the heated water results for water temperatures ranging from 90 to 315°C at corresponding pressures from 10 psia to 1500 psia. The rapid or "explosive" reactions were identified with rapid motion of the particles as shown by high speed motion pictures of the reaction process.

The results of the condenser discharge experiments could be partially explained in terms of a simple model of a sphere quenching in water(5) which took advantage of the fact that the Nusselt number for heat transfer and mass transfer to a sphere has a minimum value of 2. This minimum value should apply to small spheres which are not in rapid motion. The model considered two rate determining processes: solid-state diffusion (parabolic rate law) and gas-phase diffusion (interdiffusion of water vapor and hydrogen). The gaseous diffusion process limited the reaction rate initially until the buildup of an oxide film reduced the parabolic law rate to a lower value which initiated a decreasing temperature, a decreasing reaction rate and quenching.

The reaction of solid 60-mil wires at the melting point of 1852°C in saturated water was about 8%. The analysis indicated that these conditions resulted in a nearly isothermal reaction condition. This provided an essentially unique value of the

parabolic rate constant at 1852°C which was used to generate the "Baker-Just" parabolic rate law. The model predictions using the Baker-Just equation are included in Fig. 1.

One of the most uncertain features of the zirconium particle quenching model was the specification of the parameter, $\Delta P_w/P$, which is the ratio of the water vapor pressure to the total pressure and the effective driving force for gaseous diffusion. This ratio was unity for the saturated water experiments in which there was no inert cover gas. However, for the room temperature water experiments, to obtain agreement with the experimental results, it was necessary to give a value of $\Delta P_w/P = 0.5$ for this ratio. This effective value was interpreted to result from a dynamic equilibrium between the water interface directly facing the hot particle and the cooler bulk liquid. A recent analysis has provided insight into this problem(22).

The results of the out-of-pile quenching experiments have shown that fine fragmentation is required to produce a major reaction. Quenching of coarse fragments with diameters greater than about 2 mm results in no more than about 10% reaction for initially unoxidized molten zirconium or Zircaloy.

In-pile Experiments

A number of experiments were performed in the Transient Reactor Test Facility (TREAT) using zirconium-containing fuel samples. A series of tests were performed with unclad zirconium-uranium alloy fuel plates(23). The plates were 89.4 w/o zirconium and 10.6 w/o fully-enriched uranium. It was clear from the residue of the samples at energies of 270 cal/g and above that complete melting occurred because all semblance of the original plate structure was lost. The extent of metal-water reaction was determined from the quantity of hydrogen generated. The reaction ranged from 2.3 to 11.5% except for the very energetic test which fragmented extensively and reacted 67.2%. These results showed that plates could be melted into globules (in the alumina retaining crucibles), (11.7 mm equivalent diameter) under water and quenched to room temperature with only limited metal-water reaction and hydrogen generation.

A number of experiments in TREAT(24), CDC(25), NSRR(26) and PBF(27) have been performed with Zircaloy-clad, oxide-core fuel elements which were submerged in water. These results showed that the extent of cladding reaction was less than about 20% unless the fission energy input was greater than

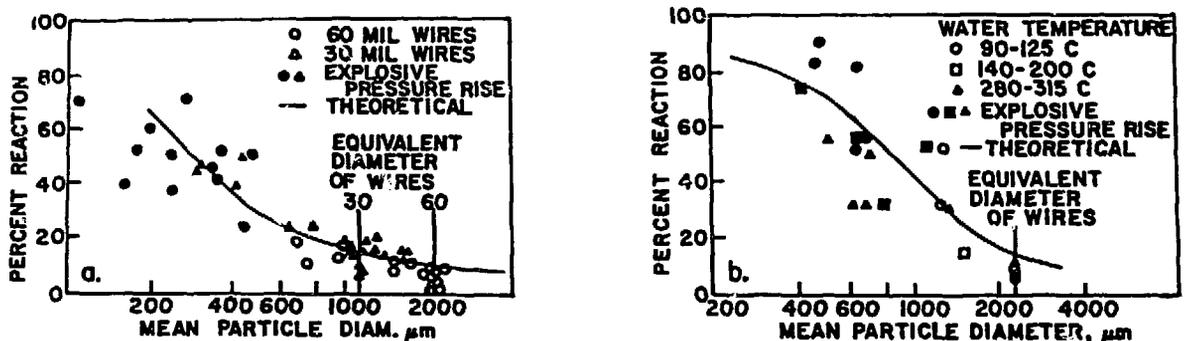


Fig. 1. Effect of particle size on the zirconium-water reaction during quenching in: a. room temperature water, and b. heated water.

300 cal/g which is sufficient to fully melt the uranium dioxide fuel.

Three experiments were performed in TREAT which simulated a loss-of-coolant accident rather than a power excursion(28). In these tests, three-pin clusters were suspended above a water pool within an autoclave. TREAT was operated in a "flat-top" mode, i.e., at an essentially constant power level, for an interval from 12 to 50 s. As a result, the fuel pins were melted down in an environment of water vapor. The results of this test indicated that quenching occurred more or less uniformly over a period of about 2 min. The total extent of reaction varied from 30 to 44% for the three experiments. This result shows clearly that the combined reaction while in the intact pin structure in the steam environment and during quenching into the water was quite limited.

REACTIONS OF STAINLESS STEELS

The stainless steel-steam reaction should depend upon the local steam-hydrogen ratio because of thermodynamic considerations(14). It has been suggested that the reaction would be limited to the formation of the spinel compound, $\text{FeO}\cdot\text{Cr}_2\text{O}_3$, in the presence of excess hydrogen. If the local steam-hydrogen ratio exceeds about 0.5, the remainder of the iron can form FeO. In an excess of steam, reaction can proceed from Fe_3O_4 and NiO. The hydrogen production and the heat of reaction depend upon the products formed. The heat of reaction varies from about 500 to 1000 J/g-steel and, therefore, is considerably less than that for the Zircalloys.

In-core Oxidation

Isothermal studies were performed at ANL by R. E. Wilson and his associates using induction heating(29) and furnace heating(30). The results covered the solid range from 1100 to 1300°C and the molten range from 1400 to 1600°C. The results at 1200 and 1600°C are indicated by the closed symbols in Figs. 2 and 3, respectively. The results at 1400°C and above were affected by a swelling and foaming process, apparently caused by the fact that both the metal and the oxide begin to melt at about

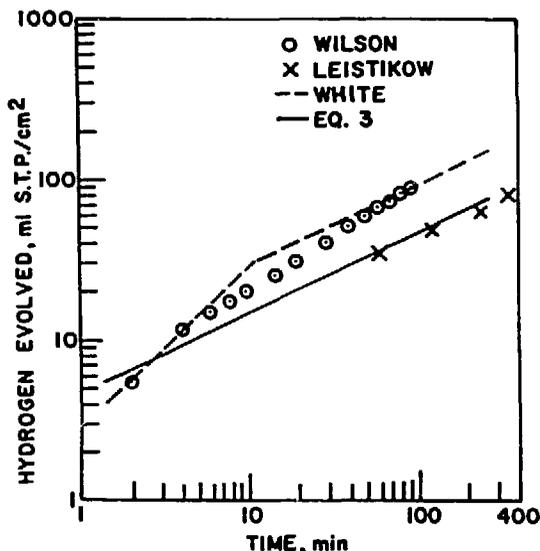


Fig. 2. Reaction of 304 stainless steel with steam at 1200°C.

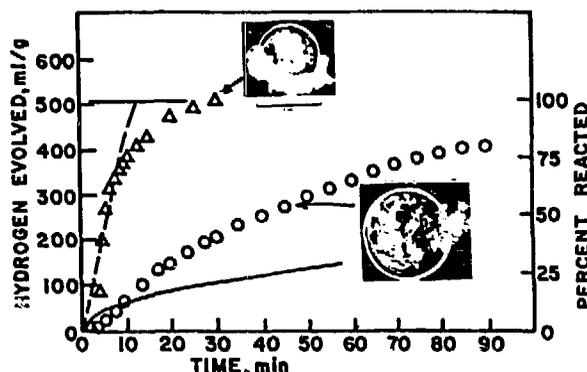


Fig. 3. Reaction of 304 stainless steel with steam at 1600°C. Symbols are from two experiments with 14 g samples; dashed line is Eq. (2); solid line is Eq. (3).

1400°C (see Fig. 3). The experimental results, at 1400°C and above, were presented in terms of hydrogen evolution per gram because of the uncertainty in the surface area.

Isothermal studies were also performed at GE-NMPO by J. F. White and his associates(31) and, very recently at KfK by Leistikow(32). Both studies were limited to the solid range below 1400°C. White reported an initial 6 to 28 min period of linear oxidation followed by parabolic oxidation. White reported the following parabolic rate equation:

$$w^2 = 2.4 \times 10^{12} t \exp(-353,000/RT) \quad (2)$$

where w = weight gain, mg oxygen/cm². White's rates, converted to hydrogen generation on the basis of $\text{FeO}\cdot\text{Cr}_2\text{O}_3$ formation, are included in Figs. 2 and 3 as a dashed line.

Leistikow reported parabolic behavior. His data at 1200°C, also converted to hydrogen generation, are included in Fig. 2 as the open symbols.

Baker, et al.,(14) have recently derived the following parabolic rate law from condenser discharge experimental results based on hydrogen excess conditions

$$w^2 = 3 \times 10^7 t \exp(-209,000/RT) \quad (3)$$

where w = mg stainless steel/cm². Predictions from Eq. (3) are included in Figs. 2 and 3 as solid lines. Overall, the results at 1200°C from all available sources agree within a factor of 2.

To compare the data above 1400°C with the available rate laws, the original total surface area of the sample was used. White's parabolic rate law, Eq. (2), appears to describe the observed reaction well at 1400°C but gives high predictions at 1600°C (Fig. 3). Predictions from Eq. (3) are low at both temperatures, however, part of this disagreement could be a result of the increase in surface area (see Fig. 3).

Non-isothermal studies showed that there was a marked interaction between the oxidized steel and UO_2 above about 1400°C(17).

Oxidation during Quenching

Molten stainless steel quenching in water was studied by the same condenser discharge method used for zirconium(33). One-inch lengths of either

30- or 60-mil, Type-316 stainless steel wires were heated within a fraction of a millisecond under water which ranged from 25 to 200°C. The experimental results showed that the hydrogen production was limited to about 0.16 μ STP/g-SS for the most energetic experiments. This corresponds to 0.155 μ STP/g-SS for reaction to FeO-Cr₂O₃ and is well below that corresponding to complete reaction to Cr₂O₃ and FeO, 0.409 μ STP/g-SS. This is consistent with oxidation under conditions of local steam to hydrogen ratios less than about 0.5. The hydrogen formed by the reaction apparently provided local concentrations around the particles rich in hydrogen. The average particle diameters for the experiments in which the wires were completely melted were about 300 μ m.

The sphere quenching model was applied to the oxidation of 300 μ m stainless steel particles(14). A best fit to the data for saturated water was obtained with Eq. (3). The calculation used the hydrogen generation and the heat of reaction appropriate for the reaction product, FeO-Cr₂O₃.

The model was also applied to recent data reported by Benz, et al.(34), for molten stainless steel quenching in water. The particle diameter was predicted by the method of Henry and Fauske(35) which takes into account the hydrodynamic stability limit when the quantity of hot material is significant in comparison with the cross-sectional area and depth of the water pool. The model, yielded reasonable predictions of the hydrogen generation as shown in Ref. 14.

Experiments were performed in TREAT with stainless steel-urania cermet fuel pins and plates which were composed of 90 w/o - Type 304L stainless steel and 10 w/o fully enriched urania(36). The results of the experiments were shown to be consistent with the sphere model in conjunction with the parabolic rate law derived from the condenser discharge experiments(14).

REACTIONS OF URANIUM METAL

Uranium will react completely to UO₂ even in the presence of an excess of hydrogen. The heat of reaction is 2475 J/g U just above the melting point.

In-core Oxidation

The isothermal reaction was studied using a volumetric method in which steam was passed over induction heated uranium cubes(37). Hydrogen produced by the reaction was collected over water in a gas burette. Experiments with uranium and uranium-1 a/o aluminium alloys showed that the reaction followed a parabolic rate law between 600 and 1200°C. The oxide formed an adherent black layer. At 400 and 500°C, the reaction was quite rapid, following a linear rate law. The oxide, in this case, washed continuously from the samples. The reaction was also studied between 1200 and 1600°C using a quartz pedestal to support the uranium cubes and depending upon the strength of the oxide shell to contain the molten uranium. The high temperature reaction was also parabolic, however, the rate law was somewhat different than that for lower temperatures. The rate equations are as follows:

$$1600^\circ\text{C} < T \\ w^2 = 6.0 \times 10^7 t \exp(-167,000/RT) \quad (4)$$

$$1200 < T < 1600^\circ\text{C}$$

$$w^2 = 7.5 \times 10^5 t \exp(-105,000/RT) \quad (5)$$

$$600 < T < 1200^\circ\text{C}$$

$$w^2 = 9.2 \times 10^4 t \exp(-77,800/RT) \quad (6)$$

where $w = \text{mg U/cm}^2$. The sphere model was applied to the data (14). A best fit to the data was obtained with the parabolic rate law Eq. (4).

The sphere calculations (Fig. 4) show marked ignition behavior with an ignition temperature of

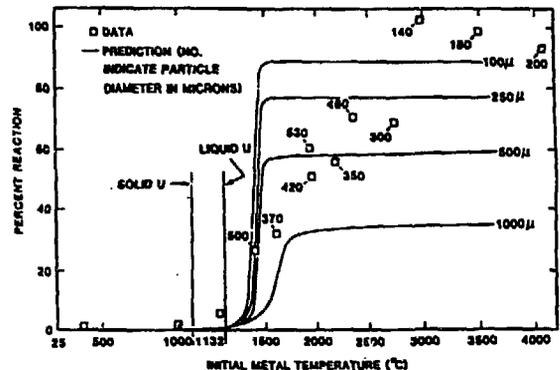


Fig. 4. Comparison of computed and experimental condenser discharge results for uranium wires melted in saturated water.

about 1300°C. This behavior is similar to that of zirconium. Both metals have a relatively high heat of reaction. Stainless steel, by contrast, has a smaller heat of reaction and does not exhibit such sharp ignition behavior.

Several series of experiments were performed in TREAT with uranium metal fuel samples(36,38). Both pure uranium and a uranium-zirconium-niobium alloy were used in the form of pins and wires. In some of the runs, the alloy pins were clad with Zircaloy-2 and the ends were capped. For these experiments, the percent reaction is based on the combined total of uranium and zirconium metals present.

The results in Fig. 4 indicate that extensive reaction was obtained only at very high energy inputs when relatively fine particles are produced. Experiments at intermediate energies showed that the metal sample could be completely melted under water with a limited reaction.

REACTIONS OF URANIUM DIOXIDE

The reaction with steam is as follows:



The extent of reaction depends upon the local ratio of the partial pressures of steam to hydrogen. The limiting reaction can be determined by plotting the partial pressures of oxygen in equilibrium with UO_{2+x} as a function of temperature and oxygen content and indicating where the partial pressures of oxygen in equilibrium with various steam-hydrogen ratios coincide with that for the UO_{2+x}. Blackburn(39) has reported a model for calculating UO₂ thermodynamic data. This equation was used to generate the dotted curves in Fig. 5. The solid

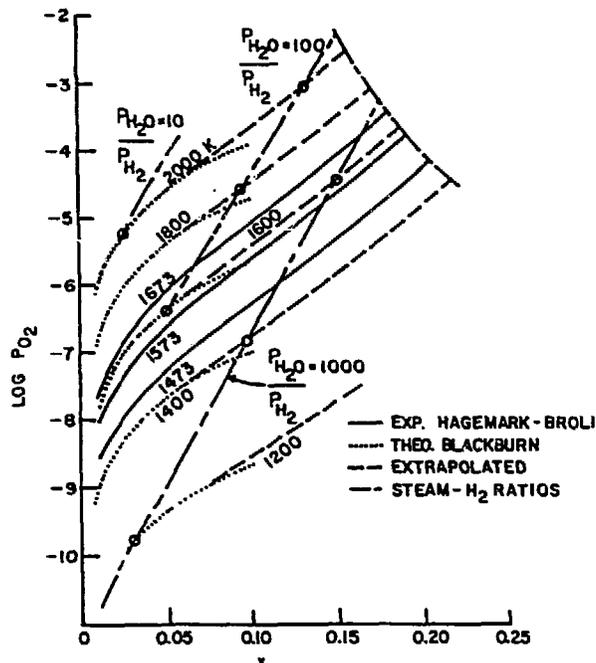


Fig. 5. Thermodynamic data for UO_{2+x} showing points of equilibria with various steam-hydrogen mixtures.

lines are experimental data from Hagemark and Broli(40) obtained at 1200, 1300 and 1400°C. In order to develop a complete set of data, the theoretical curves were extrapolated (dashed lines) to be generally parallel to the experimental results. The irregular dashed lines in the figure correspond to various ratios of the partial pressure of steam to hydrogen. These lines terminate at values corresponding to the equilibrium dissociation of pure steam. This limit corresponds to the theoretical maximum oxygen contents for uranium oxide so long as no oxygen gas is added to the system.

The results, summarized in Fig. 5, indicate for example, that at 1600K (1327°C) oxidation is limited to $x = 0.05, 0.15$ and 0.19 , for steam to hydrogen ratios of 100, 1000 and infinity, respectively. Above about 2000K, the maximum reaction is limited to $x = \sim 0.15$ and this could be obtained only in the presence of a large excess of steam over hydrogen.

The isothermal reaction was studied in the high pressure furnace apparatus at 1500°C and 1 atm(41). The samples were single pellets of $UO_{2.0}$ of greater than 95% density. The extent of oxidation, determined by weight gain, gravimetric analysis and hydrogen generation agreed well with each other. The reaction rate followed an apparent parabolic law, as shown in Fig. 6 which tapered off to a limiting value of $UO_{2.17}$ after four hours. The pellets were darkened but did not crack or fragment.

Isothermal studies of the UO_2 -steam reaction were also reported by White *et al.*(42,43). Experiments used the thermobalance technique with single pellets of $UO_{2.0}$. White also found parabolic behavior. The rate law constants could be described by the following equation, based on weight gain:

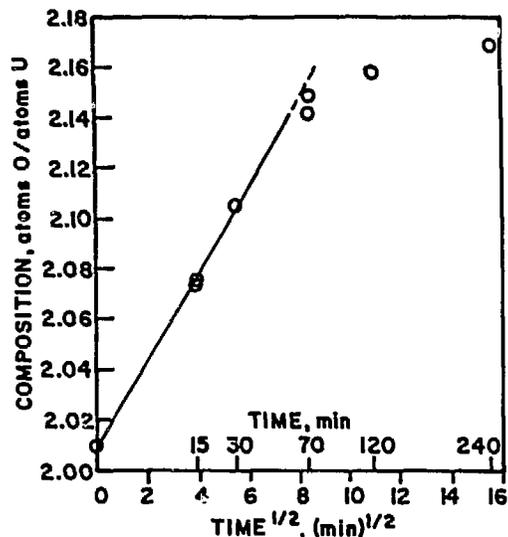


Fig. 6. Isothermal reaction of UO_2 in flowing steam at 1500°C.

$$w^2 = 8.4 \times 10^4 t \exp(-201,000/RT) \quad (7)$$

The equation applies over a very wide temperature range. The rate is believed to be controlled by the diffusion of oxygen through the crystal lattice. The experimental results appear to be quite consistent with the thermodynamic analysis.

A series of three experiments were performed in TREAT with single pellets of pure UO_2 submerged in liquid water. A similar series of experiments were performed in CDC with glass-clad UO_2 fuel rods to determine the hydrogen release from the uranium-water reaction as a function of nuclear energy deposition. The results were generally consistent with the isothermal results.

CONCLUDING REMARKS

The kinetics of the high temperature steam reactions of the metals Zircaloy alloys, uranium and austenitic stainless steels have been found to be consistent with parabolic law behavior. The actual rates, expressed in terms of hydrogen generation are very similar to each other as shown in Fig. 7. The rate of hydrogen generation from the reaction of uranium dioxide is considerably slower.

The important thermodynamic limitations to the stainless steel and the UO_2 reactions have been described in this paper and in Ref. 14. Reference 14 includes a discussion of the reactions of molten metal layers during concrete penetration. The available data indicate that the oxidation reactions go to completion in a thermodynamic sense because of the high temperature of the melts.

There is a lack of data for the high temperature steam reactions of U,ZrO interaction products and iron and steels which do not contain important quantities of chromium.

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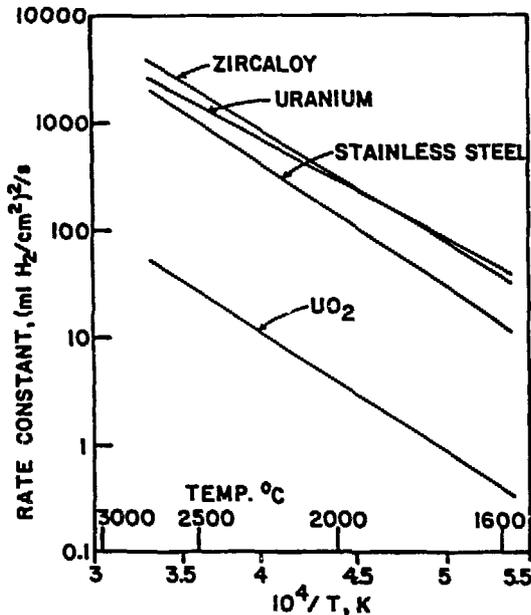


Fig. 7. Comparison of high temperature parabolic rate constants.

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