STRENGTH TESTS ON SPHERICAL FUEL ELEMENTS

A. SCHMIDT, A. KLEINE-TEBBE, H. KURTH, W. THEYMANN

Hochtemperatur-Reaktorbau GmbH,
Technische und physikalische Abteilungen, D-6800 Mannheim, Germany

SUMMARY

The fuel elements of the pebble bed reactor are exposed to different mechanical stresses during their operating life. On the one hand, due to the reactor core-flow, they are repeatedly dropped to the pebble bed from heights of up to 4 m, on the other hand, they can be hit by a dropping fuel element or by a shut-down rod being inserted into the pebble bed. In addition, it must be considered that the individual fuel elements, exposed to stresses in the reactor, may have different stress histories. A fuel element may e.g. be hit by a shut-down rod after having been exposed to several impacts by falling spheres or it may be exposed to further drop and impact stresses after several impacts have been exerted by a shut-down rod. In order to obtain a statement on sphere rupture in the reactor, the impact resistance—defined as the number of drops until rupture—and the crushing resistance of the fuel elements must be known under the given conditions.

For the drop tests a special facility was used, dropping the spheres to a steel plate or a graphite sphere in free fall from a maximum height of 4 m. The drop-test results were evaluated under application of a Weibull distribution. For this purpose a procedure was developed permitting the indication of confidence levels for the Weibull parameters. Thus, statistically secured expected values are obtained for each range of drop numbers and, after indication of the risk level, confidence intervals are attained for the expected values.

The dependence of the maximum force between the impact partners on the drop height, experimentally measured during the drop tests, can be explained by a theoretical formula. From this maximum force the maximum stress was calculated. It was found that the logarithm of the mean number of drops until rupture is a linear function of the maximum stress. This fact can be explained by means of the Weibull theory on the rupture probability of a material under an applied stress.

Further tests have shown that the crushing resistance of fuel elements as well as their impact resistance are a function of the type and extent of prior mechanical stresses; thus, for instance, the crushing resistance substantially decreases a.o. with the number of impacts, the fuel element has undergone before. These results are discussed in view of the conditions prevailing in the THTR. Here it is shown that the decrease of the crushing resistance of the fuel elements is more than compensated by the increase of the crushing resistance with temperature.

1. Introduction

The spherical fuel elements of the THTR are exposed to different mechanical stresses during their operating life. Due to the reactor core-flow, the elements are continiously circulated and repeatedly dropped to the pebble bed from heights of up to 4 m. They can also be hit by a dropping fuel element or by a shut-down rod being inserted into the pebble bed. In addition, it must be considered that the individual fuel elements, exposed to stresses in the reactor, may have different stress histories. A fuel element may e.g. be hit by a shut-down rod after having been exposed to several impacts by falling spheres or it may be exposed to further drop and impact stresses after several loads have been exerted by a shut-down rod. The safety of the pebble bed reactor requires a high degree of geometrical integrity of the fuel elements during their operating time. However, in order to obtain a statement on sphere rupture in the reactor, the impact resistance - defined as the number of drops until rupture - and the crushing resistance of the fuel elements must be known under the reactor conditions.

The present paper reports on experiments carried out for finding the impact and crushing resistances of spherical fuel elements with different stress histories. The results of these experiments are discussed. Some theoretical considerations on the impact resistance of graphite material spheres are presented.

2. Test Facility

For the drop tests a special facility was used, dropping the spheres on a steel plate or a graphite sphere in free fall from a maximum height of 4 m. The maximum force during the impact, K_{max}, was measured with a piezoelectric crystal gauge, the rebound height was calculated from the time difference between first and second impact on the support. In addition, the number of drops until rupture was determined for each fuel element.

The crush tests were carried out on a 10 Mp material testing machine between parallel steel plates.

3. Evaluation of Results under Application of the Weibull Statistics

Failure of a fuel element during the impact test is caused by fatigue of the material. Thus it is obvious to use a Weibull distribution for the evaluation (see e.g. Wilkins and Reich [1]). For the present problem it can be set up as follows:

$$F(N) = 1 - \exp\left[- N^{a}/b\right] \quad (1)$$

N being the number of loads (in this case impacts) and F(N) the cumulative failure probability; a and b are constants, also called Weibull parameters. The cumulative fatigue failure probability, F, is the probability that any specimen will survive any given number of stress cycles, N, the individual stresses being identical to each other. From the measured drop numbers until rupture the failure probability curve F(N) was found by calculating those values of the constants a and b in equation (1) which give the optimum adaptation of the curve to the available measured values. However, because of the small number of specimens used, these calculated values are uncertain. Therefore, a procedure was developed to estimate the confidence levels for both of the evaluated Weibull parameters. The calculation provides statistically confirmed expected values for each range of drop numbers and, after indication of the risk level, confidence intervals for the expected values.

4. Impact Resistance of Fuel Elements without Prior Mechanical Stresses

During the drop tests of fuel elements without prior mechanical stresses the fuel element spheres were dropped to a steel plate from heights of 1 to 4 m and to a graphite sphere from heights between 2 and 4 m. According to the theory of Hertz [2] about the contact of elastic bodies, the maximum force between the impact partners is given by the equation

$$K_{max} = \left(\frac{5}{2}\, m \cdot g\right)^{0,6} \cdot n^{0,4} \cdot h^{0,6} \quad (2)$$

in which m is the mass of the dropped sphere, g is the constant of gravity, and h is the drop height. n is dependent of the radii of the surfaces in contact and of the elastic properties of the impact partners.

From Fig. 1 which shows the experimental results it can be seen that the measured values of K_{max} are proportional to $h^{0,6}$, as required in the Hertz theory, but the values of K_{max} found by experiment are lower than the theoretical values by a factor of 2. This indicates that the impact partners have no ideally elastic behaviour, but the loss in maximum power during the impact must be proportional to the theoretical value of the maximum power. It can be demonstrated that the energy loss is caused by the deformation of both spheres during the impact. This deformation is due to a destruction of the pore system by the local stresses and, hence, to the compression of the material in the contact range of the impact partners. The compression energy is, however, proportional to the change of the sphere diameters (Lurje [3]), and this change is proportional to the maximum power acting at the pole.

On the basis of the Hertz equations, from the K_{max}-values and the elastic properties of the sphere, the maximum tensile stresses σ_{max}, occurring at the contact of both impact partners, were calculated by the formula:

$$\sigma_{max} = \frac{1-2\cdot\nu}{2\pi} \cdot \frac{K_{max}}{a^2} \qquad (3)$$

where a is the radius of the surface of contact and ν is Poisson's ratio.

If σ_{max} is plotted as a function of the logarithm of the mean number of drops to failure (Weibull mean value), a straight line is obtained in a very good approximation, as can be seen in Fig. 2, i.e. the mean number of drops to failure is proportional to exp $(-\sigma_{max})$. This result can be easily explained: The fuel element material contains a distribution of flaws, either on the surface or throughout the volume. At each impact a shock wave goes through the material, the height of which is proportional to the maximum tensile stress, in first approximation. By this effect the combination of the highest local stress concentration with the most serious flaw controls the strength of the sphere in the way that certain flaws in the material will increase, until finally parts of the sphere will peel off or complete rupture will occur. According to the Weibull statistical theory for the strength of brittle material [4], the dependence of the rupture probability of the specimen on the stress applied σ and on the specimen volume V, follows the relation quoted below:

$$W = 1-\exp\left[-V\,(\sigma / \sigma_0)^m\right] \qquad (4)$$

(σ_0 and m are constants) i.e. the rupture probability is proportional to exp $(-\sigma)$.

5. Impact Resistance of Fuel Elements Exposed to Prior Stresses

Fuel elements were exposed five times to a 5 000 N and once to a 10 000 N static load, respectively. In order to approximate the reactor conditions, they had subsequently to undergo a drop test with central impact on a graphite sphere from a height of 3 m. An increase in the impact resistance of the fuel elements which had been stressed five times with 5 000 N and a decrease of the impact resistance of the spheres priorly stressed with 10 000 N was demonstrated, in both cases however just within the scattering range of the impact resistance of spheres without prior stresses.

6. Crushing Resistance of Fuel Elements without Prior Mechanical Stresses

For simulating the conditions prevailing in the reactor a support was constructed consisting of three steel spheres flattened at the points of support of the fuel elements. A steel plate was used as comparison support. The measured crushing resistances are equal for both cases of support within the scattering range and are approximately 21 000 N for the pressure direction perpendicular to the graphite grain and approximately 23 300 N for the pressure direction parallel to the grain.

Fuel element crush tests were carried out at room temperature, at 800° C, and at 1 000° C. Fig. 3, which shows the results of these tests indicates that the crushing resistance will increase by 20 % at an increase of temperature from 20° C to 800° C or 1 000° C.

7. Crushing Resistance of Fuel Elements Exposed to Prior Mechanical Stresses

To find out whether the crushing resistance of the fuel elements depends on the number of drops undergone before and on the drop height, the fuel elements were exposed to drop tests and were subsequently crushed. The results of these tests are shown in Fig. 4, which demonstrates that the crushing strength generally decreases with the number of drops the fuel element has undergone before.
The decrease of the crushing strength is dependent of the drop height and the support, i.e. steel plate or graphite sphere. It can be demonstrated that this decrease is proportional to the maximum force inserted during the drop test, and, in first approximation, a linear decrease of the logarithm of crushing strength with increasing number of drops can be assumed.

For the numbers of drops to be expected in the reactor, a 5 % decrease of crushing strength must be expected as a result of the impact loads compared with the value for fuel elements without prior mechanical loading.

During their in-core time, fuel elements can be repeatedly hit by shut-down rods with generally different forces. For determining the influence of such prior mechanical loads (preloads) on the crushing resistance, the fuel elements were stressed five times with 4 000 N and 8 000 N, respectively. The pressure points were uniformly distributed over the sphere surface. As shown in Fig. 5, an increasing preload results in a decrease of the crushing strength of the fuel elements being below 5 % for the tests described.

8. Conclusion

For the evaluation of the drop tests with spherical fuel elements a procedure was developed permitting the indication of statistically confirmed statements on the impact resistance. The interdependence of the number of drops until rupture and the maximum force impulses occurring, found by experiment, can be explained in theory. The prior mechanical stresses prevailing in the THTR will cause a slight decrease of the crushing resistance of the fuel elements, but this effect will be more than compensated by the relatively great increase of the crushing resistance with temperature. The fuel elements which had undergone mechanical stresses did not show any increase in uranium contamination. Hence, fuel particles had not been destroyed.

Literature:

[1] B.J.S. Wilkins; A.R. Reich,
An Estimation of the Probability of Fatigue Failure of Some Graphites,
AECL-3958 (1972)

[2] H. Hertz,
J. Reine u. Angew. Math. 92, 156 (1881)

[3] A.I. Lurje,
Räumliche Probleme der Elastizitätstheorie, Akademie-Verlag Berlin (1963)

[4] W. Weibull,
Hand. Ing. Vet. Akad. No. 151 u. 153 (1939)

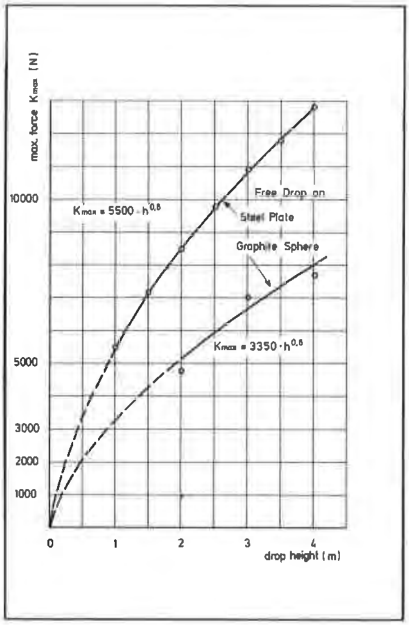

Fig. 1 Maximum force K_{max} as a function of drop height

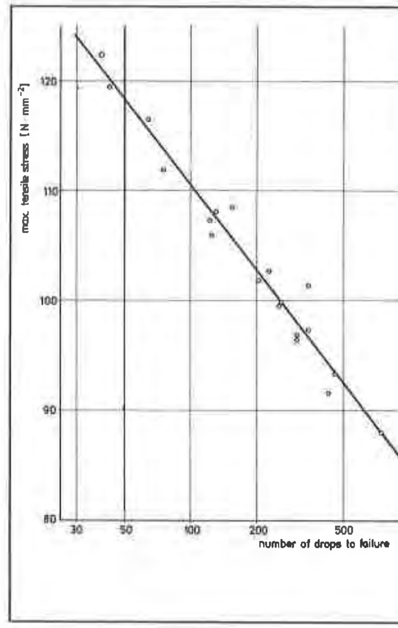

Fig. 2 Relationship between maximum tensile stress and drops to failure

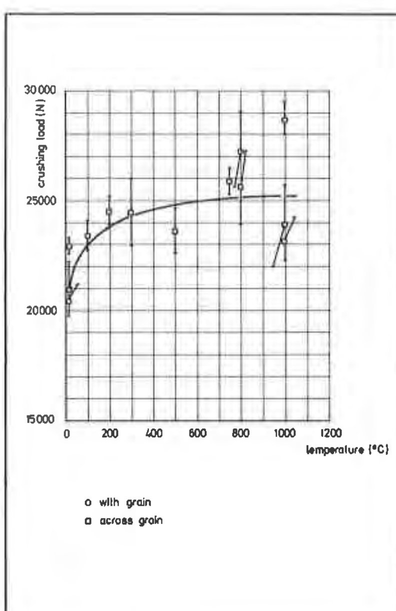

Fig. 3 Effect of temperature on crushing strength of spherical fuel elements

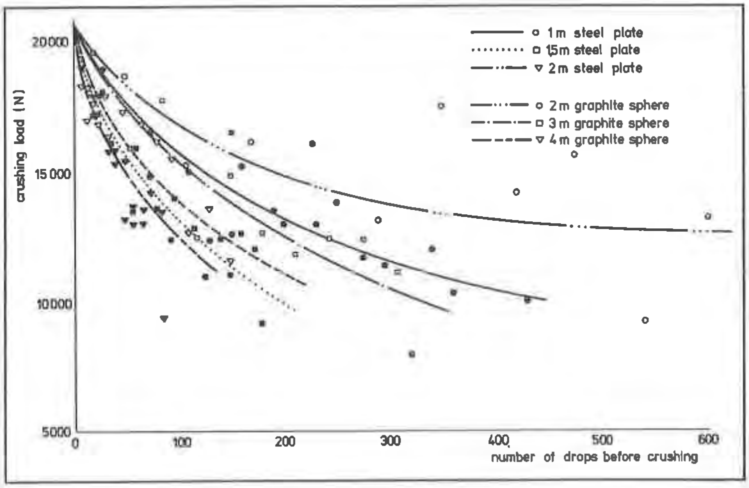

Fig. 4 Crushing load of spherical fuel elements after dropping from different heights on a steel plate and graphite sphere, respectively

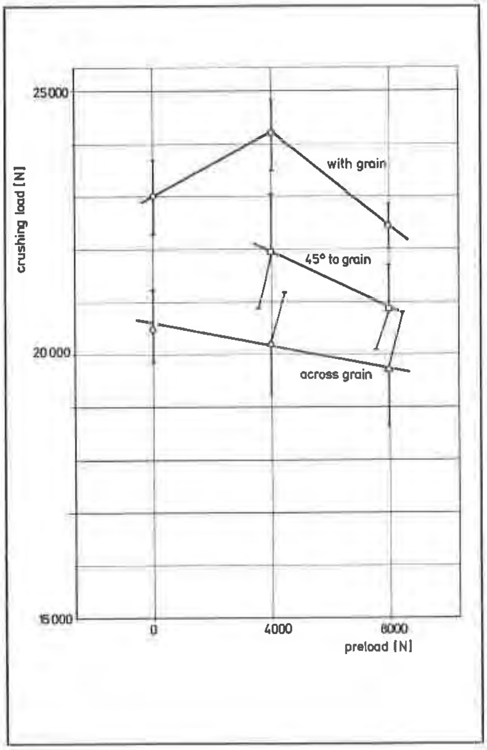

Fig. 5 Crushing load of spherical fuel elements after different preloads