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COMPARISON OF FISGAS SWELLING AND GAS RELEASE PREDICTIONS WITH EXPERIMENT

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ABSTRACT

FISGAS calculations were compared to fuel swelling data from the FD1 tests and to gas release data from the FGR39 test. Late swelling and gas release predictions are satisfactory if vacancy depletion effects are added to the code. However, early swelling predictions are not satisfactory, and early gas release predictions are very poor. Explanation of these discrepancies is speculative.

Introduction

A problem of considerable interest in the study of core disruptive accidents in oxide fueled fast reactors is the behavior of fission-gas in the fuel matrix under transient temperature conditions. In a transient-overpower accident (TOP), pressure from the release of gas from the fuel matrix is postulated to be a major cause of cladding failure. In a loss-of-flow accident (LOF), gas release has been invoked as a major fuel dispersal mechanism. Subsequent to fuel disruption, whose mode is still a matter of controversy, occluded fission gas in the fuel may produce rapid fuel dispersal. In the absence of dispersal, a prompt critical excursion can occur.

In order to accurately predict these phenomena, an accurate model of intra-granular and grain boundary fission-gas behavior is necessary.

The FISGAS code[1,2,3] was developed at Sandia Laboratories in support of the in-pile fuel disruption (FD) program.[3,4] The purpose of this paper is to explore the predictions of FISGAS to two sets of data, the FD1 fuel swelling data, and the FGR39 fission-gas release data[5], and to draw conclusions as to the validity of present modeling and possible improvements to that modeling.

Experimental Data Base

Two sets of independent experiments provide a unique data base for comparison to predictions by fission-gas models. These are the fuel swelling data from the FD1 series at Sandia Laboratories and the gas release data from the FGR39 test at Hanford Engineering Development Laboratory (HEDL).

EDB

The FD1 tests were designed to address the question of disruption and dispersal of irradiated fuel under LOF conditions. In these tests, single pellets of EBR-II irradiated fuel were triple-pulse heated to failure in the Annular Core Pulse Reactor (ACPR). Due to limitations in programmed high power operation in the ACPR, multiple pulse heating was used to simulate the ramp heating typical of an LOF accident. After the last pulse, the temperature peaked about 2/3 of the way out to the fuel surface. The temperature gradient was then in the correct direction in the gas-bearing unrestructured fuel region. The response of the fuel was recorded by high-speed cinematography.

Contrary to expectations, the initial fuel response was rapid and massive swelling, occurring on a time scale of 0.1 second after the third pulse. As has been reported previously, this rapid swelling is fully consistent with the known creep rate of high temperature urania.[3] The film record was reduced to a series of plots of the fuel swelling as a function of time. In this paper, the swelling data of test FD 1.7 is compared to FISGAS predictions.

The fission-gas release data from the FGR39 test at HEDL provides unique information on the rate of release of fission gas. Short sections of irradiated fuel were heated externally in a tungsten capsule. The inverted temperature profile in this test may have affected the mode of fuel disruption (primarily swelling) but the effect on intragranular gas release is probably not large. In the FGR39 test, the fuel was first baked out at 1200°C for 6 minutes, then heated to melt at about 150°C/s. The gas release rate was determined by dynamic pressure measurements combined with on-line mass-spectrometry to exclude release of containment gases. The FGR39 gas release data provides a singular data base for comparison to model predictions. This data, in combination with the FDl swelling data, provides a unique opportunity to judge the validity of fission-gas models.

The FISGAS Code

FISGAS is based on the same physical assumptions with respect to intragranular fission gas bubble migration as the FRAS code.[6] Bubbles are subject to both random migration and biased migration in a temperature gradient, with the mobility being due to surface diffusion of lattice atoms. An asymptotic model of bubble migration and coalescence is used to eliminate the disribution of bubble sizes. Completely independent calculations of migration and coalescence are performed for grain boundary gas and intragranular gas. Grain boundary gas bubble migration is driven by the projection of the temperature gradient onto the plane of the grain face on which the bubbles are trapped. The fact that bubbles on the grain faces are migrating in a plane changes the qualitative character of the interaction rate equations. Partly because of this, grain boundary bubbles grow much larger than intragranular bubbles. The growth of intragranular bubbles is limited by the supply of lattice vacancies, which make the results for intragranular gas approximately the same as FRAS2 code results. Grain boundary bubble growth, however, is not limited by the intragranular supply of vacancies, which is another reason that grain boundary bubbles become much larger than intragranular bubbles.

In FISGAS, gas release from the fuel involves a three step process. First, migration of intragranular gas bubbles leads to release of gas from the interior of the grain to the grain boundary. Those bubbles are then trapped on the grain face and forced to migrate along the plane of the grain face. Gas bubbles which migrate far enough to reach a grain edge (intersection of two grain faces) are then released to and trapped on the grain edge. In addition, when the fractional areal coverage of the grain face by gas bubbles exceeds 0.5, the excess gas immediately percolates to the grain edge due to the formation of a network of interconnected porosity. In FISGAS, most of the gas transfer to the grain edge occurs by percolation rather than bubble migration. Release of gas from the fuel to the ambient is controlled by percolation of interconnected porosity on the grain edges. The onset of such release is determined by the volume fraction of grain edge porosity as specified by percolation theory.

Swelling of the fuel is determined from a one-node calculation of fuel creep, based on the equations for creep of an internally pressurized thin cylinder. The driving force for the creep is the excess internal pressure in the fission gas bubbles. The creep rate of the fuel provides a mechanical restriction on the rate of bubble growth and fuel swelling.

FISGAS has a multiple node structure in the radial direction. Independent calculations of gas behavior are performed for each node. The separate nodes interact only through the creep field of the fuel. For the calculations reported here, either 3 or 4 nodes were used in the gas-bearing unrestructured region of the fuel.

FISGAS is designed as a research tool with the flexibility to include or exclude various options. Models 1 to 4 exclude grain boundary gas, and models 5 to 8 include it. Models 2, 4, 6 and 8 include delayed intragranular bubble equilibration due to lattice vacancy supply, while models 1, 3, 5 and 7 assume instantaneous equilibration. Models 3, 4, 7 and 8 include the effect of macroscopic fuel creep on restricting the size of all bubbles. This code flexibility makes it possible to explore the sensitivity of the results to model changes. Note that model 1 (M1) corresponds to FRAS-type modeling, while model 2 (M2) corresponds to FRAS2-type modeling. These model options are summarized in Table I.

Comparison of FISGAS Predictions to Experiment

Figures 1, 2 and 3 compare FISGAS predictions of gas release to the FGR39 data. Figures 4, 5 and 6 compare FISGAS predictions of fuel swelling to the FD1.7 data. Note that the swelling data prior to 1.7 seconds into the FD1.7 test is based on cladding data and represents an upper bound to the possible fuel swelling.

The gas release predictions for M1 and M2 (FRAS and FRAS2-type models) are in poor agreement with the FGR39 data. Notice that there is almost no release predicted below 2000°C, while the test data yields 20% release there. M2 is superior to M1 because the restriction on bubble equilibration yields smaller, more mobile bubbles. At the point of fuel melting, essentially all of the gas was released in the test, while M2 predicted only

1/3 release. This is a very poor agreement. The complete FISGAS calculation, M8, is even worse. It predicts no gas release at all below 2600°C. This is due to the additional gas holdup on the grain boundaries, which does not occur for models M1 and M2. At the time of fuel melting, M8 essentially agrees with M2.

In Fig. 2, modifications to the models which neglect grain boundary gas are explored. It is remarkable that M3, a model with creep restraint but without bubble disequilibrium, agrees well with M2. Clearly, fuel creep can be just as important as bubble disequilibrium in modifying fission-gas behavior. M2T is an M2 model in which the rate of supply of vacancies to the intragranular bubbles has been reduced by a factor of 100. (The T stands for a change in bubble equilibration time constant.) The reason for such a parametric variation is to explore the effect of a shortage of vacancies in the lattice. Such a vacancy depletion effect has been modeled in the NEBRAS code[7] and has been shown to be important. It is clear that inclusion of this effect substantially improves the agreement with the data. Note that the very early release seen in the test is still inexplicable. This early release suggests the existence of a substantial fraction of initial grain boundary gas. The present modeling assumes zero grain boundary gas, which may be incorrect, as suggested by Zimmermann.[8]

FISGAS was modified to allow release of all grain edge gas while allowing retention of grain face gas. Such models are designated by a suffix F in Fig. 3. While there is some improvement in gas release, the very early release is still missing. Clearly, the lack of low temperature gas release is due to holdup on the grain face. Reduction in the bubble equilibration rate leads to substantial improvement in high temperature release.

These observations may now be compared with the FD1.7 swelling data. In Fig. 4 it is seen that fuel swelling is more sensitive to bubble size restriction than is gas release. The M1 (FRAS-type) calculation is a gross overprediction of fuel swelling. The M2 (FRAS2-type) calculation tends to overpredict early swelling. It shows almost no reaction to the third pulse at 1.7 seconds, in sharp contrast to the data. This disagreement also occurs for tests FD1.4 and FD 1.8. Note that fuel creep alone (M3) has a substantial effect in restricting swelling. Calculations were performed with a reduction in bubble equilibration rate, that is, model M2T. This model led to so little swelling that it is indiscernible from the abcissa of Fig. 4. The FRAS-type modeling does not appear to be able to simultaneously predict both gas release and swelling. When M2 gas release rates are improved by including vacancy depletion (M2T), the initially poor agreement with swelling data becomes total disagreement.

Figure 5 demonstrates that models with grain boundary gas lead to excessive early swelling. A model without creep restriction to swelling, M6, is in serious disagreement with the data. Notice that the exclusion of grain face gas, M8F, does not improve the early excessive swelling of M8, and in addition, fails to predict the jump in swelling after the third pulse seen in the data. That jump in swelling, which may be seen in M8, is dramatically amplified in M8A. This latter model allows some creep relief as fuel zones exceed the solidus. It thus may be that part of the observed swelling is due to a rapid increase in creep rate for fuel above the solidus.

The effect of vacancy depletion is demonstrated in Fig. 6. The model with grain edge gas excluded is not substantially improved by vacancy depletion (M8FT). It still overpredicts early swelling and fails to show any substantial swelling increase at the third power pulse. Thus, the model with grain boundary gas which is best at predicting gas release data does poorly in predicting fuel swelling. Swelling predictions of the full FISGAS model, are almost unchanged when vacancy depletion (M8T) is included. M8T is quite good for late swelling as well as late gas release predictions.

Discussion

None of the modeling discussed here yields satisfactory agreement with both fuel swelling and gas release data. Modeling which excludes grain boundary gas is in disagreement with FD1 fuel swelling data. The models which yield best agreement with late fuel swelling are M8 and M8T. However, these models are not satisfactory for early swelling. Only models with vacancy depletion (M2T, M8T and M8FT) are in good agreement with late gas release, but none of these models agrees well with early gas release. If M2T and M8FT are excluded due to poor swelling predictions, only model M8T is left. The following question then arises, "How can the early gas release in FGR39 be reconciled with the small early swelling of FD1.7?"

The FISGAS calculations of intragranular gas behavior at low temperature is almost certainly incorrect. The diffusion coefficient of very small bubbles is drasticallly reduced due to faceting.[9] Attempts have been made to explore this effect with the GRASS code.[10] This may explain the excessive early swelling predictions by FISGAS. It is possible then that the early gas release is due to preexisting grain boundary gas. This speculation is supported by the sudden gas release in FGR39 at the point of clad melting.

The sudden swelling as the time of the third pulse for FD1.7, as well as FD 1.4 and 1.8, are very nicely duplicated by models which include the effect of fuel creep. Models without creep fail to adequately duplicate this effect.

On a broader basis, some of the basic assumptions of present day fission-gas modeling may be incorrect. Based on bubble morphology data in the FGR test series, the fundamental physical assumption that inragranular bubbles are driven by a temperature gradient is in doubt.[6]

Conclusions

None of the fission-gas behavior models discussed here yield satisfactory agreement with both fuel swelling and gas release data. The best agreement is obtained by including both grain face and grain edge gas, fuel creep, bubble disequilibrium and vacancy depletion of the lattice. There is very poor agreement with early gas release data and poor agreement with early swelling data, but reasonable agreement with late swelling and gas release data. The poor agreement at low temperatures, as well as the disturbing failure *of the FGR bubble morphology work to confirm the biased migration* mechanism, suggests that the modeling work in this area is far from the level of validity necessary for reactor licensing purposes.

Acknowledgments

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Table I. Effects Included in FISGAS Models

Model	Grain Boundary Gas	Bubble Disequilibrium	Fuel Creep
M1			
M2		X	
M3			X
M4		X	X
M5	X		
M6	X	X	
M7	X		X
M8	X	X	X

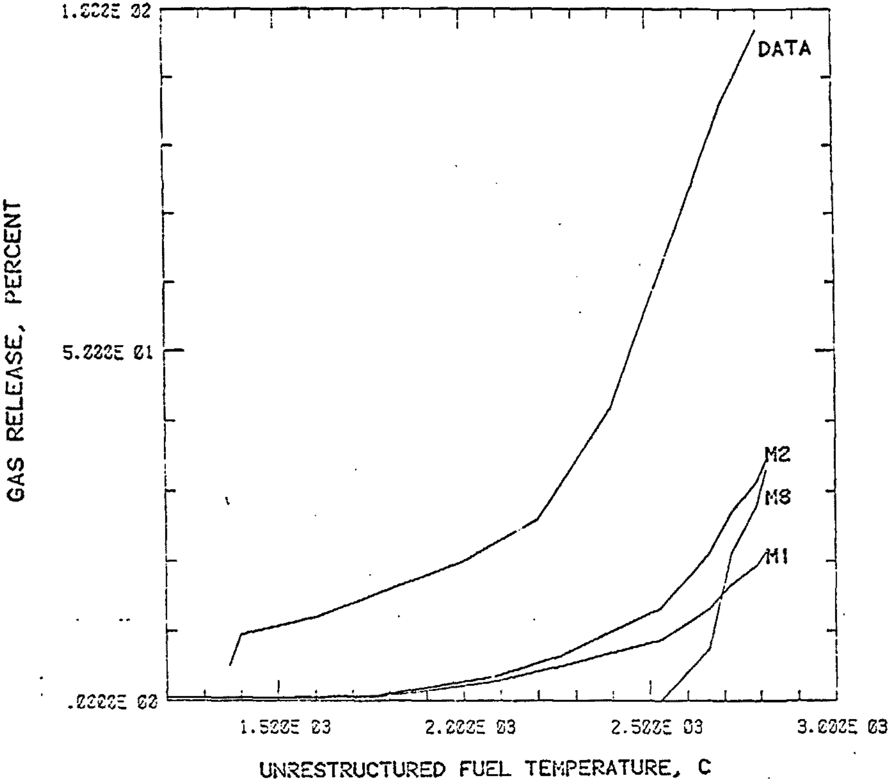

FIG 1 COMPARISON OF FISGAS TO FGR39 DATA

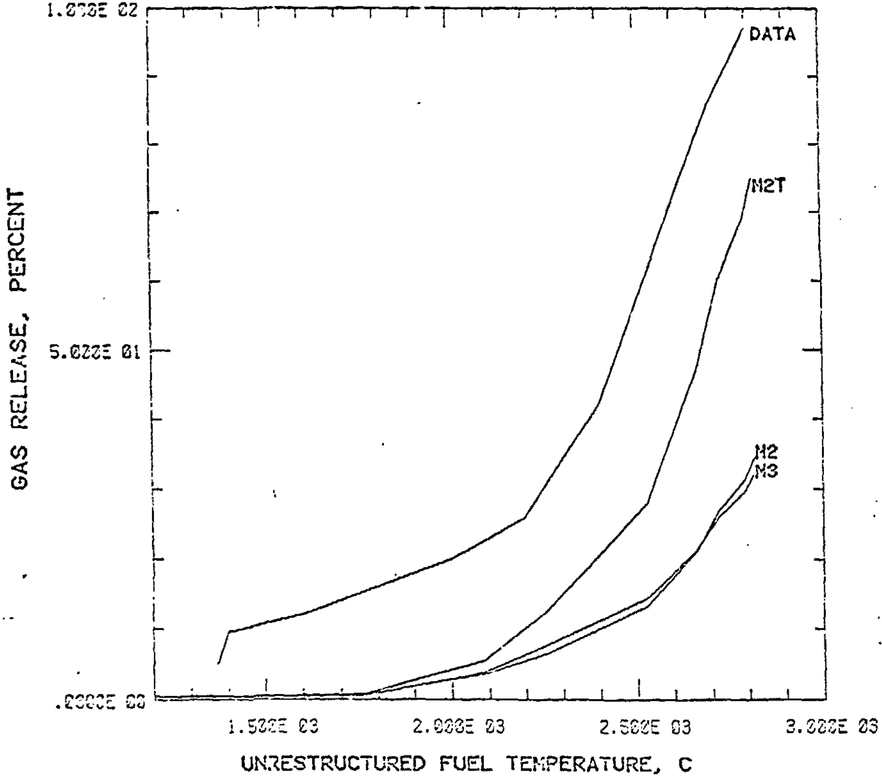

FIG 2 COMPARISON OF FISGAS TO FGR39 DATA

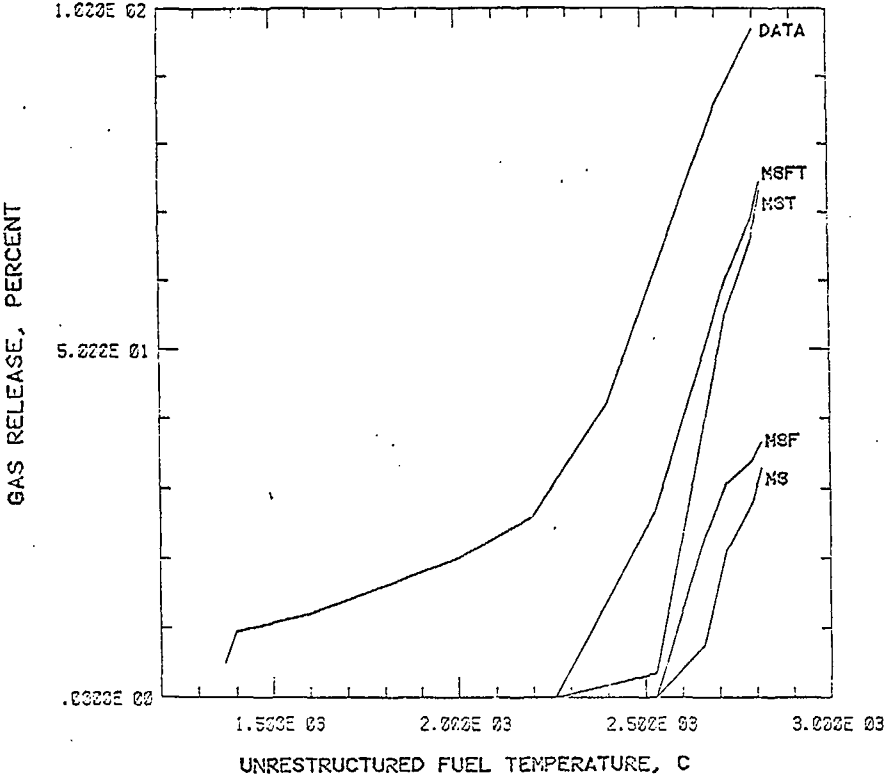

FIG 3 COMPARISON OF FISGAS TO FGR39 DATA

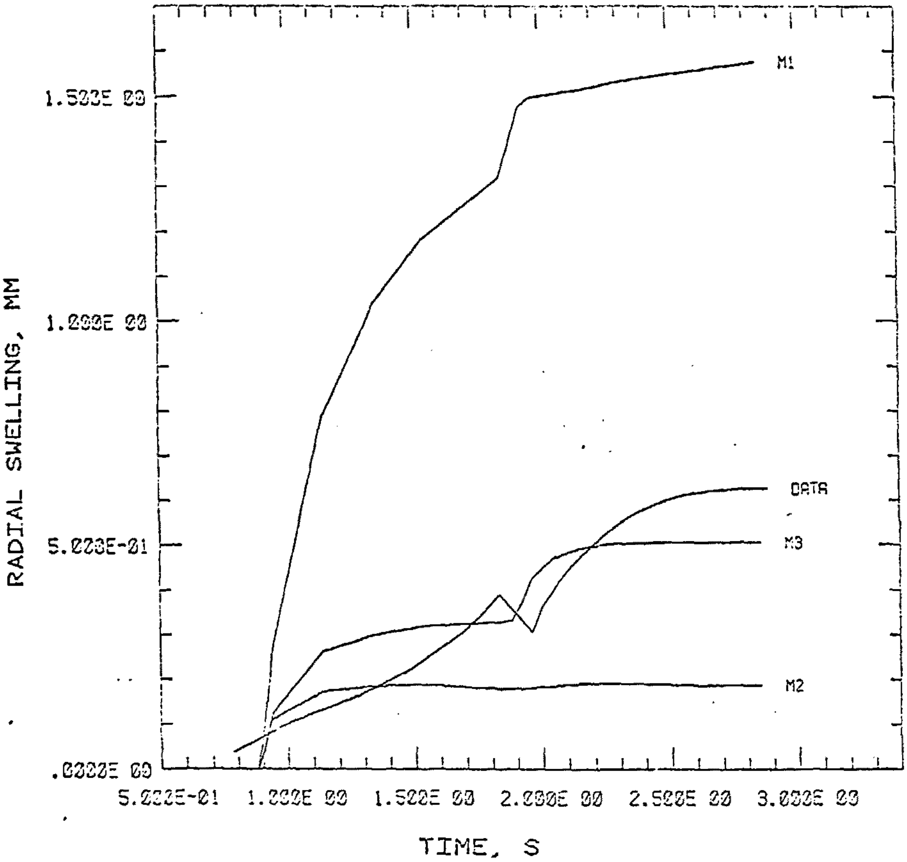

FIG 4 COMPARISON OF FISGAS TO FD1.7

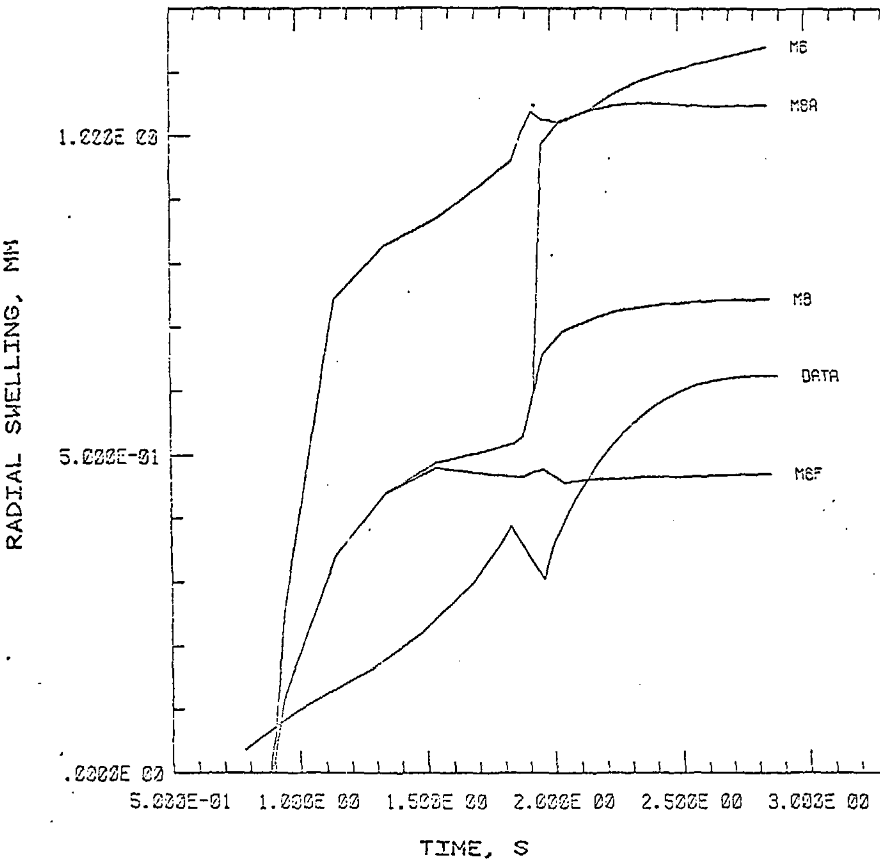

FIG 5 COMPARISON OF FISGAS TO FD1.7

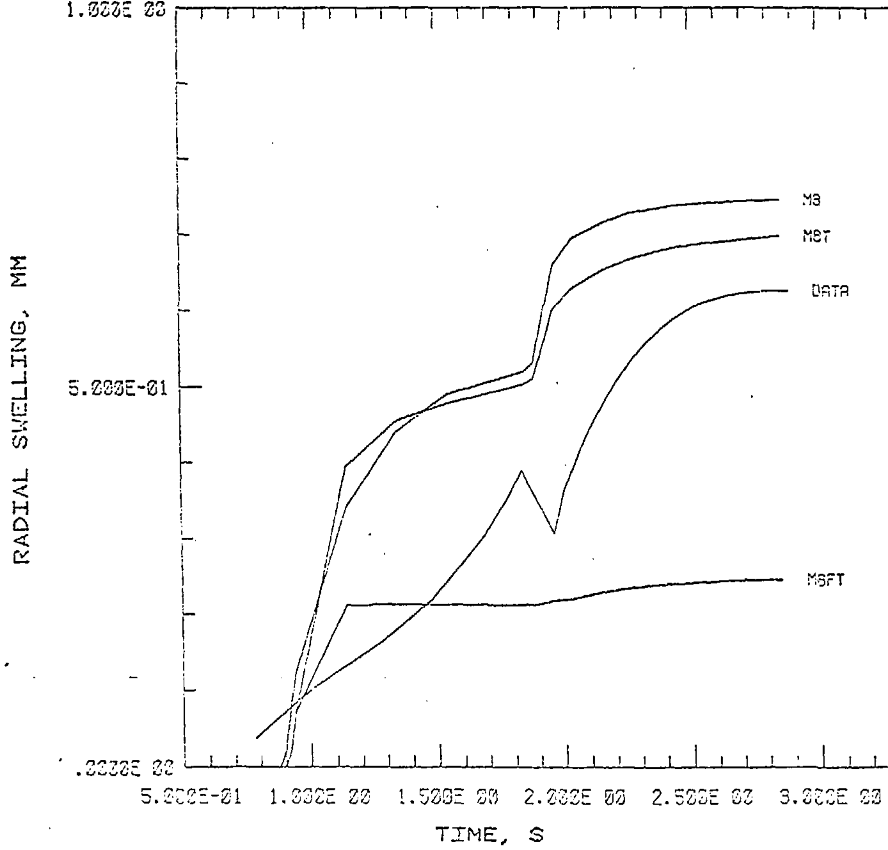

FIG 6 COMPARISON OF FISGAS TO FD1.7