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COMPARISON OF SAS3A AND MELT-III PREDICTIONS FOR A TRANSIENT OVERPOWER HYPOTHETICAL ACCIDENT

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ABSTRACT

A comparison is made of the predictions of the two major codes SAS3A and MELT-III for the hypothetical unprotected transient overpower accident in the FFTF. The predictions of temperatures, fuel restructuring, fuel melting, reactivity feedbacks, and core power are compared.

INTRODUCTION

The SAS3A code[1](SAS) has been developed at the Argonne National Laboratory (ANL) over the past several years. This code has been used extensively in the analysis of the hypothetical loss-of-flow (LOF) accident for the Fast Flux Test Facility (FFTF),[2] and in the analysis of both the transient overpower (TOP) and the loss-of-flow accidents for the Clinch River Breeder Reactor (CRBR).[3] The MELT-III code[4](MELT) has been used for analysis of the TOP accident for the FFTF[5] and for some preliminary calculations on the near-commercial breeder TOP accident.[6]

The SAS code was designed and has been used, for the most part, for the analysis of the loss-of-flow accident (but has the capability to treat a TOP accident), whereas the MELT code has been used almost exclusively for the analysis of the transient overpower accident. As the use of these two codes became more and more extensive, there has been increasing interest that a definitive comparison be made between them. It is the purpose of this paper to identify any major discrepancies between the predictions of the two codes, to attempt to explain the discrepancies, to note any deficiencies in the two codes, and to recommend changes to remove these deficiencies.

The specific problem that has been chosen for this comparative study is the base two-channel case selected for analysis[5] for the Beginning-Of-Cycle-4(BOC-4) transient overpower accident in the FFTF in which a 50¢/sec reactivity ramp was introduced. A two-channel case was also chosen to minimize the amount of computer time that would be needed, as many runs were anticipated during the course of the study. Furthermore, a two-channel case should be sufficient to show any areas of gross discrepancy between the predictions of the two codes.

PREPARATION OF INPUT DATA

The input data used in this study for the MELT runs was the same as that used previously[5]. The corresponding SAS deck was developed for the most part

using data from the MELT input deck but for those SAS input variables for which no corresponding input existed for the MELT code, the input data were obtained from a SAS deck which was obtained from the Argonne National Laboratory.

As will be noted later, there were some differences found in some of the basic physical data used as input for analysis of the FFTF between the values normally used in a MELT analysis and those normally used in a SAS analysis of the FFTF. A second SAS input deck was thus prepared for additional comparison purposes by using "differing" values from the original SAS deck. For purposes of description within this paper, the results obtained from using these three sets of data are identified as MELT, SAS (MODIFIED), AND SAS (ORIGINAL) respectively.

The MELT code uses a constant fuel density of 10.84 g/cc for sintered (columnar) and 10.0 for unsintered (equiaxed-unrestructured) oxide fuel. SAS allows for a temperature-dependent density throughout the steady state and the transient calculations which is obtained by means of either a tabular input of density with temperature or by an analytic formulation. Although MELT uses a constant density for the fuel in the calculation of the energy balances during the steady state and transient portions of the run, a density variation is used to calculate the outer radii of the fuel for determination of the gap width and, hence, the gap conductance in both the transient and steady-state calculations. This density variation is included in the SIEX subroutine[7] of the "steady state" part of MELT and a corresponding relationship is used in the TRHGAP subroutine of the transient part of MELT program when the transient gap conductance is calculated. When comparing the SAS density variation with the SIEX or TRHGAP formulations for density, the calculated density as a function of temperature varies by no more than 0.6% between the two codes.

The MELT program uses thermal conductivity as expressed in an input table as a function of temperature. However, also built into the MELT code in the SIEX subroutine is an analytic formulation for thermal conductivity of oxide fuel. As it turns out, with the usual MELT input, the two relations are identical. However, these values for the unrestructured and equiaxed fuel and columnar fuel differ somewhat from the values used in SAS analyses. A comparison of the two expressions for thermal conductivity is shown in Figure 1. As can be seen from the figure, the SAS thermal conductivities for the solid fuel are in general smaller than those used in the MELT-SIEX system.

For the thermal conductivity of liquid fuel, there is a great disparity in the values used for the SAS and MELT code. SAS uses a value for the thermal conductivity above the melting point which equals the value at the melting point for whichever fuel happened to be existent in that node before melting. MELT, on the other hand, uses a constant value of 0.05j/sec-cm-°C for both types of the fuel regardless of its original microstructure. The particular value selected can make a substantial difference in the calculated temperatures during the transient portions of the run. For this comparison study, a value of 0.05 j/sec-cm°C was used in the MELT runs and the values of the thermal conductivity at the melting point for the columnar and unrestructured-equiaxed fuel were used in the case of SAS.

SAS accepts a tabular input for the fuel heat capacity data. MELT uses an analytic relation, where the coefficients are obtained from reference 8. A large difference between the two relationships can be seen in Figure 2. Both the SAS (ORIGINAL) deck and the MELT input deck use a value of 0.502 j/g-°C for the heat capacity of fuel above the melting point. The effects of these differences in the heat capacity will only be seen during the transient portion of the run and probably only to a significant extent when the fuel temperatures are above 2000°C.

SAS uses a constant value for the heat capacity of the structure and cladding over the course of the transient. An average temperature must be presumed and the heat capacity and thermal conductivity for that temperature calculated. MELT uses both a variation of thermal conductivity and heat capacity with temperature for the cladding. For this comparison study, an average cladding temperature of 1000°C was used to compute the constant values for the thermal conductivity and heat capacity from the MELT relations for input to SAS. SAS also uses a constant thermal expansion coefficient for the cladding, whereas MELT and SIEX use one which varies linearly with temperature. The MELT coefficient at 800°C was used in SAS.

Constant values of restructuring temperatures for the equiaxed fuel and columnar fuel were selected for this study. Values of 1450°C and 1720°C were used, respectively. However, more recent correlations, as seen in the document on the SIEX code,[7] show that the columnar temperature probably should be a function of power level as well. Neither SAS nor MELT allow for this possibility and presumably if the correlation is correct, this formulation should be incorporated.

The MELT axial nodes are divided into eight zones which are respectively: the orifice zone, the lower reflector, the core itself, the upper reflector, the plenum, the handling socket (free-flow area), the instrument tree, and the sodium pool. Each of these zones has a different coolant flow area which is used in the flow calculations, pressure drop calculations, and in the determination of the boundaries of the FCI zone during the postfailure period. The eight zones are divided up into 43 axial nodes of which 18 are in the core region. The SAS setup allows for two flow-area zones. However, in this comparison case only one zone is used which makes the SAS simulation essentially that of a single pin in cylindric geometry. Use of a single zone is normally the case in most SAS analyses.

SAS allows for a maximum of 30 axial nodes throughout these two possible zones. However, practically speaking, only 28 are possible. This is required due to identification of the first node with the inlet orifice plane and the necessity of having the first node in the upper blanket and the last node in the plenum be separated by a very small distance such as 0.001 centimeters. The larger number of nodes as are available in the MELT code may not have been required in the SAS LOF runs where fuel plateout was not a consideration. However, when large FCI zones exist with the associated fuel plateout and distributed fuel worth, the breaking up of the nodes into smaller lengths seems necessary.

It should be noted that the position in the axial node of the effective values of temperatures of the coolant differ between the SAS and MELT codes. SAS identifies pressures and temperatures with the coolant at the center of the node whereas MELT effectively has the coolant nodal temperature at the top of the coolant node, and coolant pressure at the bottom of the node.

The SAS input deck hydraulic diameters were adjusted to give approximately the same pressure drops over the zones as MELT, since MELT specifies the hydraulic characteristics of the channel by means of areas in the various zones and pressure drops across these zones. SAS uses a constant area, if only one zone is used, and specifies hydraulic diameters for the core region, the upper and lower reflectors, and the plenum. It has been the experience of the MELT users that when analyses of systems other than the FTR are performed, the hydraulic input by means of pressure drops is difficult to use. In the calculation of pressures at area changes between zones, MELT uses are the same identical formula for contractions as is used for the expansions, which is incorrect by a factor of two.

In both SAS and MELT, the steady-state and transient fission power is distributed among the fuel, the cladding, the coolant, and structure. However, SAS has the additional feature of distributing part of the power to other than the core (presumably to the radial reflector). The fraction is given by the input parameter FRPR which is the fraction of fission power actually generated in the core. Therefore, in MELT, 384 MW core power was used for the comparison. The MELT values normally used for the fraction of the power in the fuel cladding and coolant were chosen for the comparison as opposed to those which are normally used in SAS.

A neutronics processing code developed at HEDL is used wherein the number of channels desired, the subassemblies which are to be lumped to make up these channels, and the axial node dimensions are inputted. The fuel worth, power profile, coolant worth, Doppler feedback weightings and stainless steel worths are then computed by this code from input data tapes prepared by running the 3DB-3DP[9] series computed for each channel and this code punches into cards a table for each of these quantities for both the MELT and SAS inputs.

SAS assumes zero fuel worth and zero coolant void worth outside the core region. This ignores a positive contribution and is nonconservative in the case of the fuel. This ignores a negative contribution and is presumably conservative in the case of the coolant void worth. Thus in the case of the analysis of the transient overpower accident, when fuel plates out above the core, it still would have a positive reactivity contribution to the overall reactivity of the reactor in the MELT calculation, whereas SAS assumes that fuel plating out in these regions would have a zero reactivity contribution. Conversely, when coolant voiding occurs above the core this contributes negative reactivity and would tend to decrease the overall reactor reactivity. It is probable that in the case of the coolant void worth, especially, that there would be some observable differences in the analysis of the FFTF LOF accident analysis if this were implemented.

The parameters used for input to the SAS code which describe the primary loop are taken directly from the ANL deck. The input numbers required in the MELT simulation of the primary loop are the ones that were used previously.[5] The values for XKE and XKC, the coolant outlet expansion and inlet contraction coefficients, were set equal to zero in the SAS analysis, because the MELT code does not allow for these terms.

The SAS gap conductance model which was used for this comparison study, depends only on the gap width (ΔX) and the input parameters A, B, C, and H.

$$h = A + \frac{1}{B + \frac{C + \Delta X}{H}} \qquad (1)$$

In the MELT code, the gap conductance is computed by a rather complex relationship which has been documented in the description of the SIEX code.[7] This correlation depends not only on the gap width, but on the jump distances and the thermal conductivity of the gaseous mixture existent in the gap, which in turn is dependent upon temperature as well as the composition of the mixture. The SAS transient gap conduction correlation is the same as that for steady state (Equation 1). The MELT transient gap conductance relation uses the same formulation as SIEX during the transient part of the analysis but neglects the radiation contribution. MELT requires no input parameters at all in order to determine the gap conductance. The relationships are built into SIEX code and the transient gap model in the subroutine TRHGAP.

The gap width itself is dependent on the expansion of the fuel and the expansion of the cladding due to temperature changes, and the swelling of the fuel due to burnup. SAS has a simple swelling correlation in which the percent swelling is a constant input parameter SW times the atom percent burnup at the axial node for each type of fuel. MELT also uses swelling in determination of the gap width, but it uses the built-in correlation that is included in SIEX.[7] Thus there is a rather basic difference in the determination of the gap conductance between the MELT program and the SAS program. The gap conductance in the MELT code is completely determined from internal well-established correlations that have been included in the SIEX code. The correlations built into the SIEX code were determined from fuel melt and restructuring patterns obtained in a large number of experiments as is described in the SIEX document.[7] In fact, one could say that the fundamental function of the SIEX subroutine is to compute gap conductance from the experimental correlation, whereas in the case of the SAS program, the determination of the gap conductance and gap width is basically parametric, where one determines the gap conductance by input of the fuel expansion and cladding expansion parameters, the heat transfer parameters A, B, C, and H, and the swelling parameters (SW). The user of the SAS code must arrive at the appropriate values for these parameters by some means.

Because of the influence on the course of the calculation that the gap conductance has both during the steady-state and transient portions of the run, this basically parametric input with user specified parameters is seen by the author to be a deficiency in the SAS code, and the assumption has been made that the values as calculated by the MELT program for the gap conductance, gap width, etc., are the correct values. As a consequence in setting up the case for the comparison, the parameters available for the user in the SAS code were manipulated to obtain a gap width and a gap conductance approximating those obtained from the MELT program. This was accomplished to a reasonable extent by adjusting the values of the parameter H and the three swelling parameters SW(1), SW(2), and SW(3). The result of this manipulation of the parameters for Channel 1 is shown in Figures 3 and 4. Figure 3 shows the gap width as a function of axial distance and Figure 4 the gap conductance for the MELT results, the SAS results (in which the H parameter and swelling parameters have been adjusted) and the SAS (ORIGINAL) results. The Figure 4 values do not include any effects due to thermal radiation. It is seen from Figure 4 that the three cases predict approximately equal results at the core center (60 cm) but predict quite differently at the ends of the fuel.

STEADY-STATE RESULTS

A comparison of the SAS and MELT code predictions for steady-state axial temperature profiles of the coolant, the inner surface of the cladding, the fuel outer surface, and the fuel inner radius in Channel 1, are given in Figure 5 as a function of axial distance above the reference plane. The small difference noted in the coolant temperature profiles can be explained in the different method by which coolant heat capacity is handled in the SAS and MELT codes. The small discrepancy noted in the predictions of inner cladding temperature can be explained by the use of a constant thermal conductivity in the case of the SAS code and the variation of thermal conductivity with temperature as is used in MELT.

When the fuel surface curves are examined, it is seen that when the original SAS swelling, thermal conductivity and heat capacity data are used (SAS[ORIGINAL]) the large difference in the gap width becomes apparent in the calculated temperatures at the fuel surface, especially at the top and bottom of the core. The predicted fuel surface temperatures in these curves are quite a bit lower at the core boundary than MELT. However, when these adjustments are made and the same thermal conductivity and heat capacity are used as in the MELT code, fairly close agreement in the fuel surface temperatures can be obtained. (SAS[MODIFIED]).

The inspection of the fuel inner radius temperatures shows that when the fuel surface temperatures are approximately in agreement, and common values of thermal conductivity are used, the two codes predict approximately the same centerline profile. When differing values in thermal conductivity are used as shown by the curve noted (SAS[ORIGINAL]) the profile is substantially drooped at the end of the core and in particular it droops below the input value of the equiaxed restructuring temperature.

It was the author's opinion that it was absolutely necessary, in order to obtain a reasonably compatible basis between SAS and MELT for comparison during the course of the transient analysis, that the steady-state prediction had to be reasonably close together. It was very evident that the primary controlling variable in this analysis was the gap conductance and gap width. Therefore, much effort was expended in determining the necessary parametric values for input to the SAS code to make the SAS and MELT predicted fuel surface temperature profiles as close as was practicable.

The restructuring prediction of the MELT and SAS codes with common thermal conductivity and swelling data is presented in Figure 6. As can be seen from this figure, the restructuring predicted by the two codes is close.

The SAS pressure profiles were adjusted by making changes in the input hydraulic diameters such that the steady-state pressure drop over the various zones was nearly identical to that predicted by MELT.

PREFAILURE TRANSIENT CALCULATIONS

The reactivities predicted during the course of the 50¢/sec unprotected transient are plotted for the first four seconds in Figures 7 and 8. As can be seen, prior to failure the reactivity plots are essentially identical. However, there is a slight difference in the Doppler feedback of about 1 to 1.5¢ between the MELT and SAS predictions which cannot be seen on the scale used. This is due to the slightly different temperatures predicted for the fuel.

The power traces computed during the course of the transient for this comparison are given in Figure 9. Prior to failure there is noted a difference in the power profiles which builds up to almost 100 MW just before failure. This is presumably due to the integration of the slight reactivity difference resulting from the Doppler feedback when the kinetics equations are integrated. There is also a slight error introduced in the MELT calculation due to the use of the "zero life" approximation for reactivities less than 90¢ positive. However, when other computer runs have been made with MELT to compare the predictions of the "finite-life" model vs. "zero-life"[4] model, the results have shown an insignificant difference in the power predicted. The zero life approximation is usually used since the length of time required to do the calculation by the more accurate method (finite-life) is larger due to the smaller time steps required.

The axial temperature profiles for the coolant inner cladding, fuel surface, and fuel inner radius at a time just before failure (2.68 seconds where failure is at 2.6955 sec) are presented in Figure 10. The coolant profiles predicted by SAS and MELT differ at the upper end by approximately 35°C and approximately the same 30° exists in the prediction of the inner cladding temperatures. However, the flat-topped profiles predicted by the SAS code differ from the straight-line segments observed in the MELT predictions in the region of fuel melting. This is due to the different way that SAS and MELT handle the molten region. SAS uses a single melting temperature, in this case (2767°C) whereas MELT uses a range of temperatures between the solidus (2760°C) and liquidus (2816°C). When these differences are allowed for, it is seen that the inner radius temperatures are essentially identical as predicted by the two codes.

Inspection of the fuel surface temperatures shows a uniform variation over the lower part of the core with a surprising bump at the top at approximately 95 centimeters above the reference plane. Some additional output was obtained wherein it was determined that the fuel/cladding gap was closed up to the 95 centimeter point and above this point, in both SAS and MELT, there is predicted a finite gap width. The unmodified SAS data show a similar anomaly in the same vicinity, though not the significant increase in temperature seen in the other predictions.

The radial temperature profiles just before failure at the core midplane are presented in Figure 11. As can be seen, the MELT temperature profile is somewhat steeper at the outer radius. The difference between the (SAS[MODIFIED]) and MELT codes predictions is not significant. However, there is a substantial difference in the profiles, as predicted by the (SAS[ORIGINAL]).

Figure 12 presents the molten fuel profiles just before failure at time 2.68 sec. As can be seen, the boundaries between the solid and partially molten for the SAS/MELT predictions are reasonably close. The all-molten region boundaries are also reasonably close. However, the SAS run with unmodified thermal conductivity and heat capacity data (SAS[ORIGINAL]) shows a rather different molten profile, which could significantly influence the failure time and location, as well as the amount of fuel available for squirting into the coolant channel.

FAILURE PREDICTION

No attempt was made during this study to use any internal mechanism available in the SAS code to predict failure. The failure time and location as was predicted by the MELT code for this base two-channel case was used for both codes. The time and location of failure was simply input as variables to the SAS code. It is the author's understanding that it is possible to use the "Damage Parameter" failure criterion[10] with the SAS code by taking some additional printout available under control of a parametric switch and hand-integrating the data to obtain the enthalpy upset. This procedure is carried on automatically in the MELT code. Since the temperature profiles were essentially identical for the predictions by the two codes just before failure, it seemed reasonable that the MELT failure prediction could be used without substantial error. It should be noted that if this failure criterion were employed for the (SAS[ORIGINAL]) case, failure time would be considerably delayed due to the lower molten fractions and reduced temperatures in the upper part of the pin.

POSTFAILURE PREDICTIONS

Figure 9 shows in addition to the prefailure power trace, the power trace after failure. As can be seen, the MELT prediction of the power level drops below the SAS prediction. At about 3.5 sec. the two power traces become approximately equal.

Figure 7 shows the net reactivity and Doppler feedback reactivities for the postfailure part of the transient. The trace for the MELT prediction shows the effect of the fuel squirting over the time period from failure at 2.6955 sec up to the time that the bubble is swept out of the channel at approximately 2.9 sec. After 2.9 sec in the MELT run there is no further activity until much later after the power is again built up to the point where fuel squirting again commences. As is described in the MELT-III document,[4] MELT allows squirting to continue into the FCI zone as long as the FCI zone pressure is below that of the fuel pin.

The SAS predictions for the feedback due to fuel motion shows a succession of steps: one between approximately 2.8 and 3.1 sec, one at about 3.5 sec, and one between 3.8 sec to the limit of the study of 4.0 sec. Upon inspection of the SAScomputer printout, it is seen that during the flat portions of the fuel reactivity profiles that fuel squirting has indeed ceased for the SAS run. However, the interface is maintained at the lower location equivalent to the bottom of the fuel pin rupture. This successive squirting continues to pull the net reactivity on down in the case of the SAS program and eventually pulls it below the net as predicted by the MELT program at about 3.45 sec.

The difference predicted for Doppler feedback is believed to be mainly derived from differences in the SAS vs MELT temperature predictions, but a difference in the computational scheme which addresses the interrelation of sodium void and Doppler feedback between the two codes could be contributing to this difference.

A very distinct difference between the prediction of the two codes is seen upon inspection of the sodium void reactivity feedback. After the bubble appears in the channel for the MELT code, the sodium void feedback decreases to a value from 0 to about -20¢ whereas the SAS reactivity feedback remains constant at a value of approximately -5¢. This marked difference in the sodium void feedback is due to the differences in the sodium void worth axial profiles between SAS and MELT. SAS allows for no sodium void worths above the upper reflector region. (In other words, above the 20 nodes that can be assigned to the lower reflector, core, and upper reflector regions). MELT, however, handles the sodium void worth and the fuel worth in a tabular manner over the entire axial distance from the bottom of the orifice region up through the sodium liquid pool. In the region above the upper reflector, inspection of the sodium void worth curves as predicted by the 3DB code are seen to be substantially finite and negative. Therefore, neglect of this sodium void worth contribution can substantially affect the net reactivity.

Because of the considerable differences noted between the two code predictions for fuel motion feedback, two options available in the MELT program were exercised. Whereas the base case employed a uniform fuel pin cavity pressure model, the curve denoted MELT (CAVITY CONSTRICTED) was derived wherein the molten fuel flow is constrained by the size of the internal fuel pin cavity. The MELT (HOTPIM) curve resulted from employing the HOTPIM[11] two-phase hydrodynamics model of the fuel pin cavity. The latter model is expected to provide the more realistic description and is noted to predict the least amount of fuel squirting, although none of the squirting models have been appropriately verified by experiment. Less fuel squirting would result in a smaller shutdown margin, but such a situation would also minimize the potential for plugging in the coolant channel.

CONCLUSIONS

As expected, each code contains particular strengths and weaknesses with regard to TOP capability. The MELT system is judged to be somewhat easier to use, since the user is totally relieved of obtaining important data for the critical area of fuel/cladding gap conditions. However, this advantage is partially offset by the superior primary loop model in SAS, which likewise relieves the user of certain input data required by the MELT system. Considerable differences were noted in the post-failure predictions of the two codes, due to modeling differences in both the fuel ejection schemes and the thermal/hydraulics representation of the FCI zone. Substantial work is needed in both codes to resolve the discrepencies in this area.

It is comforting to note that these two large computational systems, developed independently to model a very complex set of interactive mechanisms, do predict essentially the same behavior pattern. Such results provide reassurance to the LMFBR safety community that no major phenomena have been overlooked.

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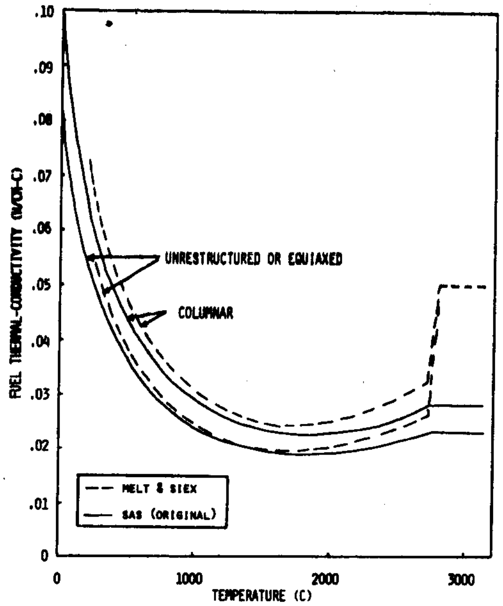

FIGURE 1 - THERMAL CONDUCTIVITY OF OXIDE FUEL

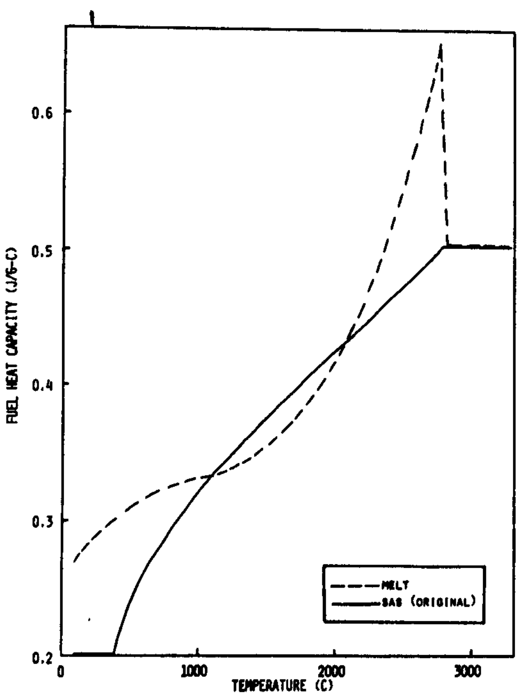

FIGURE 2 - HEAT CAPACITY OF OXIDE FUEL

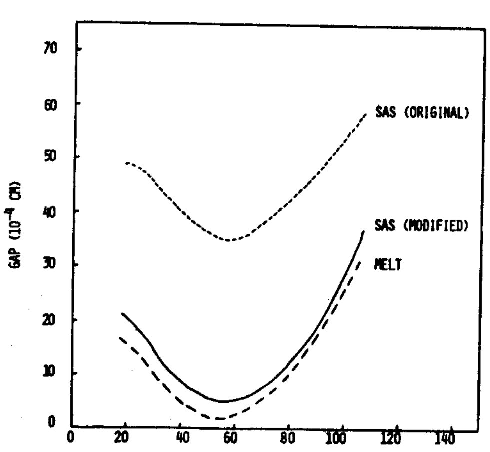

FIGURE 3: FUEL/CLADDING GAP WIDTH AT STEADY STATE

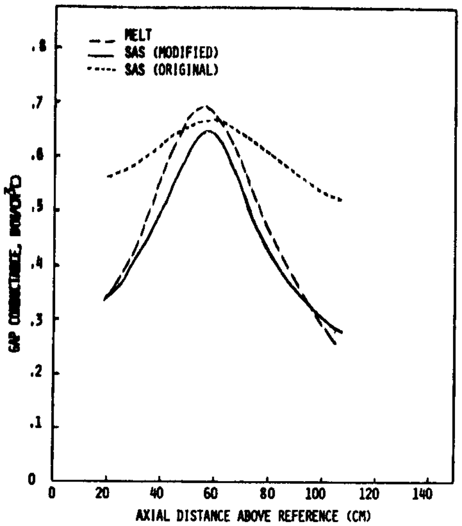

FIGURE 4: FUEL/CLADDING GAP CONDUCTANCE AT STEADY STATE

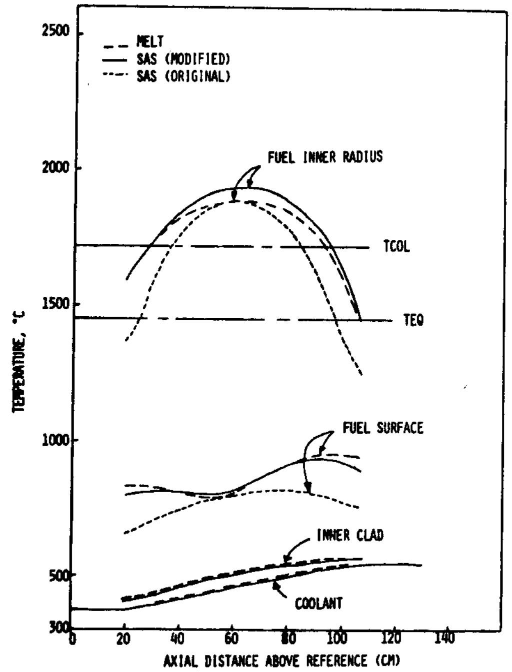

FIGURE 5: STEADY-STATE AXIAL TEMPERATURE PROFILES

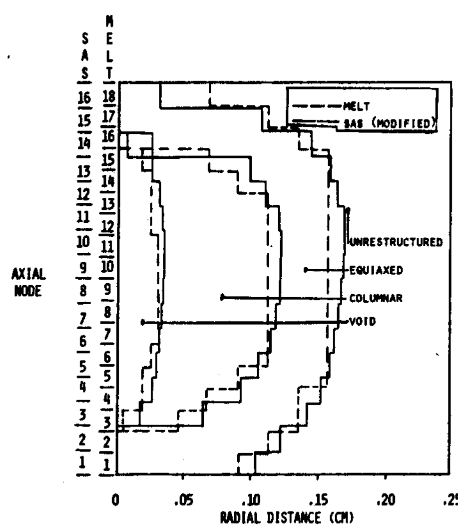

FIGURE 6: FUEL RESTRUCTURING PATTERNS

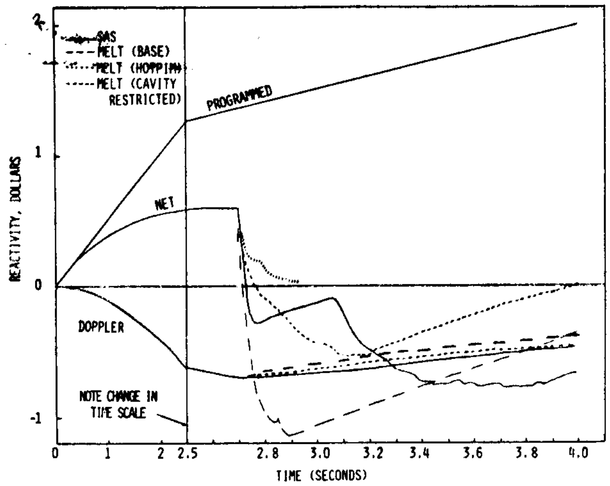

FIGURE 7 : NET AND DOPPLER FEEDBACKS FOR INTERCOMPARISON CASE

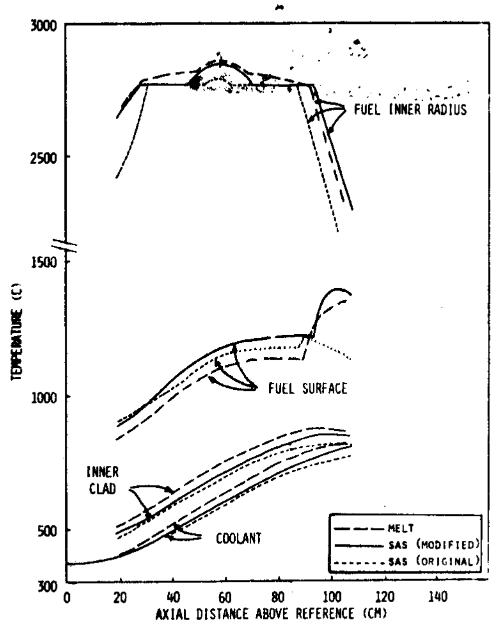

FIGURE 10 : AXIAL TEMPERATURE PROFILES (2.68 SEC)

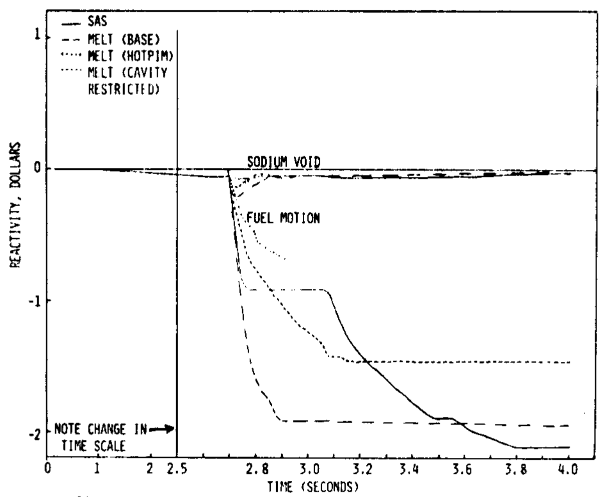

FIGURE 8 : SODIUM VOID AND FUEL MOTION FEEDBACKS FOR INTERCOMPARISON CASE

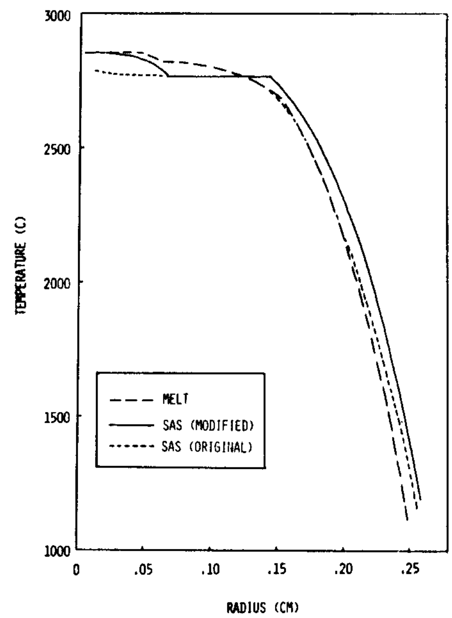

FIGURE 11: RADIAL TEMPERATURE PROFILES AT CORE MIDPLANE (2.68 SEC)

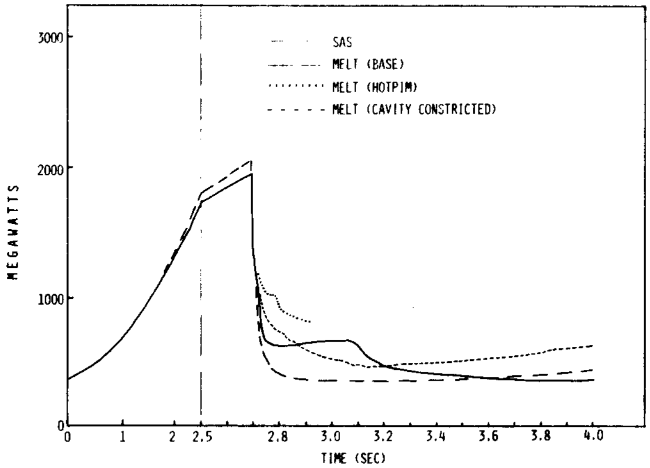

FIGURE 9: CORE POWER TRACES

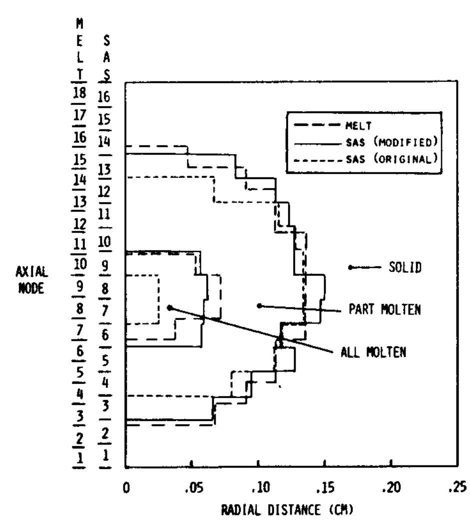

FIGURE 12: MELTING PATTERNS (2.68 SEC)