APPROACHES TO SIMULATE CHANNEL AND FUEL BEHAVIOUR USING CATHENA AND ELOCA

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ABSTRACT

This paper documents a new approach where the detailed fuel and channel thermalhydraulic calculations are performed by an integrated code. The thermalhydraulic code CATHENA[1] is coupled with the fuel code ELOCA[2]. The scenario used in the simulations is a 100% pump suction break, because its power pulse is large and leads to high sheath temperatures. The results shows that coupling the two codes at each time step can have an important effect on parameters such as the sheath, fuel and pressure tube temperature. In summary, this demonstrates that this original approach can model more adequately the channel and fuel behaviour under postulated large LOCAs.

1. INTRODUCTION

In safety analysis, the simulation of fuel and channel detailed behaviour under a postulated large loss of coolant accident are performed traditionally by different codes. A circuit thermalhydraulic calculation is first performed by simulating the primary and secondary circuits behaviour following the accident, where each pass is modelled by one average channel. Then, the detailed thermalhydraulic behaviour of a high powered channel is calculated by taking as boundary conditions the pressure, temperature and void fraction of the coolant in a pair of inlet and outlet headers as predicted by the circuit calculation. The third step is to perform the detailed fuel calculations using the thermalhydraulic results of the single channel simulation as boundary conditions.

In reality, all these phenomena are closely related and influence each others. Going from the first step to the second step assumes that the behaviour of a particular channel as no significant influence on the headers conditions. This assumption is valid because each pass contains a large number of channels (95) and the behaviour of a single channel would not affect significantly the header conditions. On the other hand, the assumption made by going from the second to the third step is more questionable. When the detailed channel and fuel behaviour are simulated sequentially by two different codes, the assumption is made that the results of the fuel calculation would have no significant impact on the detailed channel calculation. During a severe large LOCA, the fuel and sheath reaches high temperatures. The detailed modelling of the heat transfer coefficient between the fuel and the sheath, which is done in fuel codes, can have a significant impact on the sheath temperatures and consequently on the pressure tube temperatures. This paper investigates the importance of coupling in a single code the detailed channel and fuel behaviour by comparing the results of a 100% pump suction break simulation by the thermalhydraulic code CATHENA alone to those of a coupled version of CATHENA and the fuel code ELOCA.

2. ACCIDENT SCENARIO

The scenario chosen to evaluate the different approaches to simulate channel and fuel behaviour is a 100% pump suction break because its power pulse is large and leads to high sheath temperatures. The power pulse used in the present work is shown in Figure 1 and was calculated by coupling a physics and a thermalhydraulics code. After 5 seconds, decay heat is used. Figure 1 shows the power pulse of the bundle which had the highest integrated energy over the pulse. This power pulse was applied to the whole channel in the single channel calculation.

The first step of the analysis was to perform a circuit calculation. The thermalhydraulic code SOPTH-G2[3] was used to produce the headers boundary conditions necessary for the single channel calculation. In a 100% pump suction break, the discharge is very large and the primary circuit void is quite high. This is the reason for the particularly high power pulse for the 100% pump suction break. The reactor is automatically shutdown early in the transient and the depressurization is fast. The channel flows decrease rapidly and the fuel and sheath reach high temperatures. The emergency core cooling system is automatically activated and because of the relatively large pressure drop across the headers, the channels are refilled shortly.

3. CHANNEL AND FUEL MODELLING

3.1 Single Channel Modelling with CATHENA

The nodalization of channel O17 with its associated feeders is shown in Figure 2. Each horizontal and vertical section of the feeders are modelled independently. The channel is modelled by 12 thermalhydraulic nodes, one per bundle. Figure 3 shows the detailed fuel modelling. The bundle is modelled by 19 different pins because of the right-left symmetry. Each pin is divided into two circumferential sectors. Radially, each pin is modelled by 6 nodes in the fuel, 3 nodes in the sheath and 1 node for zircaloy oxide resulting from the zircaloy-steam reaction at high temperature, as seen in Figure 4. Channel O17 was chosen because it is a high powered channel (7.3 MW) which contains a bundle of 935 kW.

Thermal radiation between the fuel elements and the pressure tube is modelled as well as between the pressure tube and the calandria tube. The pressure tube ballooning at high temperature is modelled with the assumption that it retains its circular shape. The fuel-to-sheath heat transfer coefficient is set at 10 $kW/m^2/°C$ if the sheath temperature is below 700 °C and 1 $kW/m^2/°C$ if the sheath temperature is higher than 750 °C. The emissivity of the sheath is set at 0.7, the inside of the pressure tube at 0.7 and the outside of the pressure tube as well as the inside of the calandria tube is set at 0.3. The zircaloy-steam reaction is modelled with the Urbanic-Heidric correlation. The heat generation is assumed to be radially uniform inside the fuel. The axial power profile is shown in Figure 5.

3.2 CATHENA-ELOCA Coupling

CATHENA has the possibility to model more than one circumferential sector per pin and ELOCA has not. This lead to two different ways the two codes were coupled. In the first way, there is only one circumferential sector per pin and CATHENA does all the thermalhydraulic calculations and the sheath temperature calculation; ELOCA performs all calculations inside the element. In the second way, there is more than one circumferential sector per element. CATHENA performs all calculations including the sheath and fuel temperatures except for the fuel-to-sheath heat transfer coefficient and the radial heat flux profile which are calculated by ELOCA. ELOCA is used as a subroutine in CATHENA and is called at each time step to calculate the fuel behaviour while CATHENA provides the thermalhydraulic conditions. The development and implementation of ELOCA as a subroutine in CATHENA have been performed by AECL Chalk River and will be the subject of a future paper.

3.3 CATHENA-ELOCA Using 1 Circumferential Sector per Element

The basic CATHENA model is identical to the one described in section 3.1, except that there is only one circumferential sector per fuel element. In this model, the interior of the fuel element is modelled by ELOCA. ELOCA needs the input from another fuel code, called ELESIM for its initial conditions. ELESIM needs the bundle powers and fuel burnups prior to the accident in order to determine the fuel temperatures at the start of the transient and the amount of fission gas present within the fuel elements. Table 1 shows the bundle powers and burnups used in this analysis. The power/burnup histories are estimated for the outer elements of each bundle in the reference channel. Since there are a large number of possible combinations of channel power, bundle power and fuel burnups, a bounding set of power/burnup histories was constructed using maximum fuel burnups for each bundle position. The MATPRO correlation for UO_2 thermal conductivity is used, except at low temperatures where it is held constant to simulate the effect of irradiation damage. Fuel-to-sheath heat transfer and flux depression inside the element are calculated. All correlations used in ELESIM and ELOCA are consistent with those used in CATHENA, such as the Urbanic-Heidric correlation for the zircaloy-steam reaction.

3.4 CATHENA-ELOCA Using 2 Circumferential Sectors per Element

In the simulations were CATHENA-ELOCA was used with 2 circumferential sectors per element, ELOCA calculated the fuel-to-sheath heat transfer coefficient and the flux depression inside the element. All the other parameters were calculated by CATHENA. The assumptions described for CATHENA in Section 3.1 above and those described for ELOCA and ELESIM in Section 3.3 remains identical.

4. METHODOLOGY

When CATHENA was used alone, two steps were necessary for the simulation. For the given boundary conditions (channel power, header pressure, etc...), the CATHENA simulation was performed until the converged solution for themalhydraulic parameters is obtained. Then the transient was started using as initial conditions, the results of the steady state. The use of CATHENA-ELOCA needs one more step: the ELESIM code is run first to produce the initial conditions necessary for ELOCA. Then a steady state is established with CATHENA-ELOCA followed by the transient.

5. RESULTS

5.1 Fuel and Sheath Temperature and Heat Transfer Coefficient Results

Figures 6 to 9 shows respectively the fuel centerline, the fuel average, the fuel surface and the outer sheath temperatures for a 100% pump suction break. All results will be presented for the top pin of the 6th bundle. This is the pin which reaches the highest sheath temperature. The initial temperature differs for the simulations with CATHENA alone compared to the simulations with CATHENA-ELOCA. This is due to large differences in fuel-to-sheath heat transfer coefficient as seen in Figure 10 and also to the calculation of flux depression in ELOCA. In CATHENA the heat transfer coefficient from the fuel to the sheath is set by the user. Usually in safety analysis, a value of 10 kW/m^2/°C is used. Here it varies from 10 to 1 depending on the sheath temperatures. In ELOCA the initial value depends on the burnup of the fuel element. Since the initial heat transfer coefficient is more than three times larger in the CATHENA-ELOCA simulations, the initial value of the average fuel temperature is almost 100 °C higher. In CATHENA the power radial distribution is uniform. ELOCA calculates the flux depression in the fuel. This is why the initial center fuel temperature in CATHENA-ELOCA is slightly under the value of CATHENA alone and why the initial surface fuel temperature in the coupled code is 200 °C higher than in CATHENA. The initial sheath temperatures are identical since the thermalhydraulic conditions used are identical.

The transient is dominated by the power pulse (Figure 1) which lasts about 5 seconds. After that, decay heat power is assumed. The rest of the transient illustrates the fuel channel cooling behaviour which depends upon the hot steam produced during the power pulse which tries to escape from the channel and the cold water from the emergency core cooling system which tries to refill the channel. During the first seconds of the transient the temperature of the fuel increase rapidly due to the power pulse. The fuel expands radially initially increasing the fuel-to-sheath heat transfer coefficient in the CATHENA-ELOCA simulations. This effect is counterbalanced by the gas pressure inside the element which dominates after 10 seconds and cause the sheath to lift off from the fuel leading to low heat transfer coefficient between the fuel and the sheath. The initial temperature distribution in the fuel in the CATHENA-ELOCA simulations combined with the high fuel-to-sheath heat transfer coefficient during the power pulse leads to higher peak temperature at the fuel surface and at the outer sheath. The maximum sheath temperature reached during the CATHENA-ELOCA simulations is around 1220 °C while in the CATHENA alone simulations it is 100 °C lower.

5.2 Pressure Tube Temperature Results

Figure 11 shows the top pressure tube temperature results. At high temperatures, the pressure tube temperature is dominated by radiation from the fuel elements. Since the sheath reaches higher temperatures in the CATHENA-

ELOCA simulations than in the CATHENA alone simulation, the pressure tube also reaches higher temperatures (over 600 °C). CATHENA predicts that the pressure tube deforms slightly but does go into contact with the calandria tube. Pressure tube failure is not predicted for this scenario.

6. DISCUSSION AND CONCLUSIONS

This work has demonstrated that the two codes CATHENA and ELOCA can be coupled successfully. The approach using a couple code can model more accurately the channel and fuel behaviour under postulated large loss of coolant accident. In the simulations of a postulated 100% pump suction break the maximum sheath temperatures predicted using the coupled code (CATHENA-ELOCA) exceeds by 100 °C the maximum sheath temperature predicted by CATHENA alone. The effect of coupling on the fuel, sheath and pressure tube temperatures is thus important. The CATHENA-ELOCA coupled code has already been used in the calculation of fuel and sheath axial elongation under postulated accident scenarios for Gentilly-2. This approach has been compared to the previous approach where CATHENA was run alone and then ELOCA was run with its boundary conditions provided by the previous CATHENA run.

REFERENCES

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2. SILLS, H.E., "ELOCA - Fuel Element Behaviour During High Temperature Transients", AECL-6357, 1979.

TABLE 1. BOUNDING POWER/BURNUP

Bundle Position	Bundle Power (kW)	Bundle Burnup (MWh/kg U)
1	111.7	61.31
2	406.1	143.73
3	619.7	180.40
4	761.4	237.65
5	874.0	251.95
6	935.0	267.76
7	935.0	266.46
8	875.6	252.83
9	744.9	263.44
10	577.5	263.86
11	363.8	231.31
12	95.3	169.53

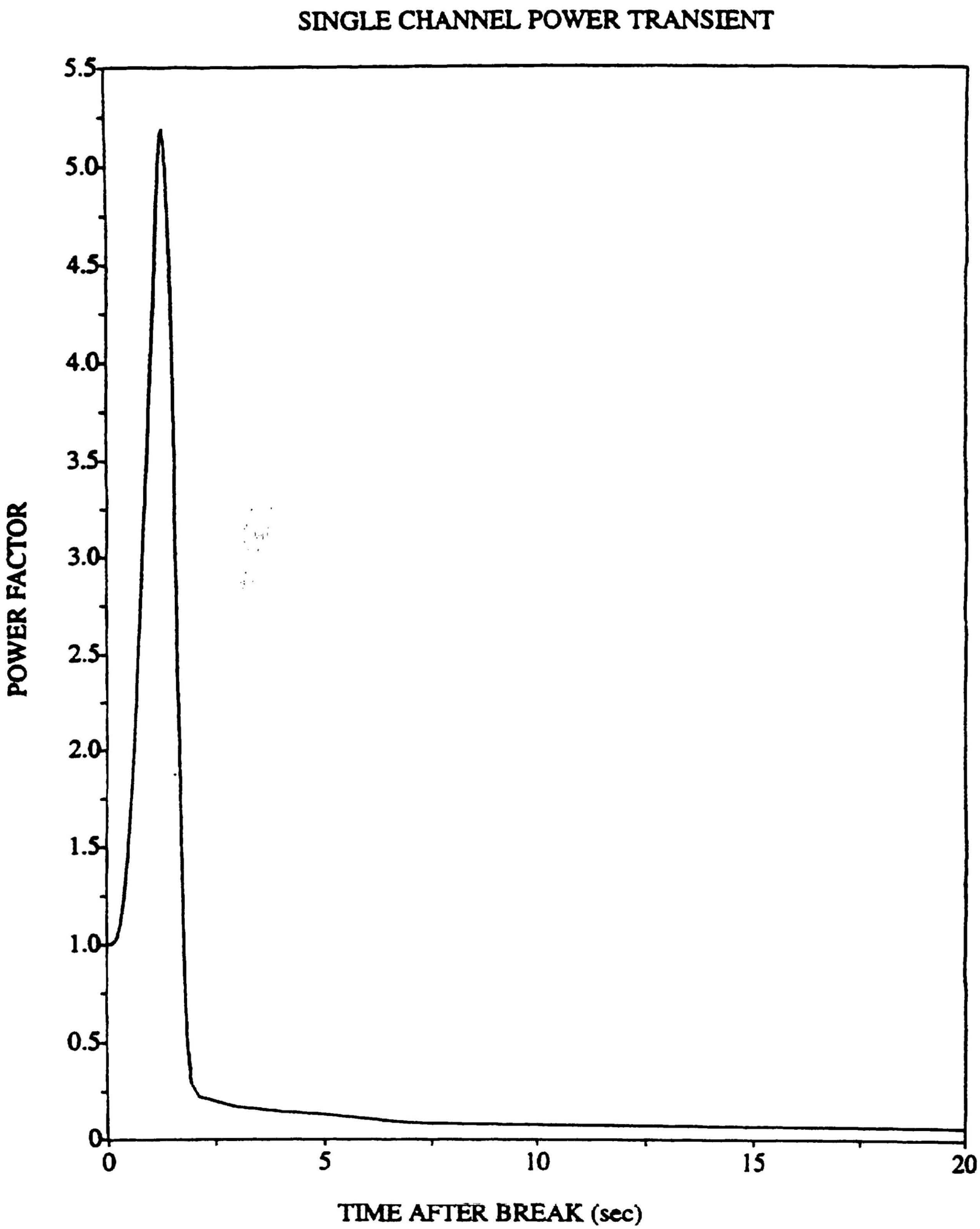

FIGURE 1. POWER TRANSIENT FOR A 100% PUMP SUCTION BREAK, CHANNEL 017

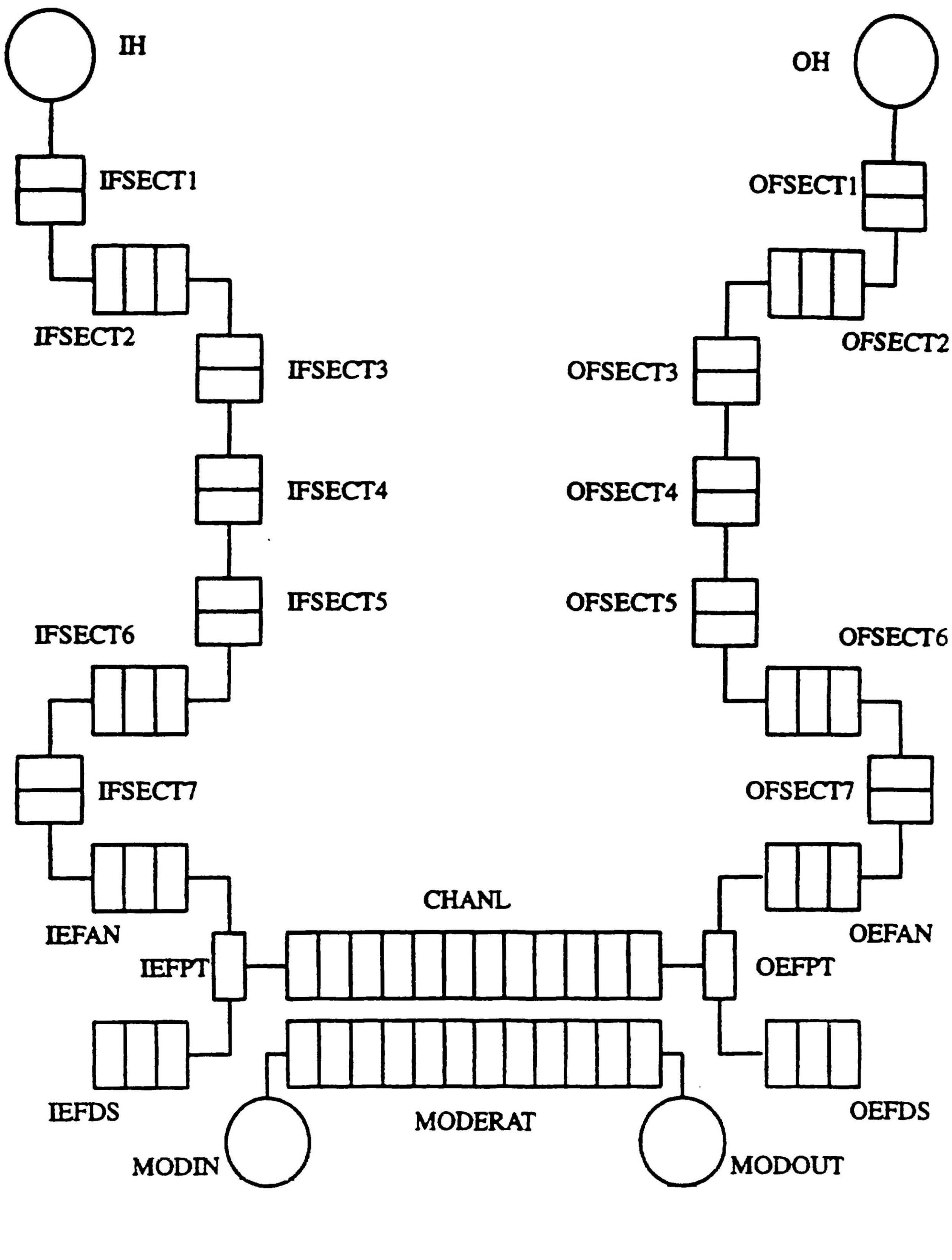

FIGURE 2. CATHENA THERMALHYDRAULIC NODE/LINK REPRESENTATION

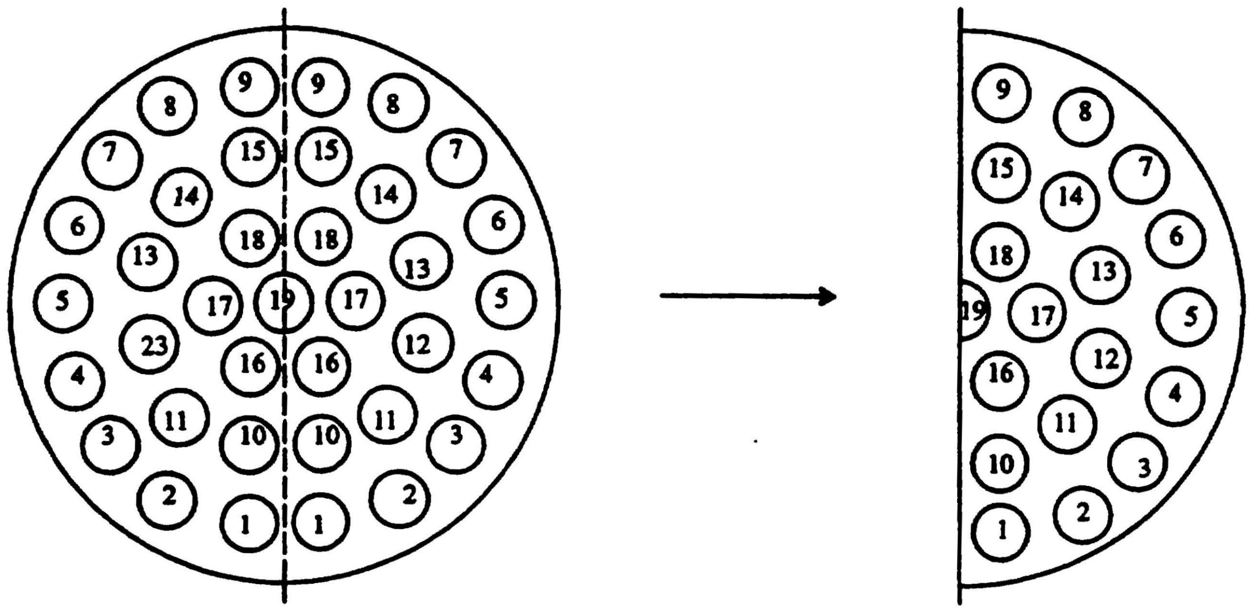

FIGURE 3. CATHENA FUEL BUNDLE MODELLING WITH 19 PINS

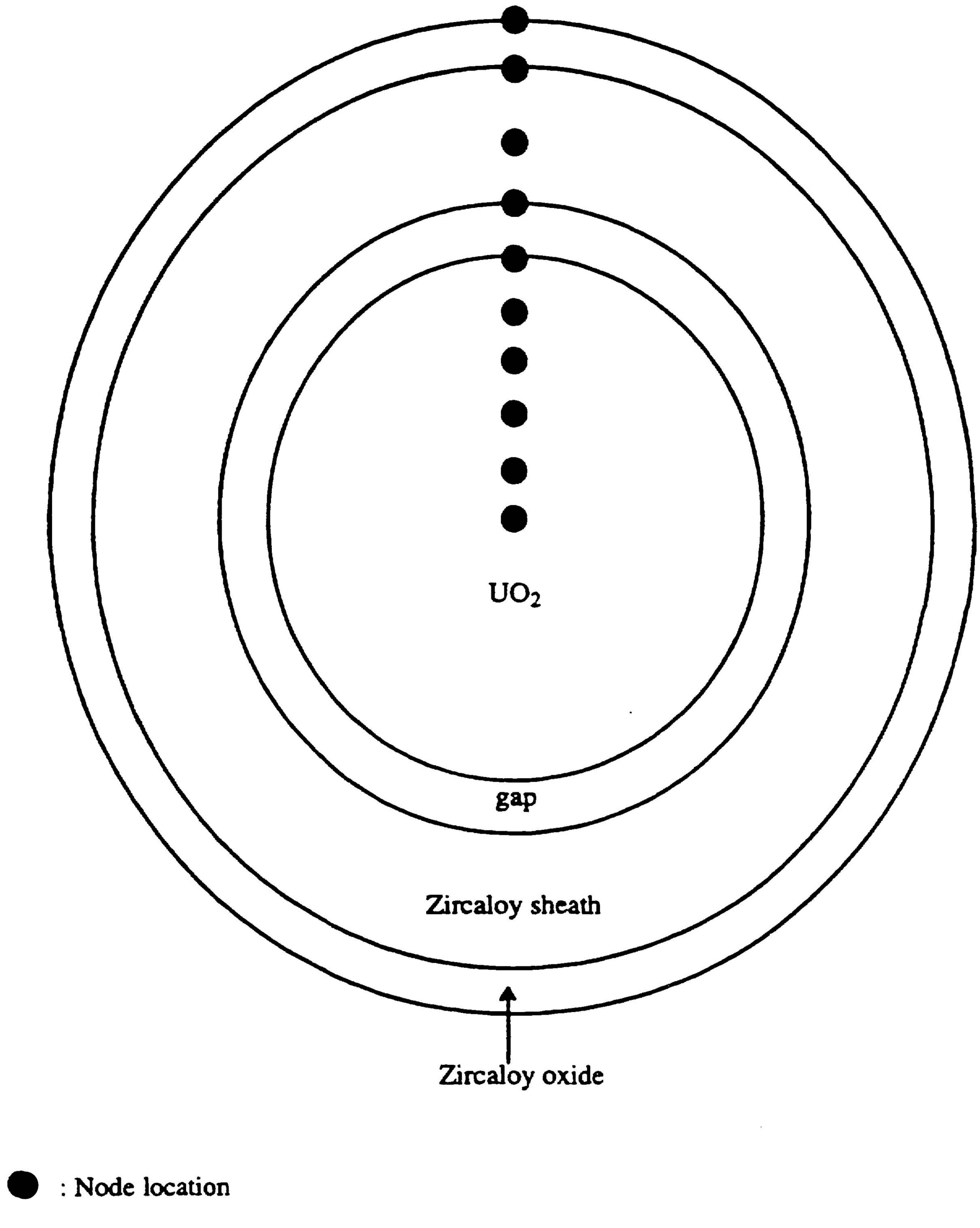

FIGURE 4. CATHENA FUEL ELEMENT RADIAL NODES AND REGIONS

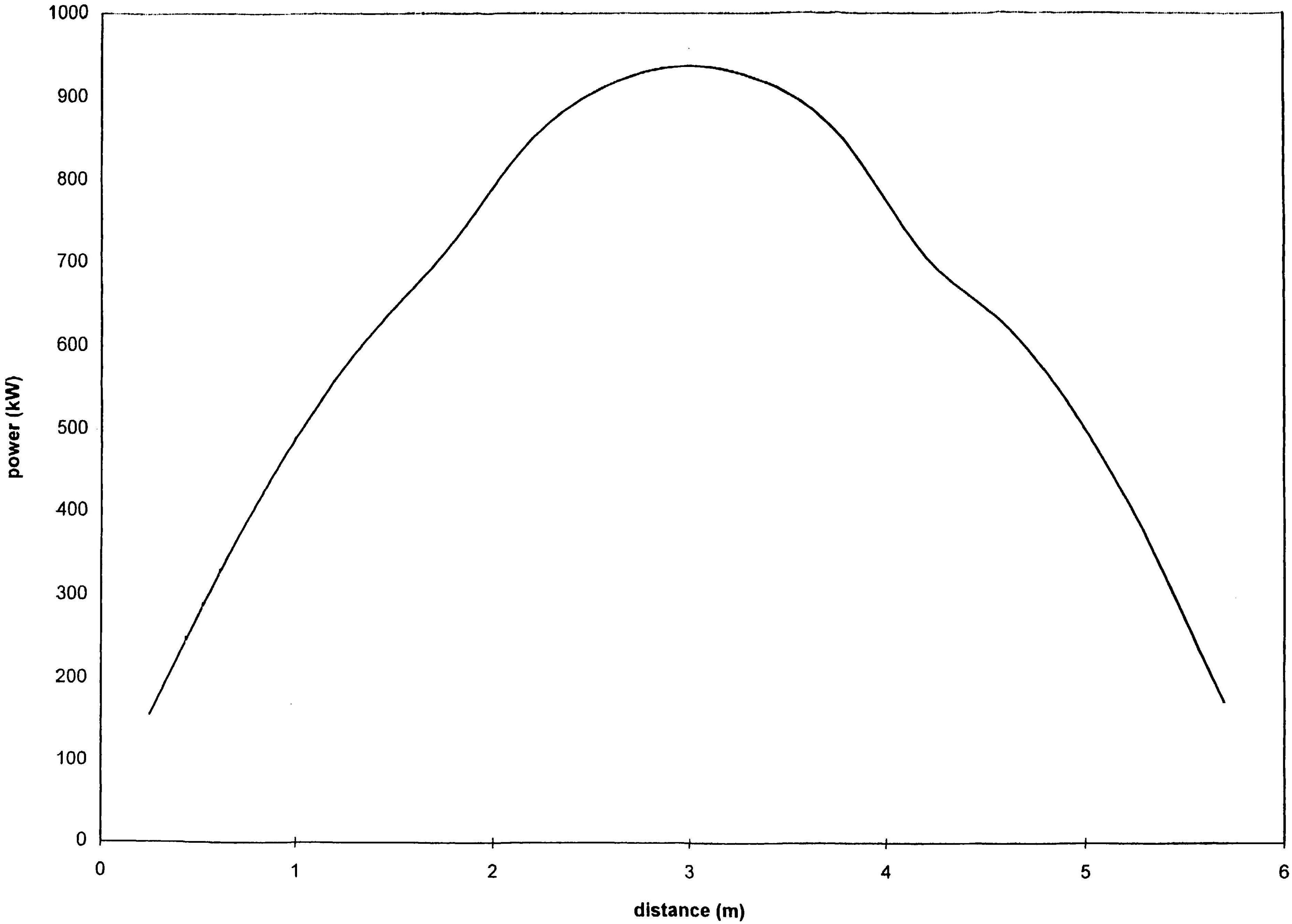

FIGURE 5. AXIAL POWER PROFILE

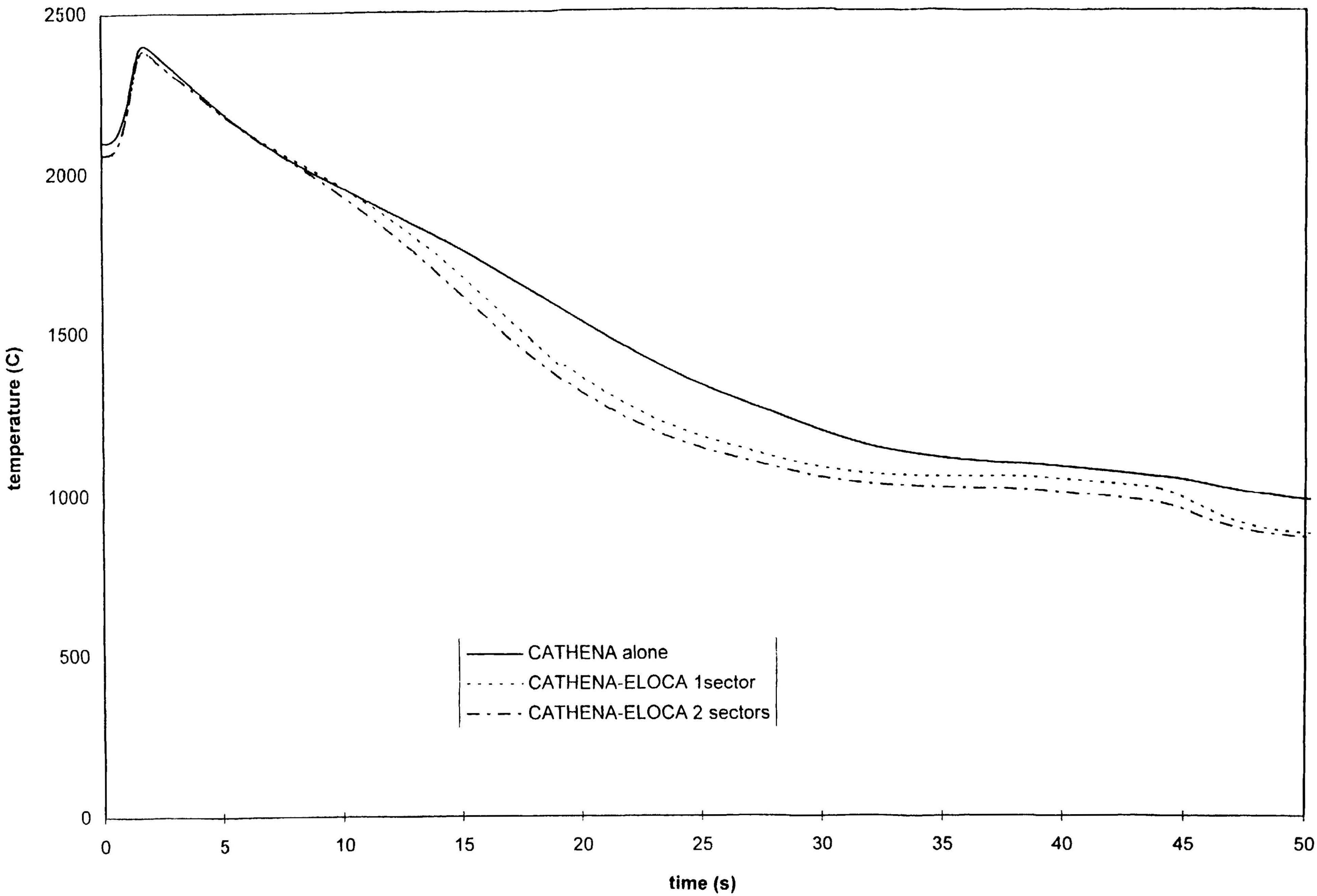

FIGURE 6. COMPARISON OF CATHENA PREDICTIONS OF CENTER FUEL TEMPERATURE AT BUNDLE 6

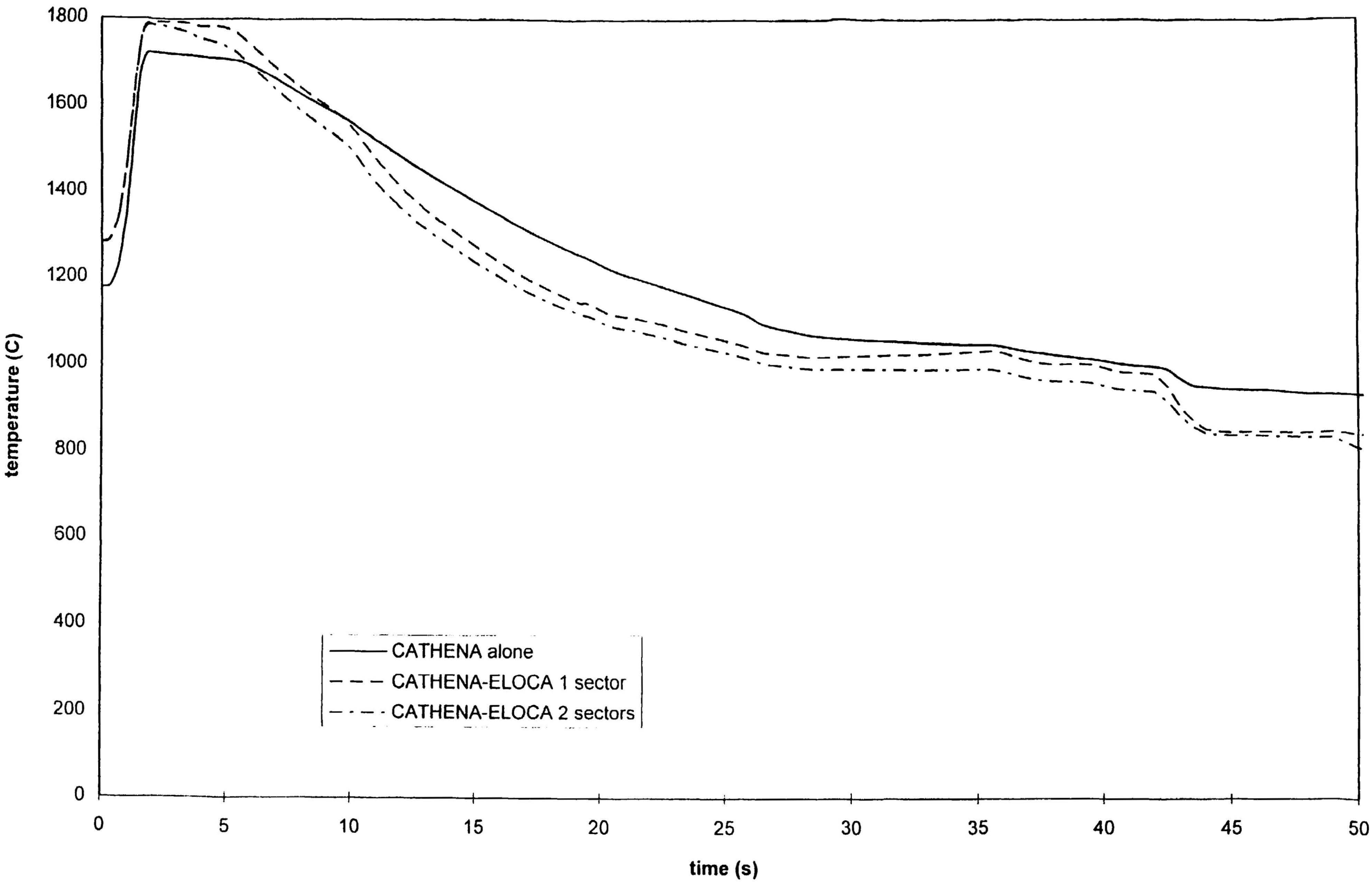

FIGURE 7. COMPARISON OF CATHENA PREDICTIONS OF AVERAGE FUEL TEMPERATURE AT BUNDLE 6

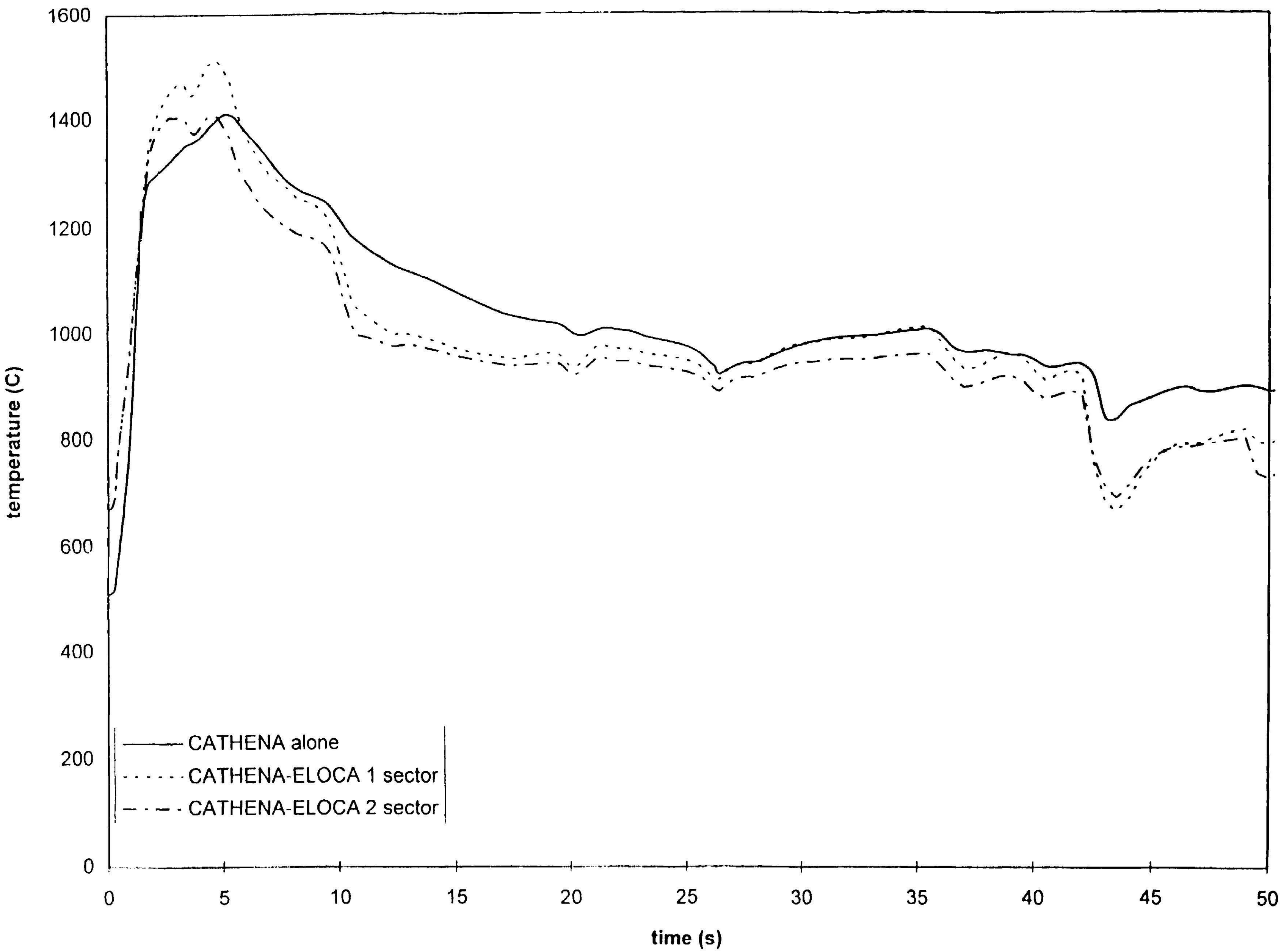

FIGURE 8. COMPARISON OF CATHENA PREDICTIONS OF SURFACE FUEL TEMPERATURE AT BUNDLE 6

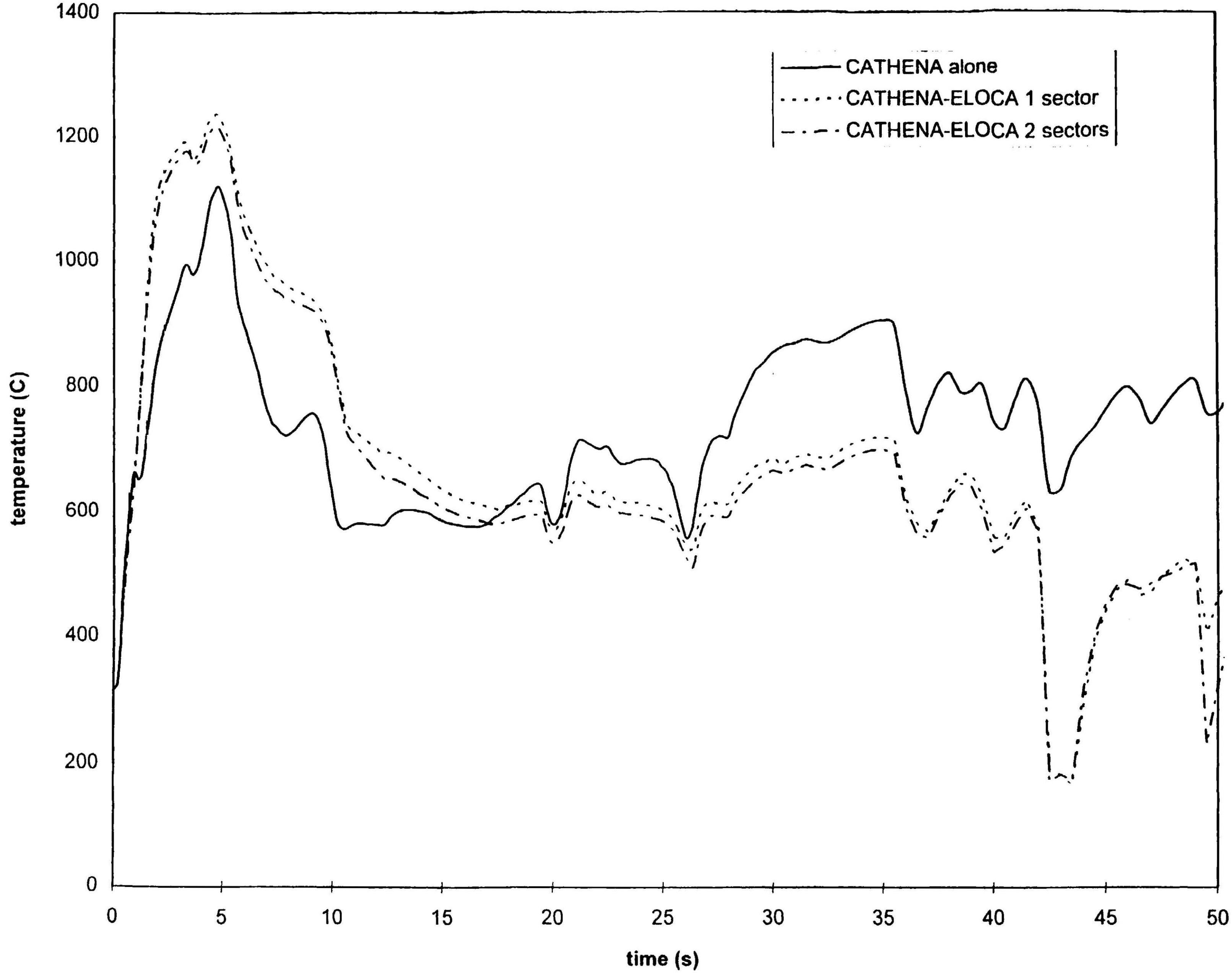

FIGURE 9. COMPARISON OF CATHENA PREDICTIONS OF SHEATH TEMPERATURE AT BUNDLE 6

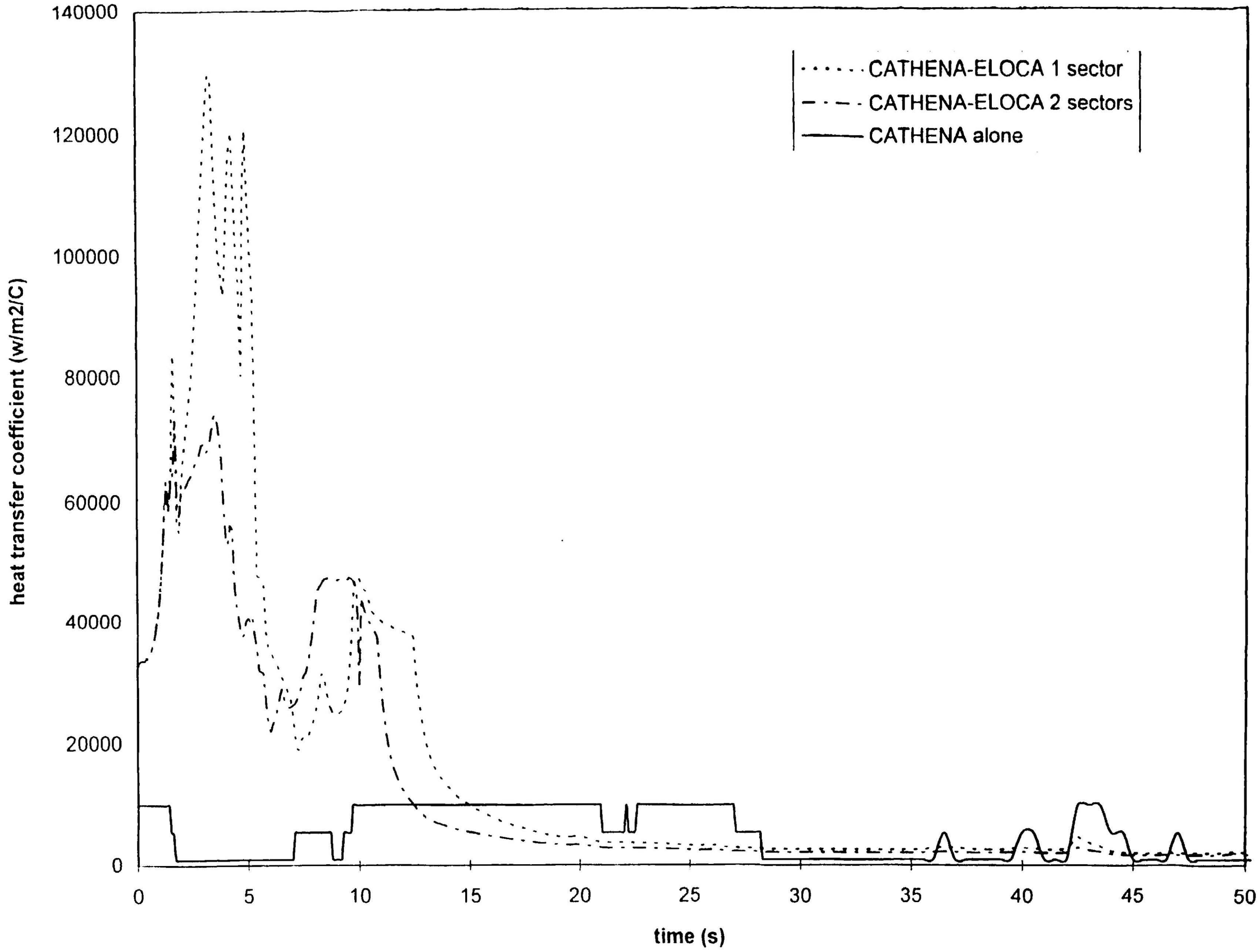

FIGURE 10. COMPARISON OF FUEL-TO-SHEATH HEAT TRANSFER COEFFICIENT USED BY CATHENA AT BUNDLE 6

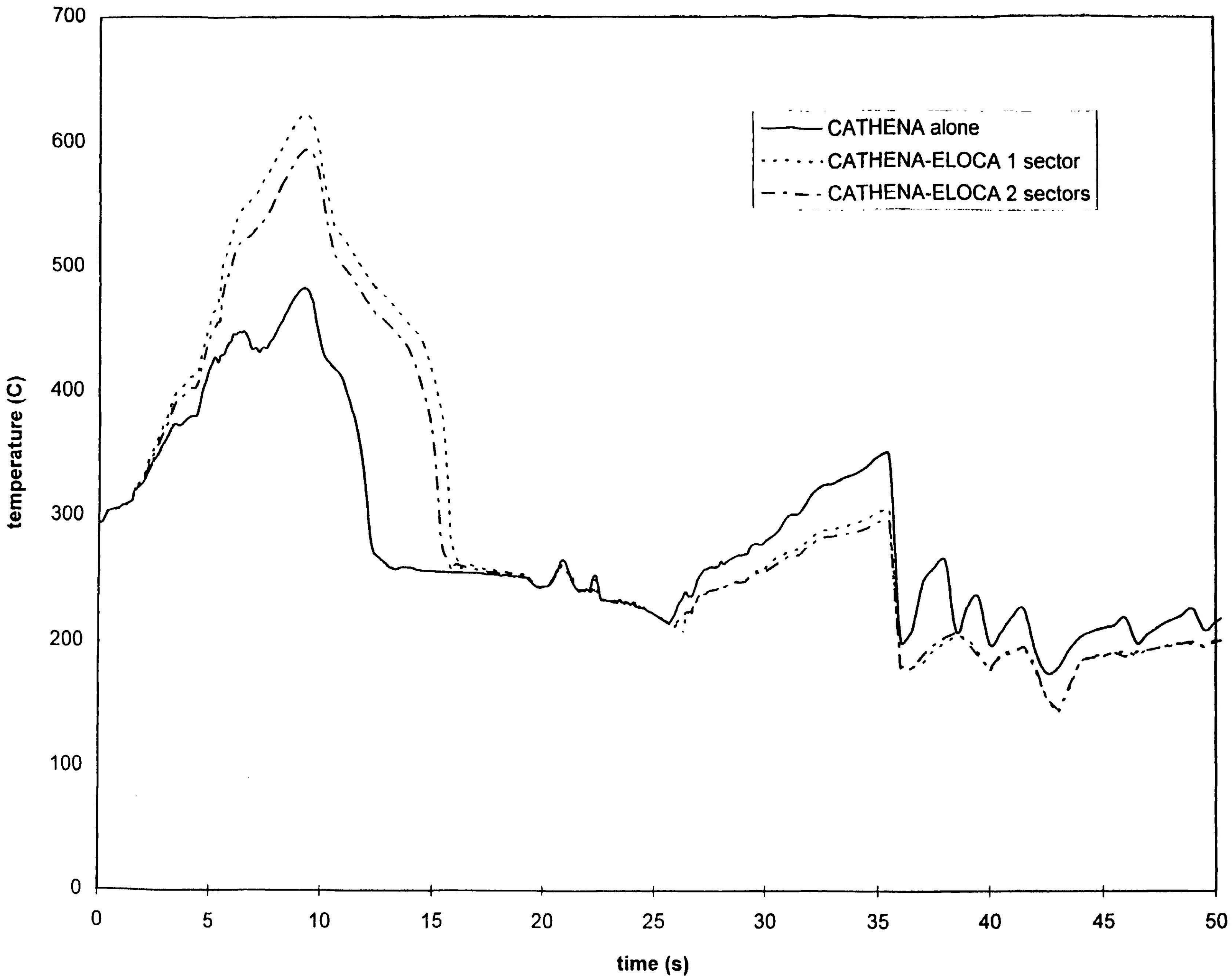

FIGURE 11. COMPARISON OF CATHENA PREDICTIONS OF PRESSURE TUBE TEMPERATURE AT BUNDLE 6