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FRAP-T5 RESPONSE TO SINUSOIDAL POWER VARIATIONS

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U.S. Department of Energy

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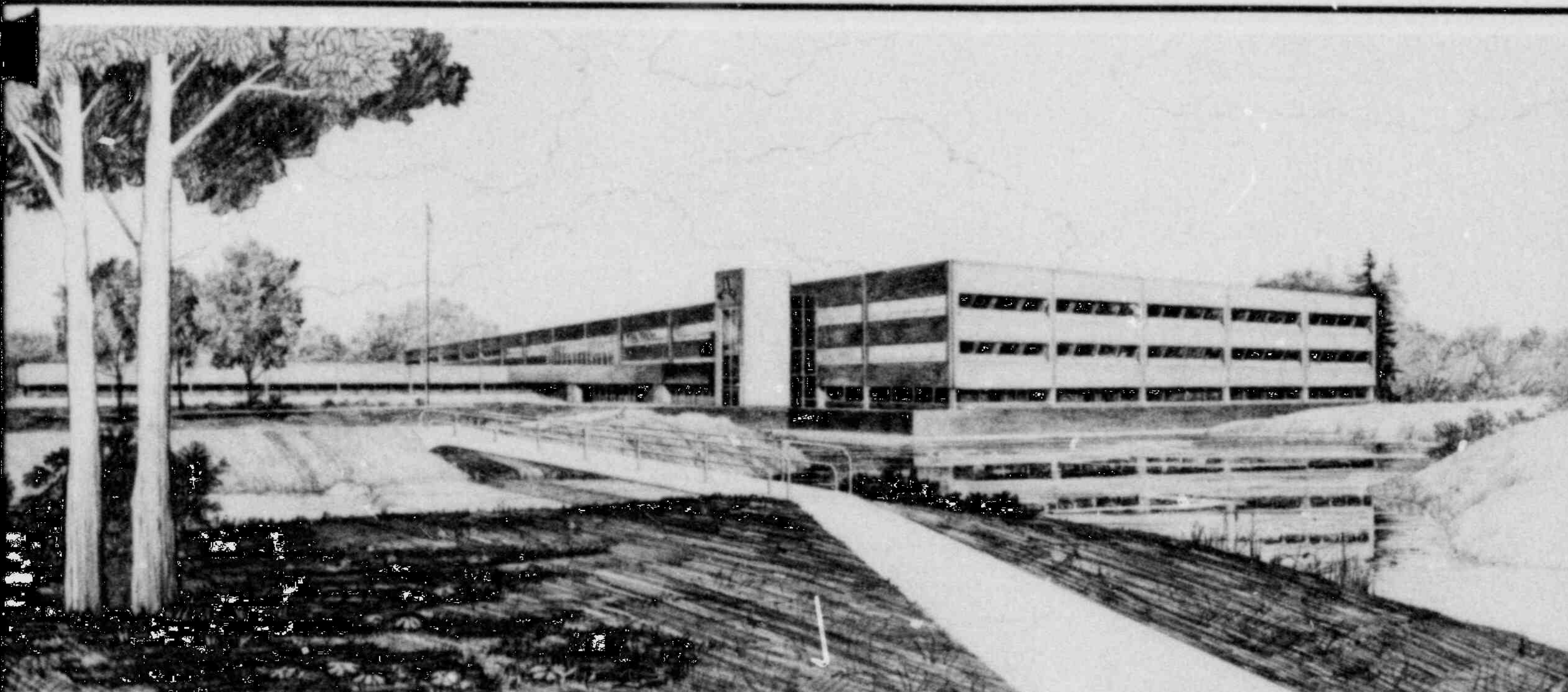

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NRC Research and Technical Assistance Report

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SUMMARY

The predictive capabilities of the FRAP-T5 transient fuel rod analysis program to simulate rod behavior under sinusoidal power variations was assessed. The primary objectives were to demonstrate where best estimate model capabilities exist, to provide guidance for future model development where improvements seem warranted, and to recommend the most appropriate input options which should be used for modeling this scenario.

Code predictions were compared with experimental data from the Gap Conductance Tests in the INEL Power Burst Facility. BWR type rods were used. The as-fabricated fuel density was 95%, and the initial pellet-cladding gap size varied from 0.94 to 3.4%.

Results indicated that overall, FRAP-T5 reproduced the basic behavior traits observed in the experiments. The FRACAS-II deformation model was the most appropriate option for simulating this type of rod behavior.

FRAP-T5 RESPONSE TO SINUSOIDAL POWER VARIATIONS

I. INTRODUCTION

During the power oscillation phase of testing in the Gap Conductance Tests at the Power Burst Facility, the response of the thermocouple measurements to a sinusoidal power variation was significantly different from a sinusoidal or periodic response.[1,2] This distortion in the thermocouple response will be referred to as wave shape changes. It has been postulated that these wave shape changes were the result of pellet-to-cladding gap closure during power increases and pellet-to-cladding gap opening during power decreases. These wave shape changes were observed for both pressurized water reactor (PWR) and boiling water reactor (BWR) type fuel rods. The magnitude of the wave shape changes for nominally identical power levels were different for the PWR and BWR designs. That is, the magnitude of the wave shape changes increased in the BWR rods as the nominal rod power increased, but the signal distortion was greatest at low power levels in the PWR rods. This suggested that the PWR design maintained a more uniform fuel stack geometry during power oscillations than did the BWR design. It was further postulated that the expansion of the thermocouple holes was compensated by the dished end design of the PWR fuel pellets, which would produce a stabilization effect on the fuel stack geometry. In the case of the flat end design of the BWR fuel pellets, the expansion of the thermocouple holes may have resulted in bowing of the pellet end faces, which produced an unstable effect on the fuel stack geometry.

This report summarizes a study to examine FRAP-T5 code 3 behavior under these observed sinusoidal power operation conditions. A description of FRAP-T5 is given in Section II. The procedure used in this study is presented in Section III and a description of the gap conductance experiment is given in Section IV. The results are discussed in Section V. The conclusions and recommendations are listed in Section VI, and the references are given in Section VII.

II. CODE DESCRIPTION

The FRAP-T5 code is capable of calculating fuel rod transient temperature distributions which are the result of changes in power level or surface heat transfer conditions. The transient heat conduction equation is solved at specified time intervals. Changes in material properties, gap and surface heat transfer, rod internal pressure, fuel-cladding mechanical interaction state, and rod deformation are taken into account. The current structural analysis model computes elastic and plastic cladding deformation occurring as a result of thermal expansion, hydrostatic pressure differentials, gap closure, and high temperature cladding rupture. Fuel deformation occurs by thermal expansion or hydrostatic pressure differences, or both, as specified by input. The thermal and mechanical analyses at a particular time, progress in series and interact until convergence criteria for temperature, pressure, and deformation conditions are satisfied.

Development activity has resulted in a modular subroutine framework which fulfills thermal-mechanical feedback requirements. Constituent models are not all in final versions, but the overall feedback structure itself is considered established for single-rod applications. Initial rod geometry, coolant channel geometry, inlet fluid conditions, and power history are normally the independent variables available for user input. If required, thermal hydraulic boundary conditions can be externally supplied by selection of input data from supporting analyses. The code is dimensioned to handle rod arrays of limited size, but currently no feedback is provided to account for subchannel interactions occurring as a result of flow redistribution, cladding deformation, or fuel rod failure.

III. ASSESSMENT PROCEDURE

Analytical results have previously been reported[2] which indicated that when a sinusoidal power oscillation was used in the FRAP-T2 code, the temperature response would change significantly from a sine wave when the calculated pellet-to-cladding gap was opening and closing. That initial effort using FRAP-T2 was limited and somewhat incomplete. Therefore, this effort was initiated to investigate the response of the new FRAP-T5 code to sinusoidal power variations. First, a comparison was made of the measured and predicted power levels at which gap closure occurred. The predicted power levels at which gap closure occurred could then be compared to the power levels at which wave shape changes occurred. This would yield information on the relationship of soft and hard gap closure, which is required for cladding strain calculations at the onset of gap closure. Also, information related to the current relocation effective conductivity model would be provided. Second, the response of FRAP-T5 to sinusoidal power variations when gap closure did not occur was investigated. This would allow a qualitative assessment of the transient conduction solution without the complicating effects of the gap closing and opening. Third, the response of FRAP-T5 to sinusoidal power variations when gap closure occurred was investigated. Both of the mechanical deformation subcodes, FRACAS-I and FRACAS-II, were used.

IV. RUN IDENTIFICATION

A helium filled (2.58 MPa cold pressure) BWR type fuel rod was simulated in the FRAP-T5 analysis, since the majority of the experimental data was obtained from this type rod design. The fuel rod design parameter that was varied in the analysis was the initial pellet-to-cladding gap size. Three gap sizes were considered 0.94%, 2.2%, and 3.4%, where gap sizes are given in percent of as-built fuel pellet diameter. The three experimental rods that were simulated were designated in the experiments as GC503, GC522-3, and GC522-4, and represent test rods used in Gap Conductance Tests GC2-1, GC2-2, and GC2-3, respectively. All of these fuel rods were 95% theoretical density. In addition to the gap sizes, the initial power level, and amplitude and frequency of the sinusoidal power variation were considered as a variable in the analysis.

V. ASSESSMENT RESULTS

The analysis was conducted in three parts. First, three steady state runs were performed to define the power levels at which gap closure (thermal and structural gaps) would be predicted for the three different gap sizes considered, using both FRACAS-I and FRACAS-II. This simplified the number of sinusoidal power analyses that would be required. Table 1 contains a summary of the predicted steady state power levels at which gap closure occurred and the lowest measured power levels at which observable wave shape changes were identified. The measured power levels at the onset of wave shape changes increase slightly as the initial gap increases. Using FRACAS-I, the predicted power level at which the structural (unrelocated) gap closes also increases with increasing initial gap size; however, the calculated power at which structural gap closure occurs is significantly larger than the power level at which wave shape changes were observed in the experiment. The predicted power level at which the thermal (relocated) gap closes decreases with increasing initial gap size. This is due to the current relocation model which has no limit on the amount of relocation. That is, as the gap size increases, the relocation increases with no upper limit on the relocation. This is somewhat unrealistic, especially for large gap rods. The fuel conductivity is also reduced as the relocation increases. As a result, the fuel temperatures for a given linear heat rate are higher for the large gap rods, which causes thermal gap closure at a lower power level than in the case of the small gap rods. The power levels at which the thermal gap was predicted to be closed is more comparable to the test fuel rod power at which wave shape changes occurred than the power levels at which the structural gap was predicted to be closed. Using FRACAS-II, the power level at which the structural gap closes increases with increasing gap size and the predicted power at gap closure is comparable to the test fuel rod power at which wave shape changes were identified. Therefore, it appeared at this point that FRACAS-II would be more applicable for investigation of wave shape changes than FRACAS-I.

Second, to qualitatively assess the transient conduction solution, the response of FRAP-T5 to sinusoidal power oscillations was investigated using FRACAS-I and FRACAS-II. Using FRACAS-I, the initial power level and amplitude were selected to preclude closure of the structural (unrelocated) gap and the

TABLE 1

COMPARISONS OF MEASUREMENTS AND PREDICTIONS OF LOCAL LINEAR HEAT RATE AT WHICH WAVE SHAPE CHANGES WERE NOTED

Test Rod Designation (Description)	Test Rod Local Power* (kW/m)	**Predicted Steady State Local Power for Thermal Gap Closure (kW/m) FRACAS-I	**Predicted Steady State Local Power for Structural Gap Closure (kW/m) FRACAS-I	**Predicted Steady State Local Power for Structural Gap Closure (kW/m) FRACAS-II	Experimental Indication of Waveshape Changes: Off-Center Thermocouple	Experimental Indication of Waveshape Changes: Cladding Surface Thermocouple
GC-522-3 (Helium - 0.94% gap)	24.3	30.0	50.0	18.5	yes	yes
GC 503 (Helium - 2.2% gap)	24.0	22.0	77.0	29.5	yes	no
GC 522-4 (Helium - 3.4% gap)	29.7	18.0	99.0	31.2	yes	Questionable

* Lowest test rod transient power at which observable wave shape changes were identified.

** The predicted power levels for gap closure are steady state results and do not reflect transient conditions. The frequency and amplitude, or ramp rate affect the predicted power level for gap closure. The transient values are larger than the steady state values. For frequencies slower than 20 s/cycles and amplitudes less than $\pm 35\%$ of nominal power, the steady state and transient values differed by approximately 10-15%.

thermal (relocated) gap during the power oscillation. Next, the initial power level and amplitude were selected to preclude closure of the structural gap, while the thermal gap opened and closed. Figures 1 and 2 show the input power versus time that was utilized and the fuel pellet surface temperature response for fuel rod, GC503. The initial gap size was 2.1%. The input power versus time consisted of a sinusoidal variation, followed by a constant power level at the time averaged value as shown on Figures 1 and 2. For these two cases wave shape changes were not observed.

Finally, the initial fuel rod power was increased and the response of the fuel centerline temperature to power oscillations was investigated. The power oscillation utilized was 45 $\pm$ 15 kW/m at a frequency of 20 s/cycle. Two cases were considered, as shown in Figures 3 and 4. In the first case the power was initially increasing and in the second case the power was initially decreasing. In both cases, the initial fuel centerline temperature response is non-symmetric, followed by a symmetric or periodic response to the input sinusoidal power variation. Using the procedure described in Reference 4, the analytical expression for the derivative of the normalized fuel centerline temperature* for an input sinusoidal power variation contains a decaying

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* The normalized fuel centerline temperature is defined as

$$\frac{T_{\mathfrak{L}}(t) - T_w}{T_{\mathfrak{L}}(o) - T_w}$$

where

T_w = coolant temperature

$T_{\mathfrak{L}}(o)$ = initial steady state fuel centerline temperature

$T_{\mathfrak{L}}(t)$ = time dependent fuel centerline temperature

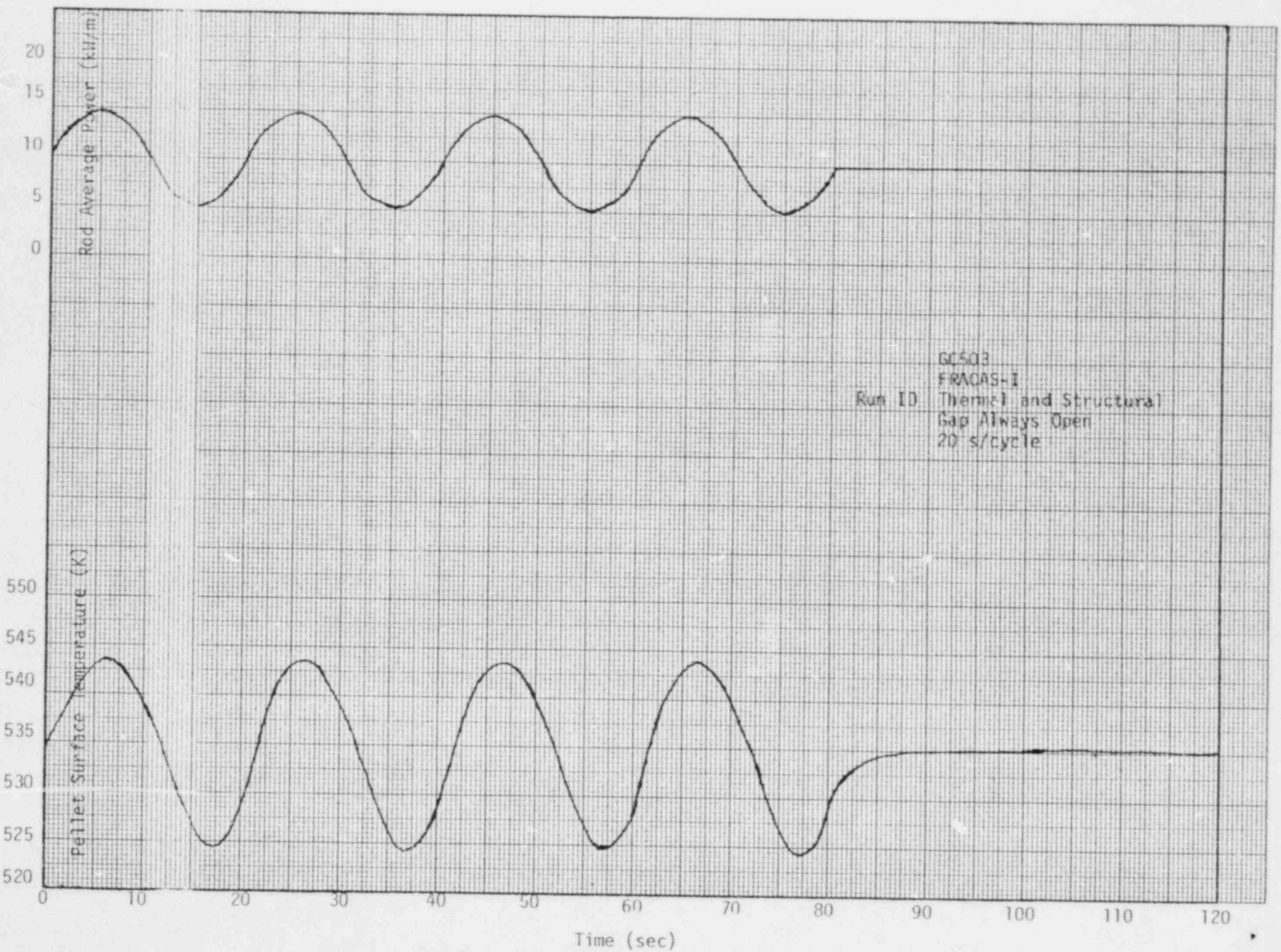

Figure 1. Pellet surface temperature versus time (FRACAS-I, all gaps open).

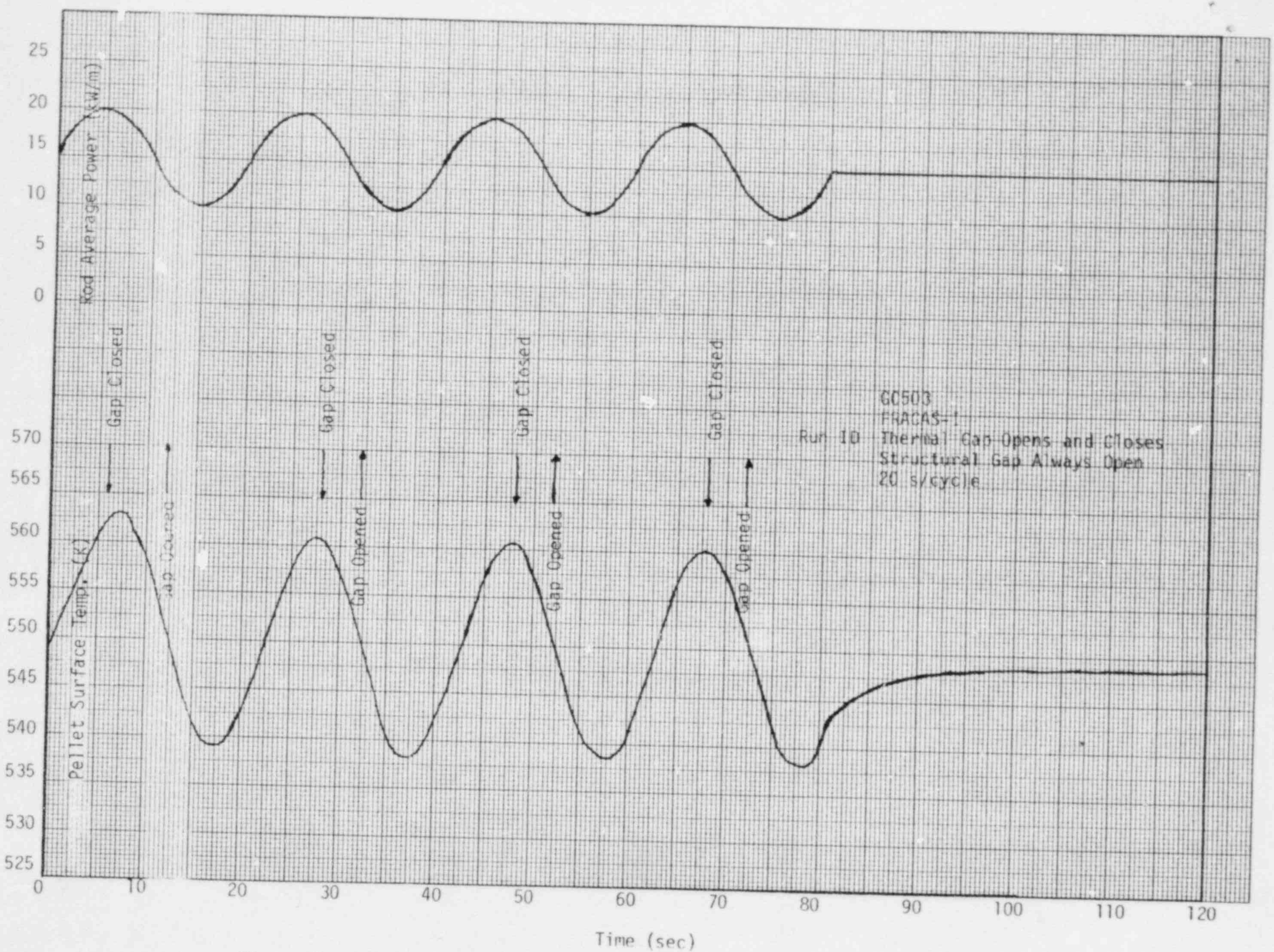

Figure 2. Pellet surface temperature versus time (FRACAS-I, structural gap open).

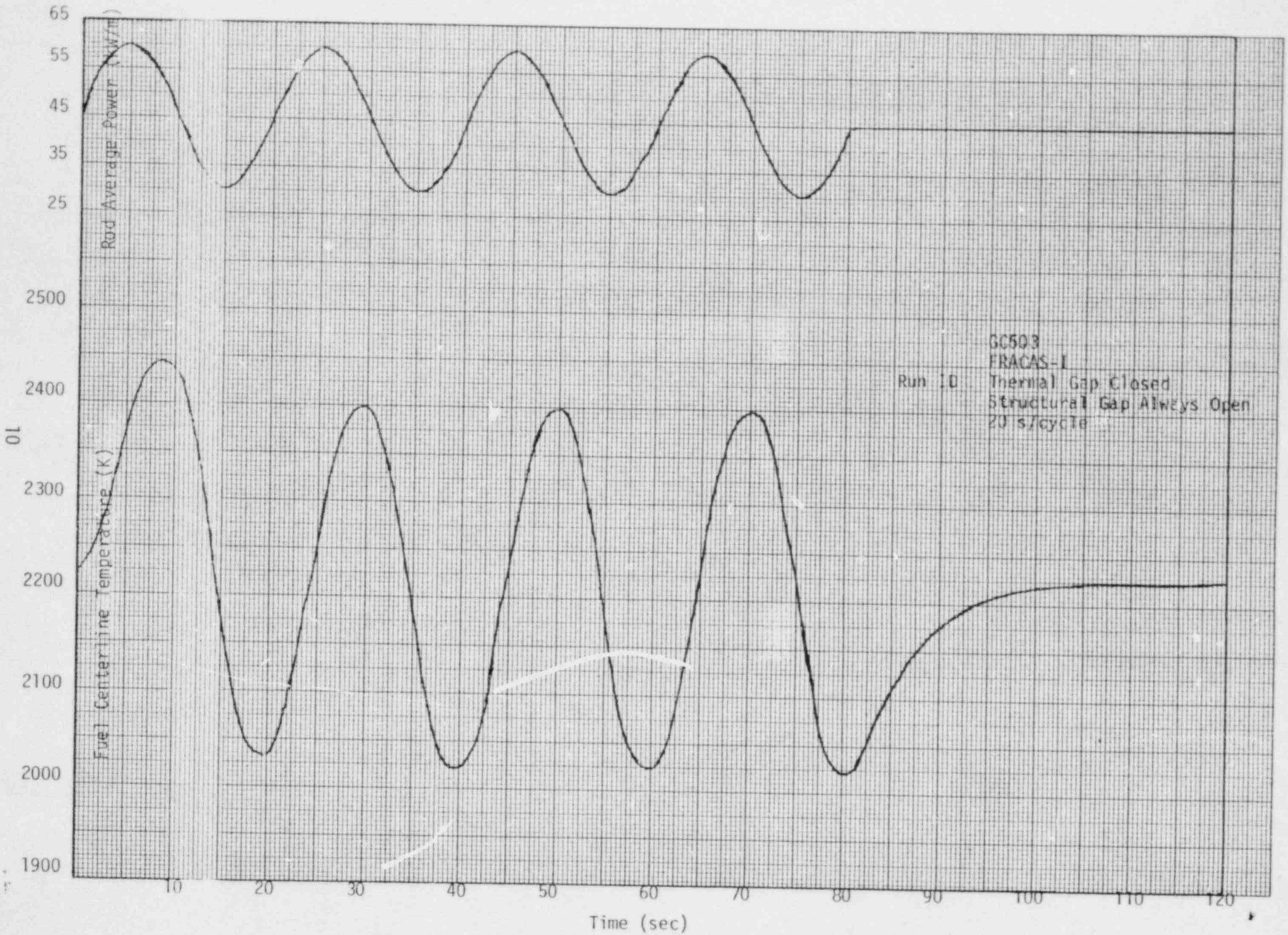

Figure 3. Fuel centerline temperature versus time, initial power increase (FRACAS-I).

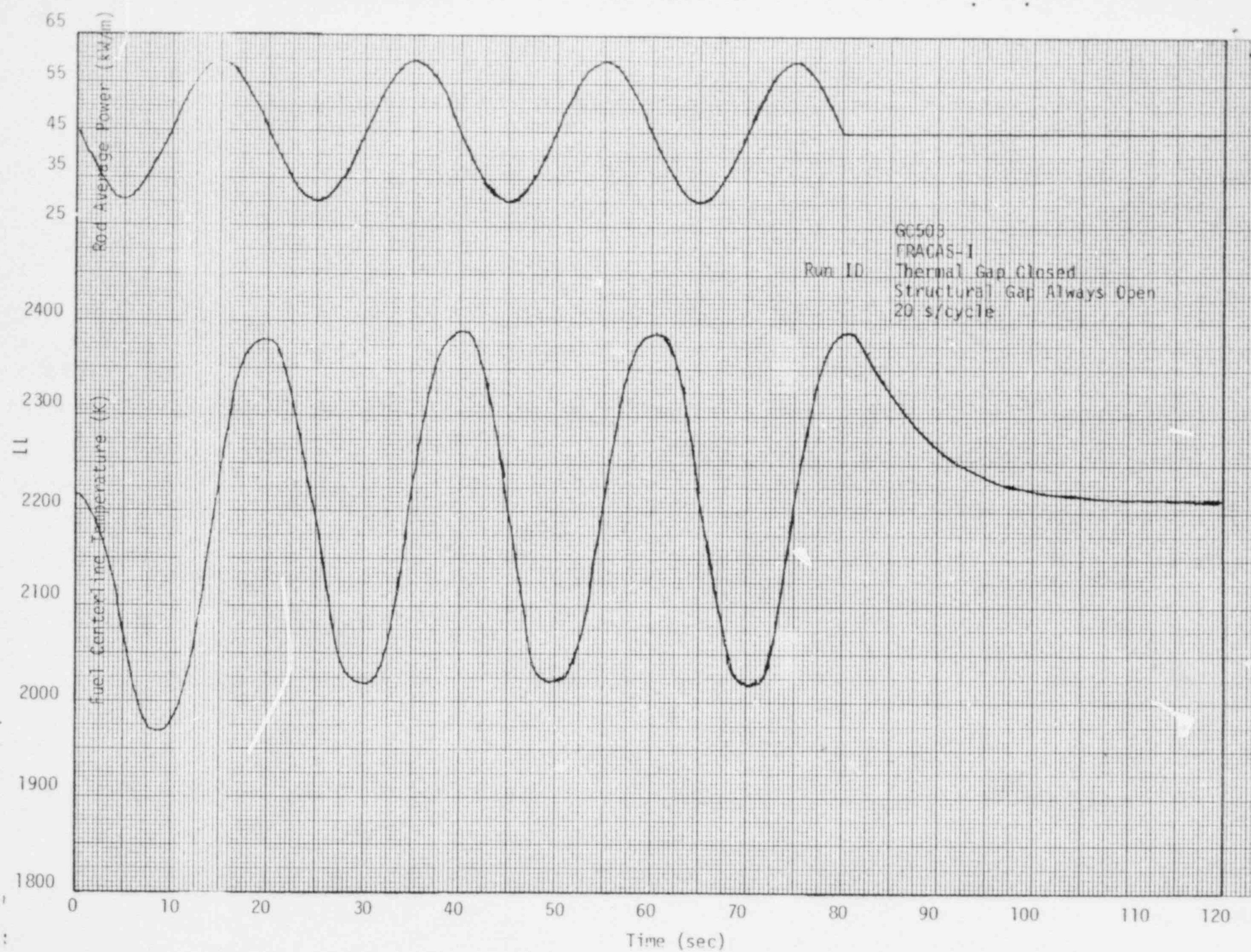

Figure 4. Fuel centerline temperature versus time, initial power decrease (FRACAS-I).

exponential term, similar to that presented in Reference 4. The effect of this exponential term should approach zero on the order of the time span observed in Figures 3 and 4, i.e., approximately 20 s or approximately three time constants. Following this time, the derivative of the normalized fuel centerline temperature is predicted to be periodic. This implies that the response of the fuel centerline temperature would also be periodic as shown in Figures 3 and 4. In Figure 3, the power is increasing just prior to the period of steady state power at 45 kW/m. In Figure 4, the power is decreasing just prior to the period of steady state power at 45 kW/m. Therefore, the approach to an equilibrium power level was made from an increasing and decreasing transient temperature distribution. In both cases the equilibrium fuel centerline temperature was essentially identical. The initial fuel centerline temperature response, the periodic response of the fuel centerline temperature, and the approach to equilibrium from an increasing and decreasing transient temperature distribution reflect favorably on the transient conduction solution. Also, wave shape changes were not observed for the results presented in Figures 1 through 4, where the structural (unrelocated) gap did not close. Similar results were obtained using a frequency of 40 s per cycle, as shown in Figure 5. The exponential effect on the fuel centerline temperature response is slightly smaller during the initial oscillation for the 40 s per cycle result, as compared to the 20 s per cycle result, (compare Figures 3 and 4 with Figure 5). This might be expected since the slope of the normalized temperature is predicted to be less perturbed by the slower oscillation.

Finally, using FRACAS-I oscillations where the thermal gap was always closed and the structural gap opened and closed during the power oscillation were investigated. The results given in Figure 6, show that gap opening and closing affects the pellet surface temperature response. The results during the first cycle are considered to be atypical due to the fact that asymptotic transient terms affect the results during this time.

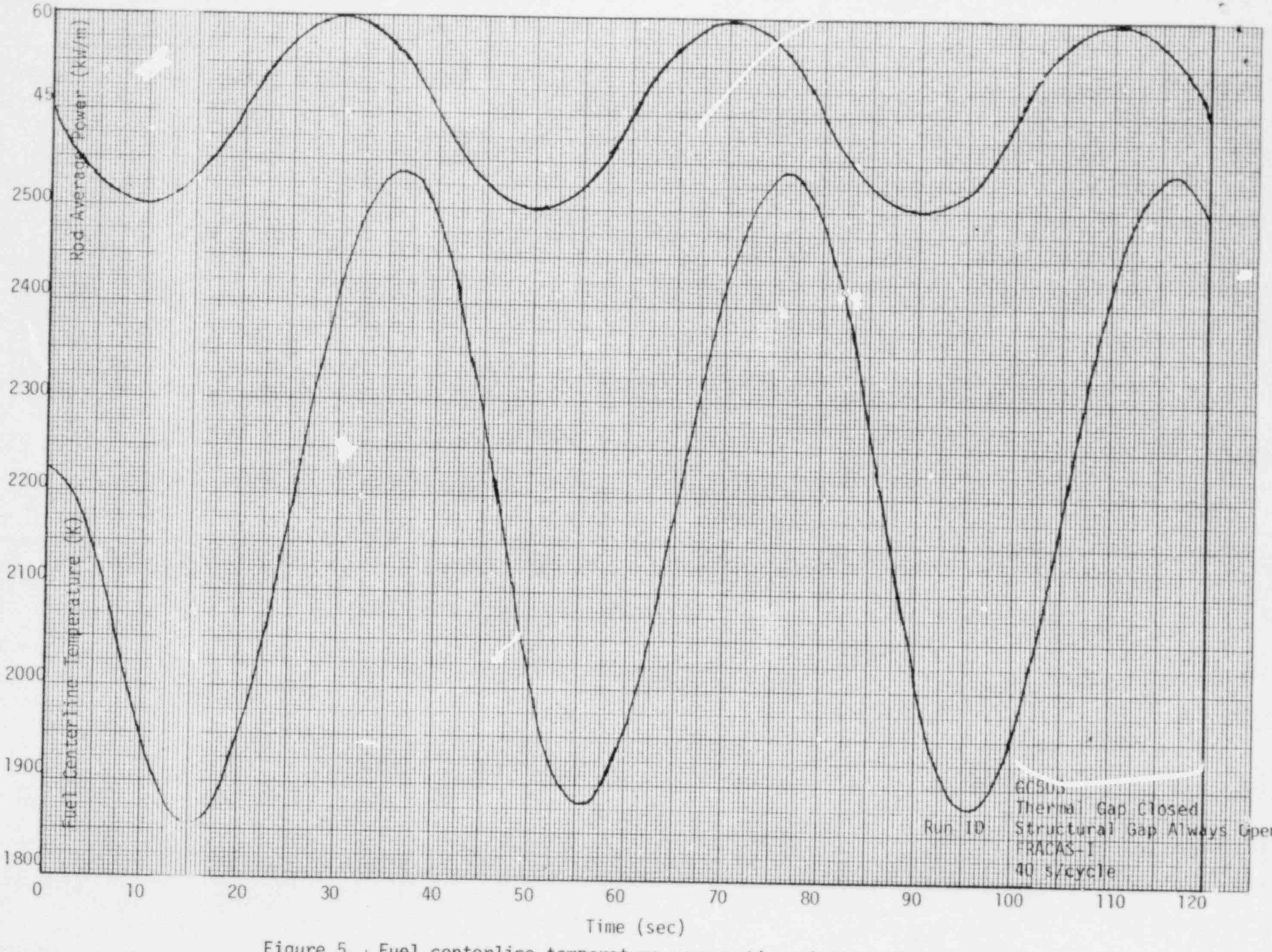

Figure 5. Fuel centerline temperature versus time, initial nower decrease (FRACAS-I, 40 s/c).

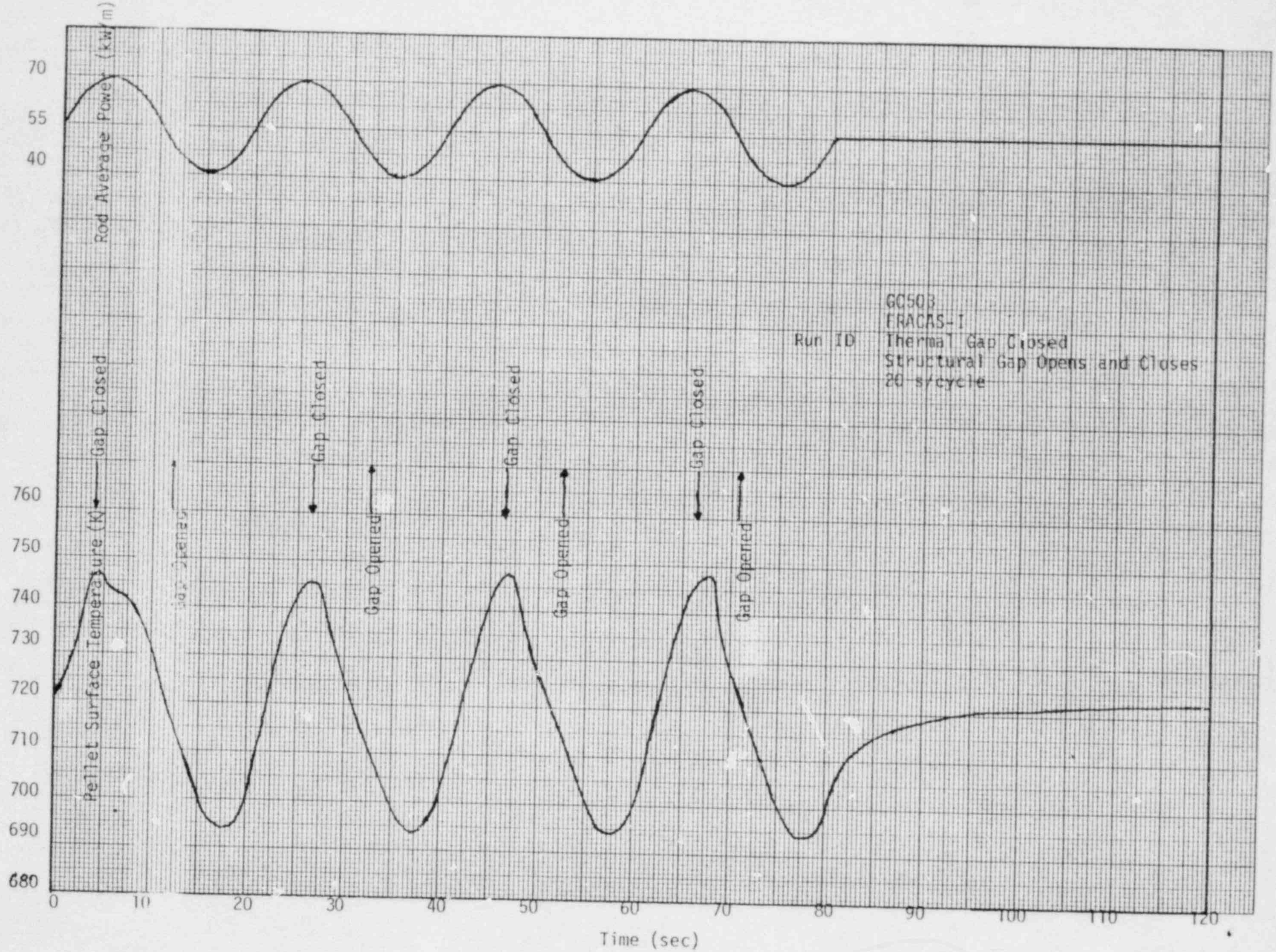

Figure 6. Pellet surface temperature versus time (FRACAS-I).

Using FRACAS-II, there is only one gap to be considered the structural gap. Oscillations about power levels which did not cause the structural gap to close did not result i observable wave shape changes.

Using FRACAS-II, oscillations wh ch caused closure of the structural gap produced the results shown in Figures 7 and 8. In this case the frequency was 20 s/ ycle and the amplitude was +35% and ±50%, respectively. These results demonstrate that wave shape changes in the predicted pellet surface temperature are related to the opening and closing of the structural gap for both FRACAS-I and FRACAS-II. However, the relationship is complicated. The amplitude, frequency, and initial power determine the time span between opening and closing of the gap, and hence the overall effect of the gap opening and closing. For example, in Figure 7, the following effect is shown; the gap closes shortly after the peak power, and the increase in gap conductance then causes a reduction in the pellet surface temperature. Since the power is decreasing when gap closure occurs, the gap re-opens in a very seconds, which causes an increase in pellet surface temperature due to the decrease in gap conductance.

In the case of the results shown in Figure 8, gap closure occurs closer to the power maximum. This again results in a decrease in the pellet surface temperature. However, an increase in the pellet surface temperature is observed prior to the gap re-opening, and the increase is less than that observed in Figure 7. The increase seen in Figure 8, is probably due to conduction from the inner radial nodes overcompensating the effect of increased gap conductance. Finally, the gap re-opens, closer to the power minimum and the decrease in gap conductance at this point is overcompensated for by the decreasing fuel temperatures. The fact that the amplitude, frequency, and initial power level determine the time span between opening and closing of the gap, and hence the overall effect of the gap opening and closing, is further illustrated in Figure 9. In this case, the type wave shape changes shown in Figure 7 and 8, which were similar to the type seen during the Gap Conductance Testing, were not observed. Also, the predicted time between the gap closing and opening in Figure 9 was significantly different from that shown in Figures 7 and 8.

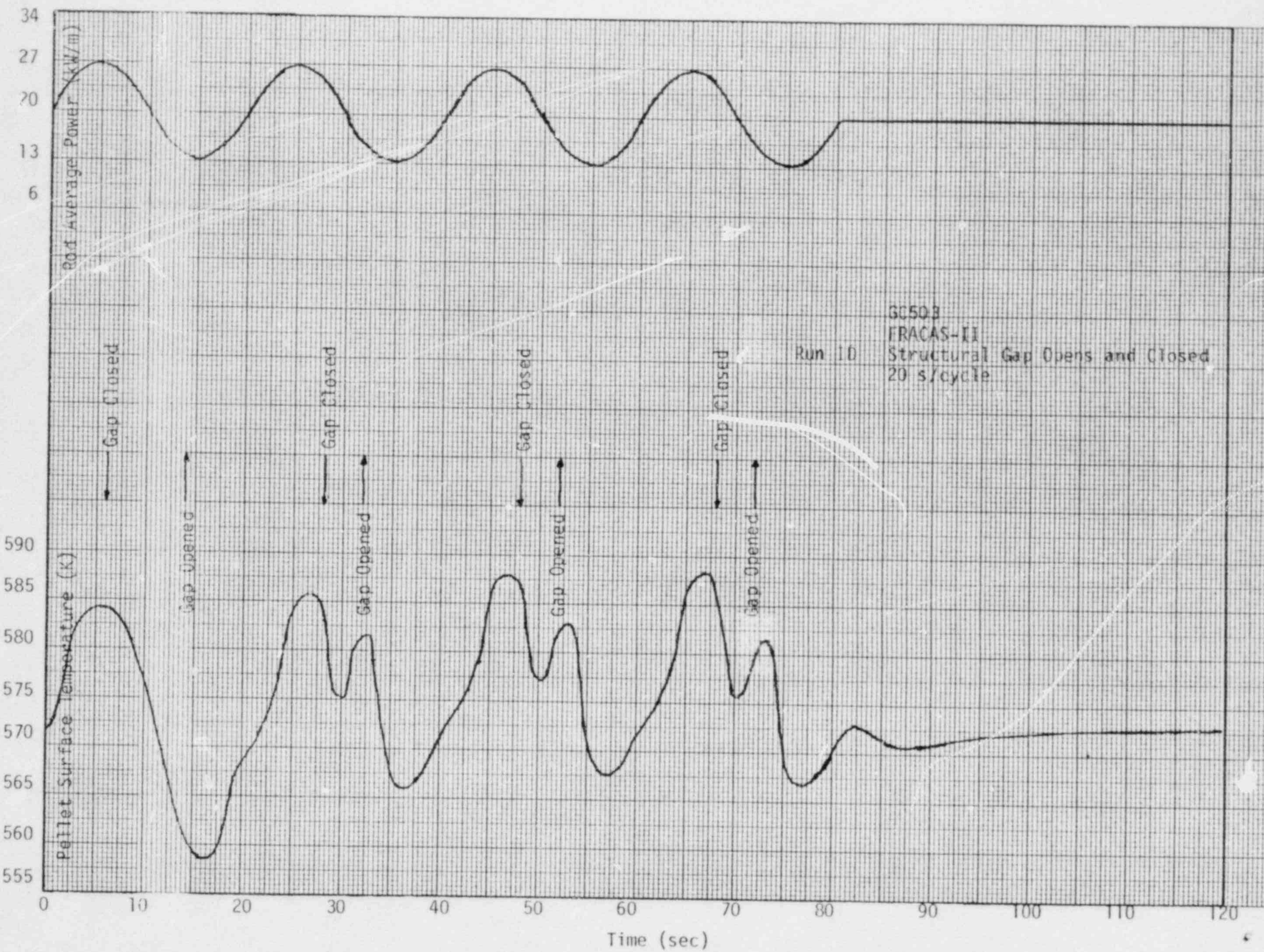

Figure 7. Pellet surface temperature versus time (FRACAS-II, low oscillation amplitude).

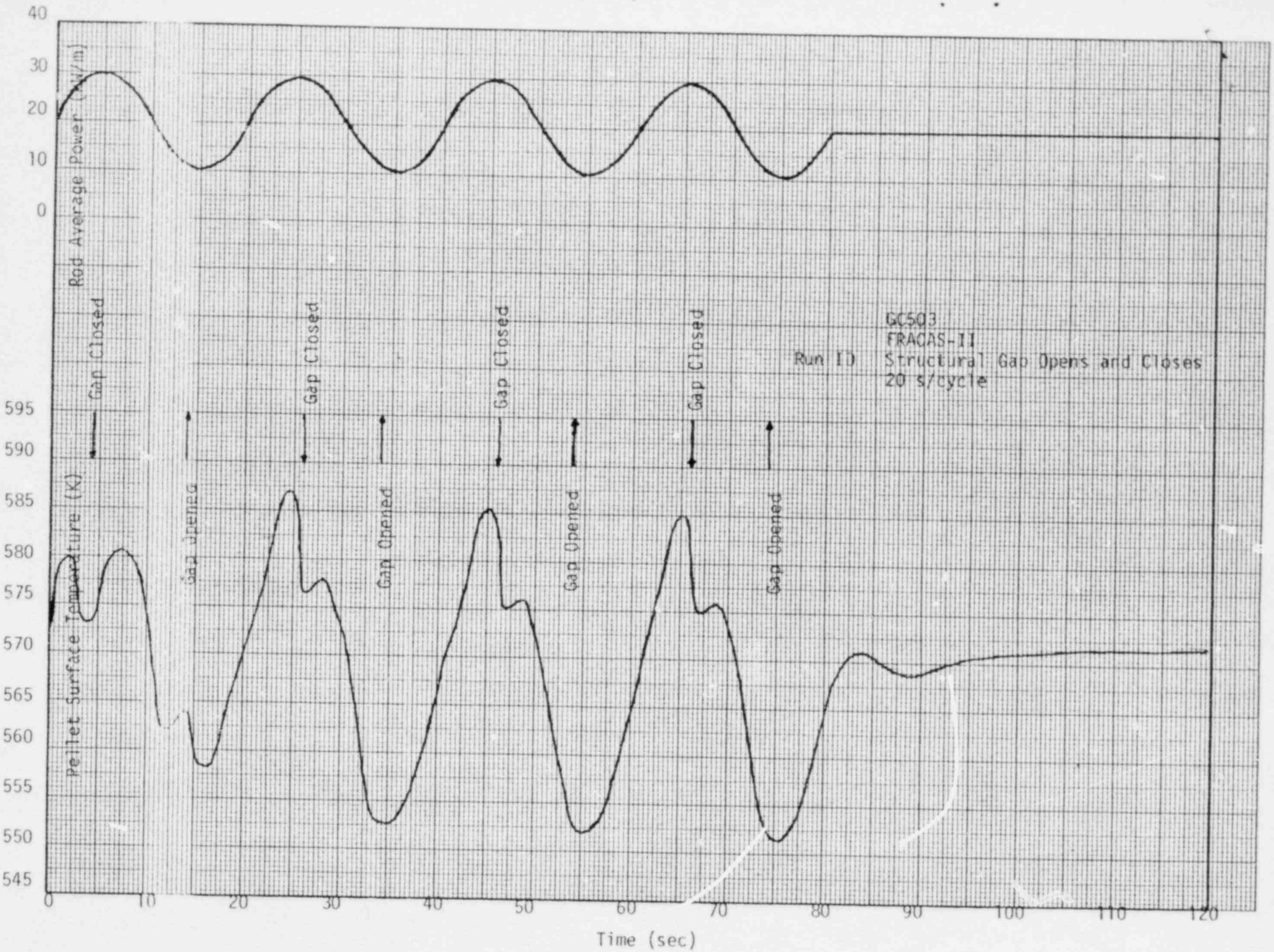

Figure 8. Pellet surface temperature versus time (FRACAS-II, high oscillation amplitude).

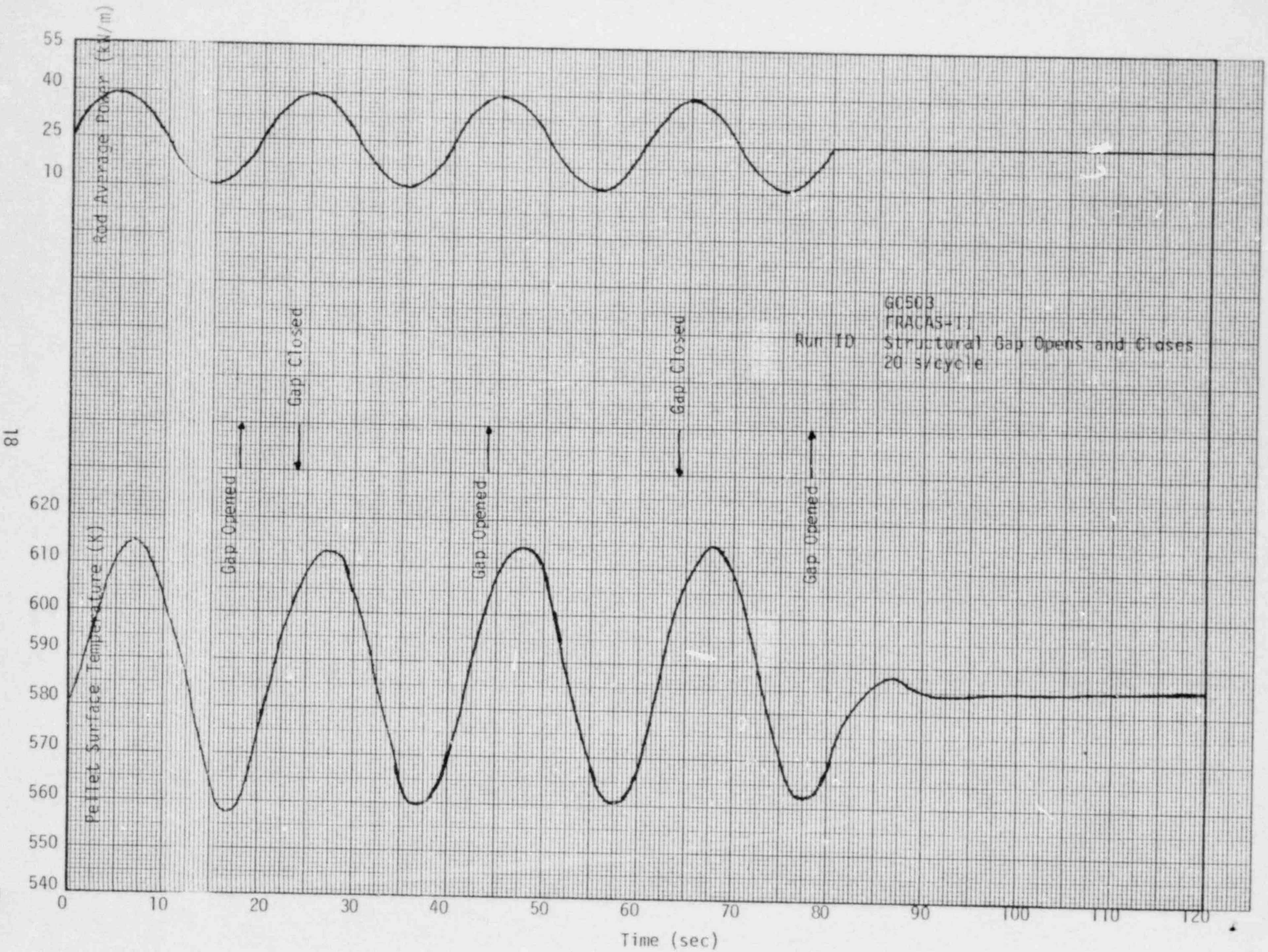

Figure 9. Pellet surface temperature versus time (FRACAS-II, high initial power).

In all of the analytical cases considered, wave shape changes were not observed at the off-center thermocouple location or the cladding surface temperature. However, wave shape changes were observed in the experiments at both the off-center and cladding surface thermocouple location.[5] This discrepancy may be due to the fact that in the experiment pellet fragments and chips near the pellet surface made contact with the off-center thermocouples when gap closure occurred. This may have resulted in increased conduction to the thermocouple and observed wave shape changes. Similarly, when the gap opened, the pellet fragments and chips moved away from the thermocouple which resulted in decreased conduction to the thermocouple and the observed wave shape changes. In other words, the movement of pellet chips and fragments near the thermocouple produced an effect on the off-center thermocouple similar to the predicted effect of pellet gap closure and opening on the calculated surface temperature. In the case of the cladding surface themocouple, it is postulated that in the experiment, the effect of the gap opening and closing either changed the effective thermocouple heat transfer area or the resistance between the cladding surface and the thermocouple. Therefore, there are physical mechanisms which occurred during the experiment that may have resulted in wave shape changes in the off-center and cladding surface thermocouple, which are not modeled in FRAP-T5. This probably explains why wave shape changes were not predicted at the off-center and cladding surface thermoucouple locations. However, different initial power levels, amplitude, frequency, fill gas, and gap widths which were not considered in this study may have resulted in wave shape changes being predicted at the off-center and cladding surface thermocouple locations.

VI. CONCLUSIONS AND RECOMMENDATIONS

Using FRACAS-II, the steady state power at which structural gap closure was predicted was more comparable to the test rod power at which wave shape changes were observed than in the case of FRACAS-I. The FRACAS-II fuel deformation model relocates the fuel pellet for both thermal and structural calculations. The FRACAS-I fuel deformation model relocates the fuel pellet only for temperature calculations and the structural gap varies only as a function of thermal expansion. However, as shown in Reference 6, the steady state results indicated that FRACAS-II should be modified for soft gap closure (i.e. gap closure when cracks are still present in the fuel pellet) and that the predicted cladding response to gap closure should be between the FRACAS-II and FRACAS-I results. This transient study also indicates that the cladding response to gap closure should be between the FRACAS-II and FRACAS-I results, and probably closer to the FRACAS-II results.

The response of the normalized fuel centerline temperature, and hence, the fuel centerline temperature was predicted to be affected by decaying exponential terms, when the input power was a sinusoidal. This was observed in the FRAP-T5 predictions. The effect of the decaying exponential terms was also predicted to decrease with decreasing frequency. This was observed in the FRAP-T5 predictions in comparing the 20 s/cycle and 40 s/cycle results.

Both the predicted and observed phenomena of wave shape changes is related to the closing and opening of the pellet-cladding gap. The exact nature of the observed and predicted wave shape changes is principally affected by the initial power level, amplitude, frequency, fill gas, and gap size. That is, the time over which the gap is opened and closed. Also, the effect of the gap opening and closing is affected by the power time history (i.e., whether the power is increasing or decreasing when the gap opens or closes).

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