Active and Passive Safety Control Performance in Sub-critical, Accelerator-Driven Nuclear Reactors

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by

James E. Cahalan
Argonne National Laboratory
Reactor Analysis and Engineering Division
9700 South Cass Avenue
Argonne, Illinois 60439 USA
jecahalan@anl.gov

and

Marcus Eriksson
Royal Institute of Technology
Department of Nuclear and Reactor Physics
10691 Stockholm, Sweden
marcus@neutron.kth.se

Abstract

Traditional safety performance requirements for nuclear reactors have been developed for critical reactors, whose kinetics characteristics differ significantly from sub-critical, accelerator-driven nuclear reactors. In a critical nuclear reactor, relatively small amounts of reactivity (negative or positive) can produce large changes in the fission rate. In sub-critical reactors, the self-multiplication (k) decreases as the sub-criticality (1–k) increases, and the responsiveness to small reactivity changes decreases. This makes sub-critical nuclear reactors less responsive to positive reactivity insertions than critical reactors. Also, larger negative reactivity insertions are needed in sub-critical reactors to shut down the fission chain if the neutron source remains. This paper presents the results from a computational analysis of the safety performance of sub-critical, accelerator-driven nuclear reactors. Coupled kinetics and thermal-hydraulics models are used to quantify the effectiveness of traditional protection and control system designs in sub-critical reactors. The analyses also quantify the role of inherent, passive reactivity feedback mechanisms in sub-critical reactors. Computational results are used to develop conclusions regarding the most favorable and effective means for reactor control and protection in sub-critical, accelerator-driven nuclear reactors.

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Introduction

Accelerator-driven sub-critical nuclear reactor designs are being considered for transmutation of long-lived radioactive nuclides produced in commercial nuclear power reactors during operation and discharged with the spent fuel. The objective of this transmutation process is to lessen spent fuel storage requirements by converting heavy radioactive nuclides, primarily plutonium and higher actinides, into lighter, shorter-lived nuclides. Plutonium will fission in conventional light water reactors, but the higher actinides have small thermal neutron fission cross sections, and are more efficiently destroyed in fast spectrum nuclear reactors.

Accepted safety design requirements for critical nuclear reactors dictate that the reactor shall be designed to have an inherent, prompt, negative reactivity feedback mechanism to counter any insertion of positive reactivity that makes the reactor supercritical. A supercritical reactivity excursion can raise the reactor power to a level that results in coolant boiling or fuel melting, and subsequently the potential for harm to the public by release of radioactivity. A prompt negative fuel temperature reactivity feedback is normally achieved by adjusting the fuel composition so that in increasing temperature transients, the effective capture cross section increase due to Doppler broadening of resonances dominates the increase of the fission cross section. For a feed stream of higher actinides, such an adjustment of the fuel composition may not be consistent with mission requirements, since the fertile nuclides that provide a negative Doppler feedback also transmute into heavy, long-lived nuclides.

Sub-critical nuclear reactor designs driven by a spallation neutron source targeted by a high-power proton accelerator have been proposed for transmutation of higher actinides. In these designs, the accelerator becomes the controller of the reactor neutron kinetics. The level of sub-criticality provides a margin for inadvertent positive reactivity insertions, compensating for the possible absence of a prompt negative Doppler effect. From a safety standpoint, a deeper level of sub-criticality provides a larger margin of safety for positive reactivity insertion. However, from an operational performance standpoint, a lesser level of sub-criticality provides greater reactor self-multiplication and a higher reactor power from a given neutron source strength. Therefore, the decision on the level of initial sub-criticality involves a trade-off and optimization among competing factors.

The potential reactor kinetics implications of the level of initial sub-criticality are illustrated in Fig.1. This figure shows the reactor power history, normalized to unity at the initial steady state, in response to insertion of an amount of reactivity corresponding to the effective fraction of delayed neutrons in a liquid sodium-cooled fast reactor operated at various levels of sub-criticality. (Criticality is measured by the ratio of the population of self-multiplication neutrons of a given generation to the population on the prior generation, exclusive of any source neutrons. In equilibrium, this ratio, called the effective multiplication factor “k”, is unity and the multiplication process is self-sustaining. When k is unity, the reactor is critical. If k is less than unity, the chain reaction will die away without an external source of neutrons, and the reactor is sub-critical). The reactivity is inserted as a linear ramp beginning at 50 s and terminating at 150 s, and all reactivity feedbacks have been neglected. For the initially critical reactor and the design with the smallest sub-criticality (k = 0.999), the reactor becomes supercritical during the reactivity insertion and the power rises exponentially to a level that raises the coolant temperature to coolant boiling, where the simulation was ended. However, for the higher levels of sub-criticality (k = 0.99 and k = 0.98), the reactor remains sub-critical, and the power increase stops when the reactivity insertion ceases.

The results shown in Fig. 1 illustrate the safety advantage of sub-critical operation in response to reactivity insertion when the level of sub-criticality is greater than the amount of inserted reactivity. Based solely on safety goals, it would seem desirable to make the initial sub-criticality as large as possible, i.e. to make the initial multiplication factor, k, as small as possible. However, the numerous and complicated factors determining the optimal level of sub-criticality can not be summarized in a single analysis. There are multiple considerations that impact control and protection systems design choices, operating conditions and procedures, and ultimate safety margins. Some of the reactor kinetics aspects involved in the design decision process will be explored and discussed in this paper.

Shutdown System Design

One of the issues under discussion in the area of safety design features concerns the role of control rods for power shutdown. In nuclear reactors, it is customary to include special-purpose shutdown control rods for emergency power shutdown. Current regulatory standards require two independent and diverse shutdown systems, each capable of stopping the fission process in the event the other system fails. These control rods contain a material that is a strong absorber of neutrons, typically boron. Strong neutron absorption interrupts the chain reaction process, which dies away completely with time if the multiplication factor from one generation of neutrons to the next becomes less than unity. The stronger the inserted neutron poison, the greater the multiplication factor is degraded, and the faster the fission power decays.

In a sub-critical, source-driven reactor, the primary emergency power shutdown system will likely be a trip, interruption, or diversion of the beam, thus terminating the source neutrons and extinguishing the fission process. Shutdown absorber control rods have been proposed for the second, independent shutdown system. In a sub-critical reactor, the relative poisoning strength of a given mass of neutron absorber is determined by the degree of initial sub-criticality, as measured by how fast and how far that amount of absorber will reduce the fission power. As the initial sub-criticality becomes larger, the relative importance of self-multiplication decreases, and the relative importance of the source increases. Because the absorber shutdown system functions by interrupting the chain reaction process, the effectiveness of a given amount of absorber material decreases as the initial sub-criticality increases. This performance characteristic is illustrated in Figs. 2 through 5.

Figures 2 through 5 contain results from reactor kinetics simulations of a nuclear reactor operated in sub-critical mode at three different levels of sub-criticality, and also as a critical system. The calculations reported in Figs. 2 through 5 show the kinetic behavior resulting from insertion of differing amounts of neutron absorber material into a reactor operating with k = 0.98, 0.99, 0.999, and 1.0, respectively. In these calculations, the amount of neutron absorbing material is measured in terms of a unit of reactivity corresponding to the effective fraction of delayed neutrons. In the reactor considered here, the effective delayed neutron fraction is 0.002, and this amount of reactivity is one dollar (1$) of reactivity.

Figure 2 shows the kinetic behavior of the reactor with k = 0.98. At the initial steady state, the reactor is operating with an external source of neutrons that just balances the sub-critical reactivity state to yield an equilibrium neutron population from one generation to the next. At 5 s, different amounts of absorber material are instantaneously inserted, and the curves in the figure show the time history of the reactor power following the negative reactivity insertions. For comparison, the fraction of the reactor power coming from decay of fission products, called decay heat, is also shown. Energy from fission product decay will appear following shutdown regardless of continuing fission energy, and is a thus measure of the effectiveness of shutdown. Figure 2 indicates that several hundred dollars of negative reactivity are necessary to bring a sub-critical reactor with k = 0.98 from normal power to near decay heat power if the external neutron source continues to operate (i.e. failure of the primary shutdown system). For a critical reactor physicist, this is a very large amount of reactivity, since it is customary in critical reactor design to limit the amount of reactivity in any single control rod to one dollar. Such a limit is assumed in order to prevent the possibility of criticality on prompt neutrons alone following the inadvertent withdrawal of a single control rod. Imposing the same requirement of making a diverging power excursion impossible in a sub-critical reactor would necessitate that no single control rod could bring the system to criticality with the source present.

Figure 3 shows the effect of decreasing the initial sub-criticality by increasing the initial k to 0.99. This tends to make a given amount of negative reactivity more effective in reducing the power. However, many tens of dollars of reactivity are required to bring the reactor power to near the decay heat level.

In Fig. 4, the initial k has been raised to 0.999. The computed results show that power reduction to decay heat in this case can be achieved rapidly with a few tens of dollars of control material at this level of sub-criticality. For the sake of reference, the behavior of a critical system (initial k = 1.0), is shown in Fig. 5. In terms of minimizing the amount of reactivity needed for shutdown, the critical system is optimal, with a requirement of about ten dollars or less, depending on other factors such as the capacity of the post-shutdown heat removal system.

The results shown in Figs. 2 through 5 indicate that designing a reactivity-based shutdown system in a sub-critical reactor involves a trade-off between the initial sub-criticality and the amount of reactivity needed for shutdown. There are physically-based limits on both of these quantities. First, the permissible level of initial sub-criticality is based on the conceptual principle and requirements associated with the goal of sub-critical reactor operation, namely, to avoid the possibility of supercritical reactor kinetics for accidental positive reactivity additions. The level of initial sub-criticality is set by the safety requirement for the magnitude of the positive reactivity addition that must be accommodated before supercriticality results. Also, the sub-criticality level is determined considering accelerator performance and the strength of the neutron source. Deeply sub-critical operation requires a significant increase in accelerator capability to supply the neutron source needed to overcome the associated degradation of self-multiplication. In addition, the level of initial sub-criticality can not be reduced beyond the threshold established by the achievable performance of instrumentation and control systems in normal operation. Second, the total amount of shutdown reactivity is limited by the allowable reactivity in each control rod, and the practical limit on the number of control rods. The allowable reactivity per rod is based on an accepted industry design principle based on making supercriticality impossible given the inadvertent withdrawal of a single shutdown control rod. The upper physical limit on a single rod's reactivity worth is set by the amount of control material that can be contained in the volume allocated to one control rod. The practical limit on the number of control rods is set by the reactor geometry and by the number of locations available for control assemblies. In addition, there is an economic incentive to reduce the number of costly, safety-grade control rod assemblies.

In summary, there are significant challenges facing the reactor designer in arriving at a satisfactory shutdown control system employing absorber control rods in an accelerator-driven sub-critical nuclear reactor. For sub-criticality levels that meet conceptual goals and performance requirements in normal operation, the amount of negative reactivity required for power shutdown may be very large, and may exceed realistic physical limits.

Startup System Design

In the preceding section, the role of control rods for emergency shutdown was considered, and it was shown that very large control reactivity requirements exist for shutdown to decay heat levels for source-driven sub-critical systems. However, the same results show that much smaller amounts of reactivity can change power levels substantially. For example, Fig. 2 shows that for the system with $k = 0.98$, only 10$ of negative reactivity are required to reduce the power to near half its initial value. Starting from the reduced power level, the same amount of positive reactivity would bring the reactor to full power. This indicates that conventional control rods could be used for power maneuvering required for burnup compensation and load changes, possibly including startup operations.

Existing sodium-cooled reactor design and operating procedures provide guidance on power maneuvering and startup system requirements. In normal startup and shutdown operations in a liquid-metal cooled reactor, the rate of coolant temperature change is limited to control temperature gradients in structural members and the resulting internal stresses. (The impact of beam reliability on coolant system design is addressed in Ref.

1). In the Experimental Breeder Reactor-II (EBR-II) reactor startup procedure [2], bulk sodium temperature changes in the tank are limited to 10^{o}F (~5.6^{o}C) per hour. The Fast Flux Test Facility (FFTF) startup procedure [3] limits coolant hot leg temperature changes to 50^{o}F (~28^{o}C) per hour. These limits have been established in a design process considering not only structural member strength requirements, but also the features and capabilities of the primary coolant pump control system and the reactor power control system. Both EBR-II and FFTF have conventional centrifugal pumps driven with electric motors in the primary coolant system. Both EBR-II and FFTF employ conventional moveable control rods for power maneuvering. EBR-II control rods contain fuel, and FFTF control rods contain absorber material. Although these designs and performance requirements are strictly relevant only to their original application, they do indicate general ranges for realistically achievable control rod speed of motion and reactivity worth characteristics.

Based on the apparent reactivity requirements for power maneuvering and experience with sodium-cooled reactor design and operation, it seems likely that conventional control rods could be used for power regulation in sub-critical reactor operation. In addition, the apparent rate of reactivity change required seems to be achievable with conventional control rod drive mechanisms.

Unprotected Reactivity Insertion Accident Response

In design basis accident sequences, the reactor protection system functions and the accident sequence terminates without damage to the plant or danger to the public. In liquid metal-cooled fast reactor safety assessments, it is customary to consider the consequences of protection system failure as a test of containment capability and a measure of safety margin beyond the design basis. For the accelerator-driven sub-critical reactor design, one such beyond design basis scenario considers the system response to an inadvertent positive reactivity insertion with failure of the reactor scram system. In such a sequence, the system response is determined by the thermal, hydraulic, mechanical, and neutronic performance characteristics of the plant in off-normal operating conditions.

The sub-critical reactor design considered here is based on the design analyzed in Ref. 4. The design consists of a metallic-fueled, liquid-sodium-cooled, fast sub-critical reactor with a nominal operating power of 840 MWt. The coolant system configuration is taken to be typical for a pool-type primary system. For the purpose of the analyses reported here, the reactor was assumed to have reactivity feedbacks from changes in 1) fuel temperature, 2) coolant temperature, and 3) structural temperature.

The fuel temperature reactivity feedback was assumed to be associated with the Doppler effect. The value of the Doppler coefficient, T dk/dT, was treated parametrically by assuming values of -0.0005 and -0.00005 to cover the range typical for fuel compositions with a small but negative Doppler effect.

The coolant temperature reactivity feedback was assumed to be associated with the change in coolant density. The value of the coolant density feedback coefficient was assumed to have values corresponding to full coolant voiding reactivity worths of -3$ and +3$ to cover the range typical for a small, high leakage, sodium cooled fast reactor.

The structural temperature reactivity feedback was assumed to be associated with radial core expansion associated with thermal expansion of the above-core subassembly load pads. As in the FFTF core restraint design, thermal expansion of these load pads tends to spread the core apart and introduce negative reactivity. For the analyses report here, a single radial core expansion reactivity coefficient of -0.0016 $/K was assumed.

The positive reactivity insertion assumed in these analyses was 1$ ($\Delta k = 0.002$) at a rate of 0.01 $/s beginning at 50 s of transient time. The results for the case of no reactivity feedback for various initially sub-critical effective multiplication factors are shown in Fig. 6. For the highest value of k (0.9995), the reactivity insertion takes the reactor supercritical, and the power increases until the coolant heats to the boiling point. For the other sub-criticality levels, the reactivity insertion leaves the reactor sub-critical, and the rapid power increase stops with the end of the reactivity insertion. Because there are no reactivity feedbacks, the power continues to slowly approach an asymptotic maximum value with a time constant determined by the combined effects of the buildup and decay of the delayed neutron precursors and of the nuclides contributing to gamma heating.

Figure 7 presents the results for the reactivity insertion with the most unfavorable combination of assumed reactivity feedbacks: a positive coolant void worth of +3$, the small Doppler coefficient of -0.00005 $/K, and the nominal radial core expansion feedback. The reactivity feedbacks are not sufficient to prevent supercriticality for the high multiplication case. The remaining cases stay sub-critical, and in the long term the power slowly approaches an asymptotic minimum value.

In the next Fig. 8, results are presented for the larger Doppler coefficient and the positive coolant void worth. The results are only slightly different from the results in Fig. 7, indicating that even the larger Doppler coefficient considered here is so small that it has little effect.

Lastly, Fig. 9 presents results for the larger Doppler coefficient and the negative coolant void worth of -3$. As the plotted curves show, the change in coolant void worth feedback limits the net reactivity sufficiently to prevent coolant boiling in the highest multiplication case ($k = 0.9995$). In fact, in this case the negative reactivity feedbacks are sufficiently strong to take the system sub-critical again once the reactivity insertion stops, and the reactor power decreases afterward.

The results of this parametric analysis of the unprotected reactivity insertion accident sequence indicate that passive reactivity feedbacks can provide beneficial protection against progression into severe accident conditions (coolant boiling, fuel melting), even in sequences in which the reactor is temporarily supercritical. However, it is clear that the most significant factor in preventing supercritical transients is the level of initial sub-criticality compared to the reactivity insertion.

Unprotected Beam Excursion Accident Response

Accelerator driven system designs have been proposed in which the power decrease associated with fuel burnup over one reloading cycle is compensated by increasing the beam strength. This implies a beam control system capable of regulating the beam intensity, and brings into question the reactor response to combined beam control and protection system failures. To study this accident sequence, the same initial conditions and parametric reactivity feedback variations employed in the previous (unprotected reactivity insertion) section were assumed for a beam increase to 180% of the initial value. It should be noted that such a transient will not progress into coolant boiling conditions for the design studied, since a power increase to at least 400% must occur to raise the coolant to the boiling point in a liquid-sodium cooled reactor.

Figure 10 shows the results for the case of a beam increase to 180 % at 50 s with no reactivity feedbacks for various levels of sub-criticality. Recall that the higher the self multiplication (the larger values of k), the greater the fraction of neutrons from fission, and the less the fraction of neutrons from the source. Hence, for the same reactor power the neutron source is smaller for the higher self multiplication cases. In Fig. 10, this contributes to the slow response of the near-critical case (k = 0.9995), since for this case the source is very small and the time constant for adjustment to the asymptotic condition is very long. On the other hand, for the highly sub-critical cases, the source constitutes a larger fraction of the total neutron population, the system time constant is shorter, and the step increase in the source more immediately brings the power near the asymptotic value.

Figure 11 presents the results for the beam excursion with most unfavorable assumed reactivity feedbacks: a positive coolant void worth of +3$, the small Doppler coefficient of -0.00005 $/K, and the nominal radial core expansion feedback. Compared to Fig. 10, the moderating influence of the reactivity feedbacks is evident, especially for the near-critical case (k = 0.9995).

Figure 12 presents the results for a positive coolant void worth and the larger Doppler coefficient. The additional negative feedback provides a small increment in retarding the power increase compared to Fig. 11, with the most significant effect in the near-critical case.

Figure 13 shows the results for a negative coolant void worth of -3$ and the larger Doppler coefficient. Compared to Fig. 12, the additional negative coolant feedback reactivity provides further reduction in the peak transient power.

The results for the parametric analysis of an unprotected beam excursion accident sequence indicate that passive reactivity feedbacks will act to limit the overall transient power increase and to bring the reactor back into balance with the heat rejection level. The degree of limitation is more significant and timely for initial conditions that are nearer to critical, and the impact of the passive feedbacks decreases for cases that begin far from critical. This is to be expected, since the magnitude of the reactivity feedback is proportional to the temperature increase and limited by the magnitude of the temperature increase. A fixed amount of negative reactivity feedback will have less influence in limiting reactor power as the initial sub-criticality becomes larger, and the feedback reactivity becomes a smaller fraction of the net reactivity.

Conclusions

This paper presents discussions and analysis results concerning the safety characteristics of sodium-cooled, accelerator-driven, sub-critical fast reactors, with a focus on design features and their performance in normal operation and in accident sequences. Specific design features considered here include shutdown control rods and inherent reactivity feedbacks in unprotected accident sequences.

Reactor kinetics analyses of sub-critical reactors operating initially at various levels of sub-criticality show that such designs provide significant safety margin and protection against severe accident progression in reactivity insertion accident sequences, so long as the amount of inserted reactivity does not result in supercritical reactor conditions. The question then becomes the degree of initial sub-criticality, and this design choice is influenced by a number of safety, economic, and performance considerations.

Specific analyses of secondary shutdown reactivity requirements indicate that the amount of reactivity needed for initial sub-criticality levels around 1% or more may be so large that the use of control rods may be impractical. Hundreds of dollars of reactivity will be required to lower the reactor power to near decay heat levels if the beam continues to operate, and it may not be possible to find a poison material of sufficient strength and compactness. In contrast, the reactivity requirements for routine power maneuvering (i.e. burnup swing compensation, load following, or startup from stand-by) are relatively modest, in the neighborhood of a few tens of dollars, and control rods could be used for routine power maneuvers.

Parametric analyses of passive reactivity feedback effects in reactivity insertion without scram accident sequences indicate that such feedbacks can be effective in preventing supercritical transients and severe accident progression for some combinations of initial and feedback conditions. In general, the passive reactivity feedback effects are most effective for low sub-critical initial conditions (high k, near critical), in which the amount of reactivity coming from the passive feedbacks is significant compared to the initial sub-critical reactivity. However, the primary factor in preventing supercritical reactor kinetics remains the level of initial sub-criticality in comparison to the magnitude of inserted reactivity.

A study of passive reactivity effects in unprotected beam excursion accidents also quantifies the role of passive reactivity effects in limiting reactor power excursions and in reducing the reactor power after the beam excursion. Once again, the passive reactivity feedback effects are most effective for nearer-to-critical initial conditions, and less effective for highly sub-critical systems. For these later systems, the thermal margin provided by the sodium coolant, equivalent to more than 400% of the normal full power, prevents short-term severe accident progression.

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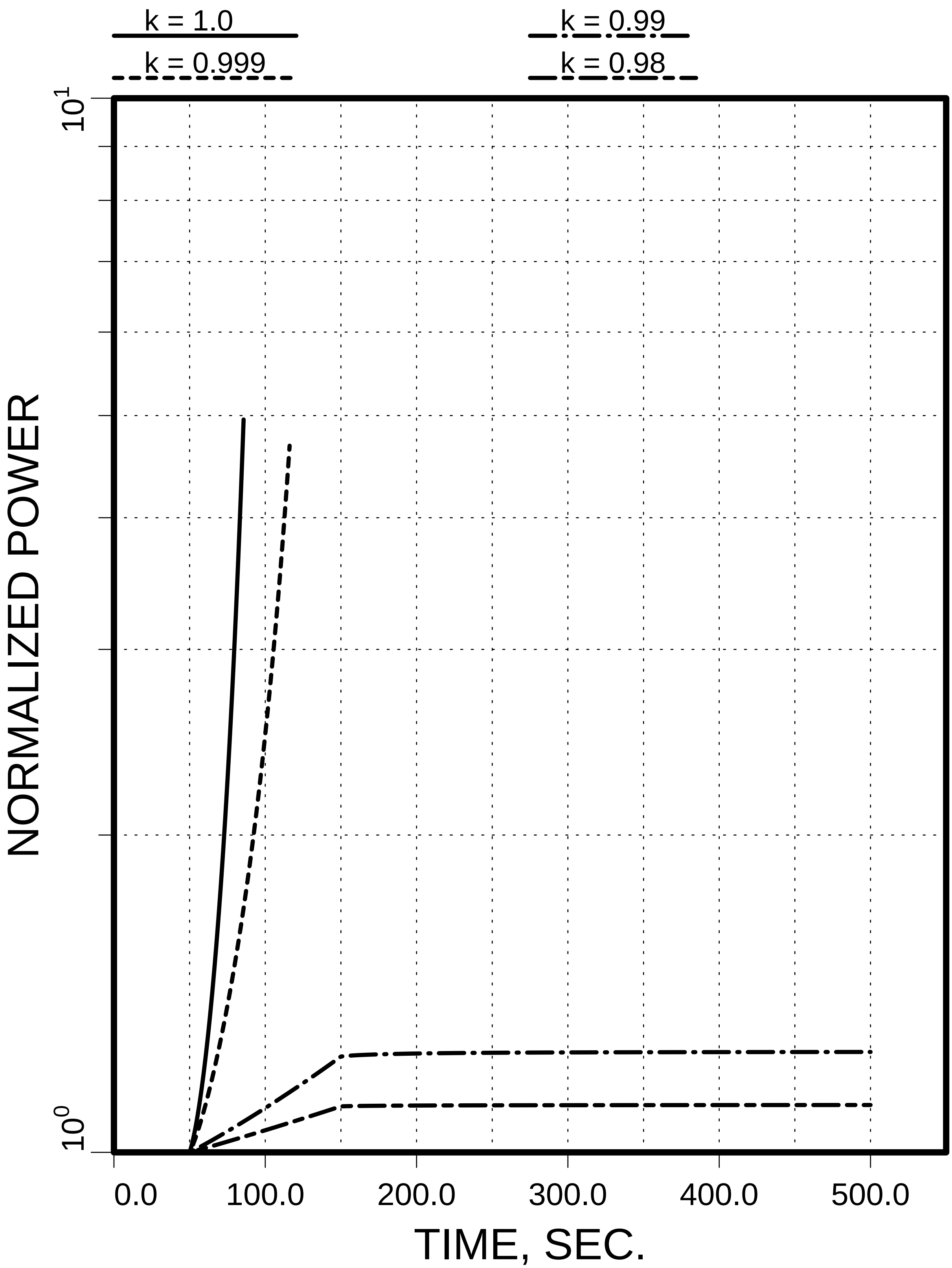

Fig. 1. Reactor Response to Reactivity Insertion for Various Multiplication Factors.

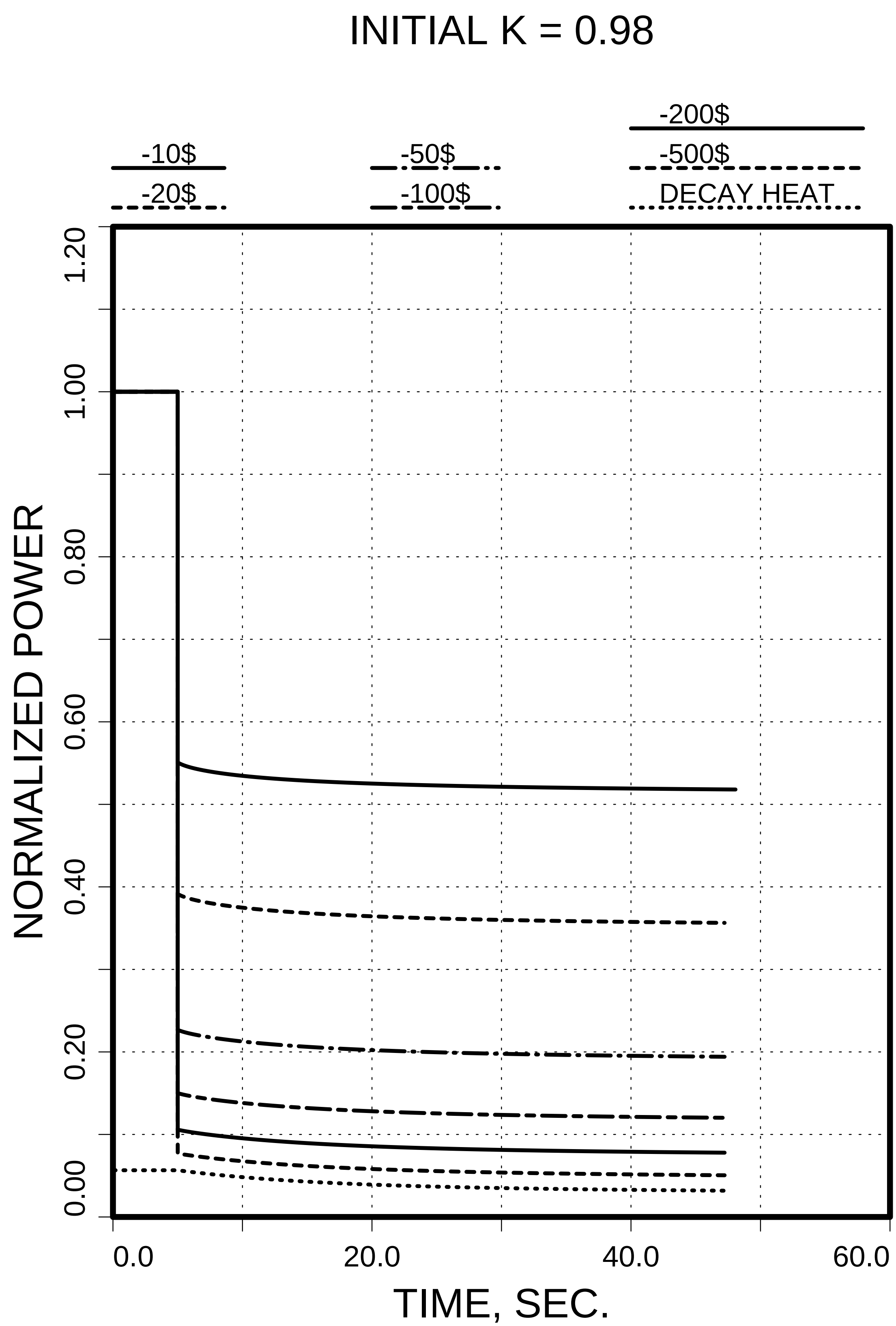

Fig. 2. Shutdown Reactor Kinetics Behavior for Initial k = 0.98.

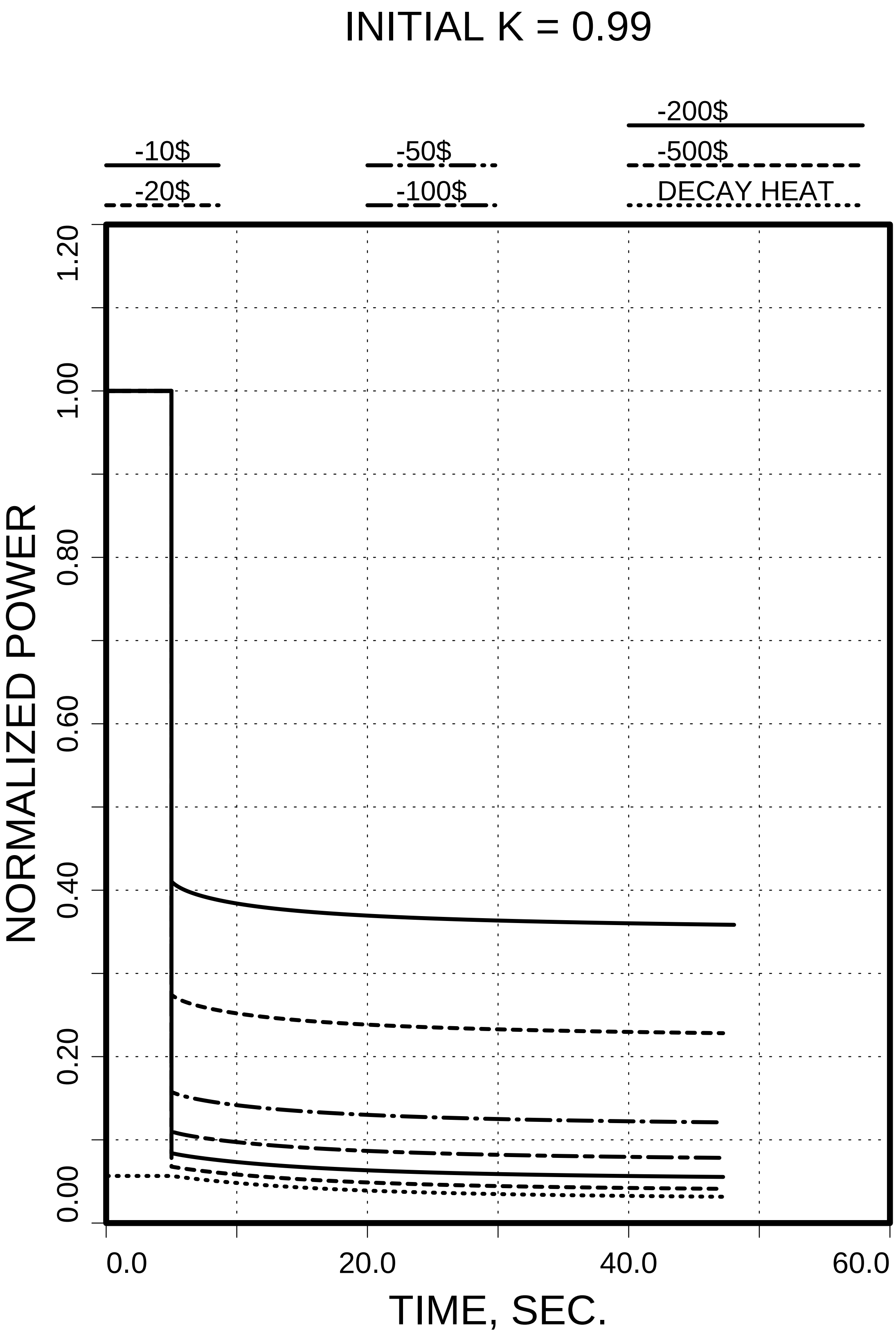

Fig. 3. Shutdown Reactor Kinetics Behavior for Initial k = 0.99.

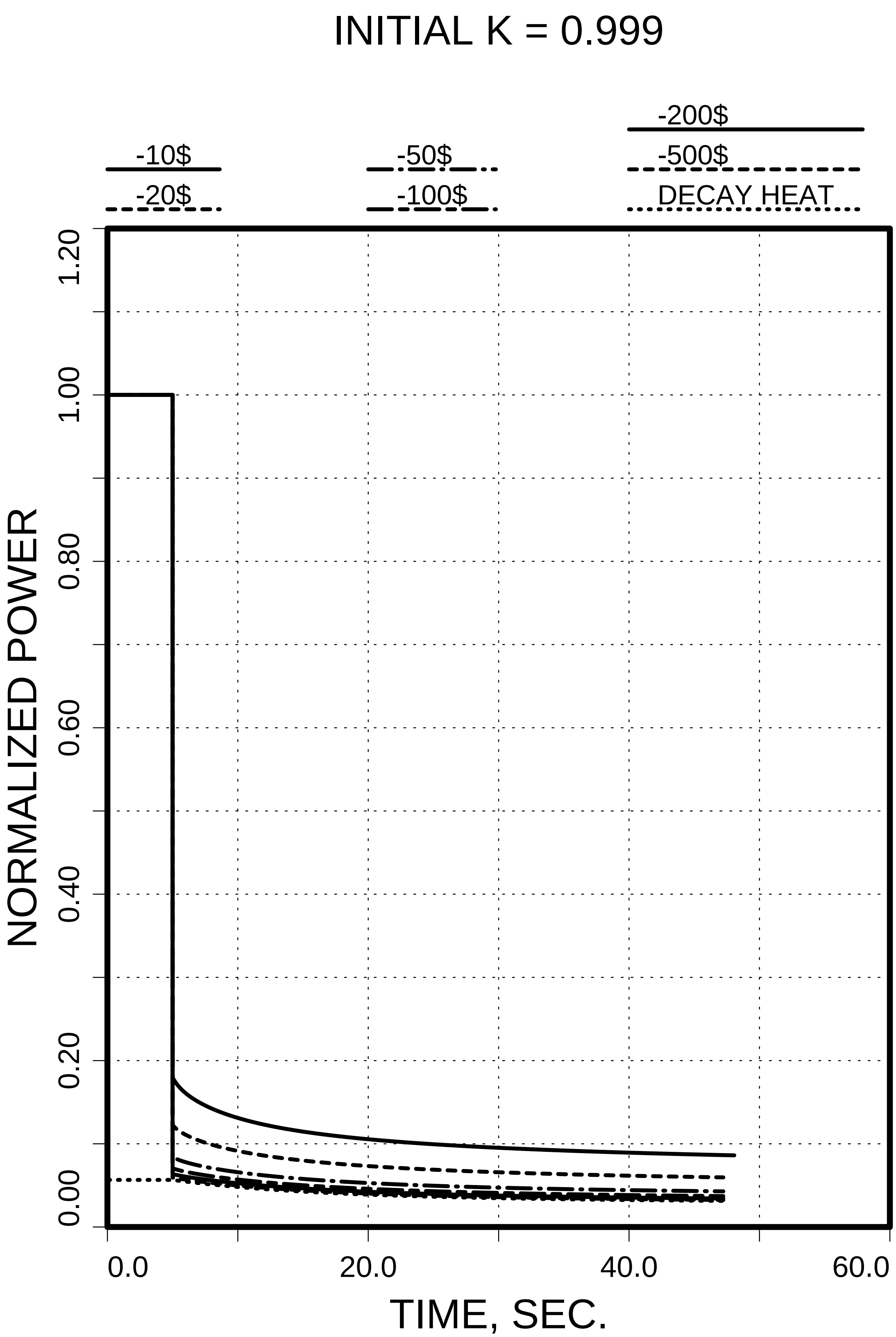

Fig. 4. Shutdown Reactor Kinetics Behavior for Initial k = 0.999.

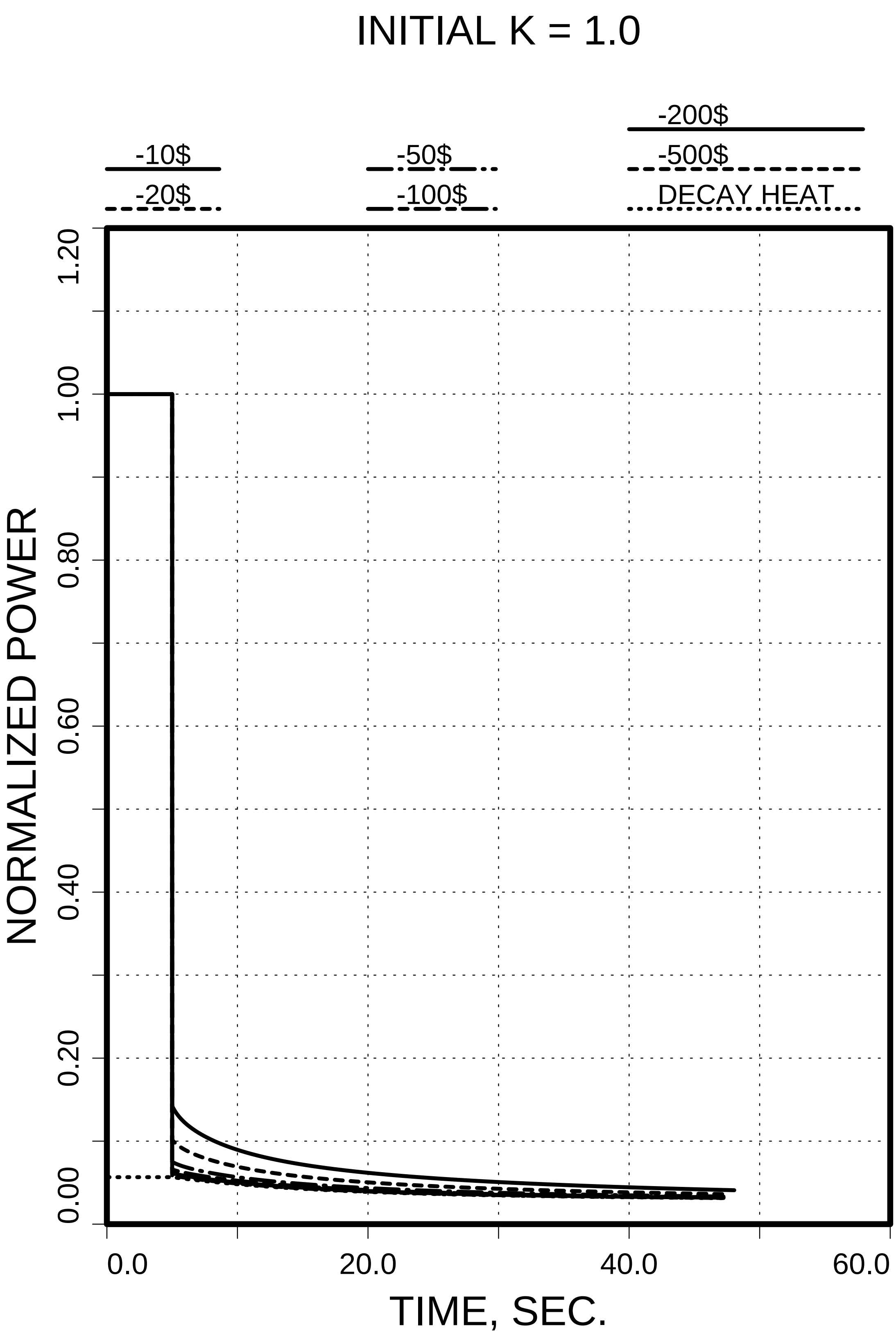

Fig. 5. Shutdown Reactor Kinetics Behavior for Initial k = 1.0.

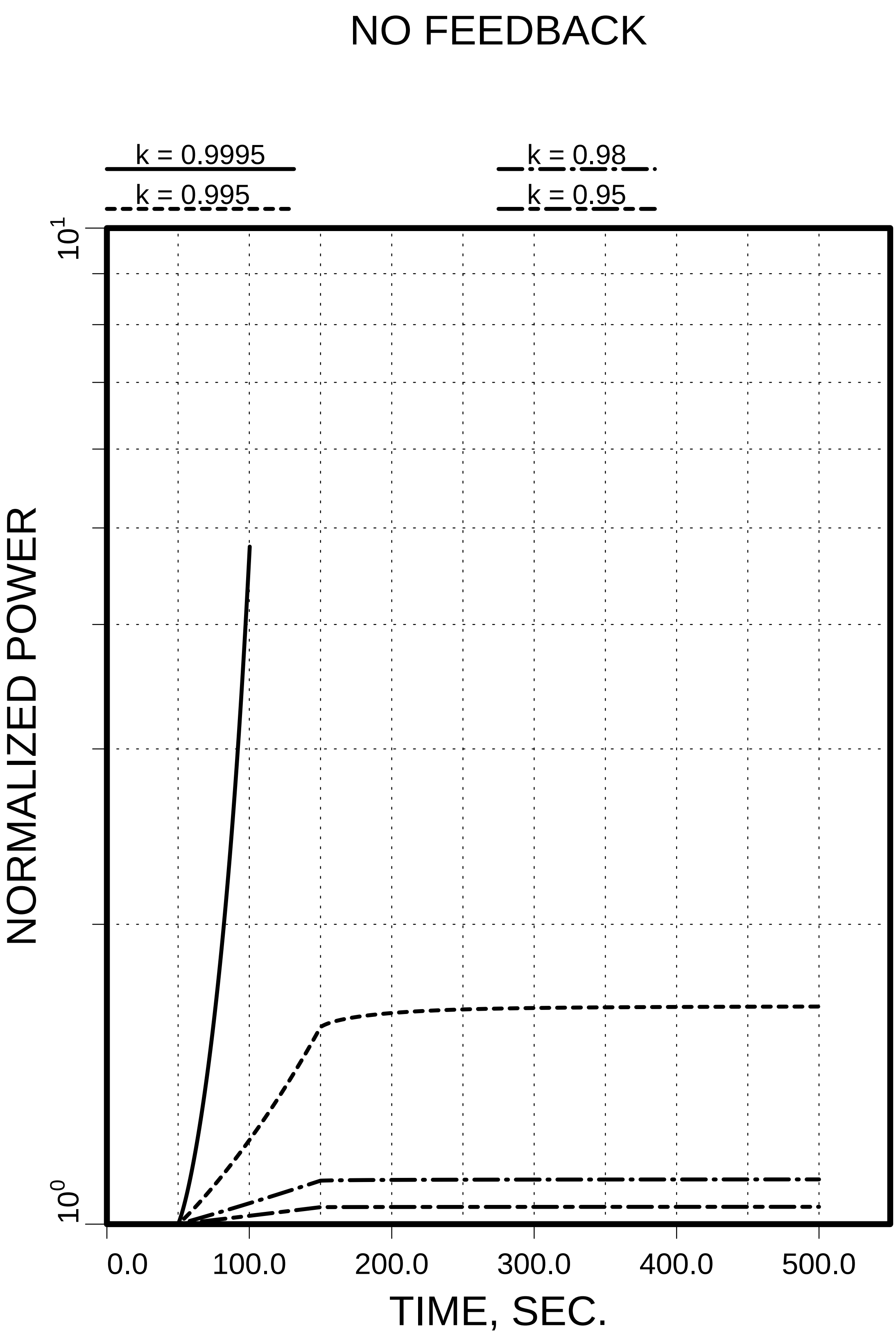

Fig. 6. Reactivity Insertion Analysis Results for No Feedbacks.

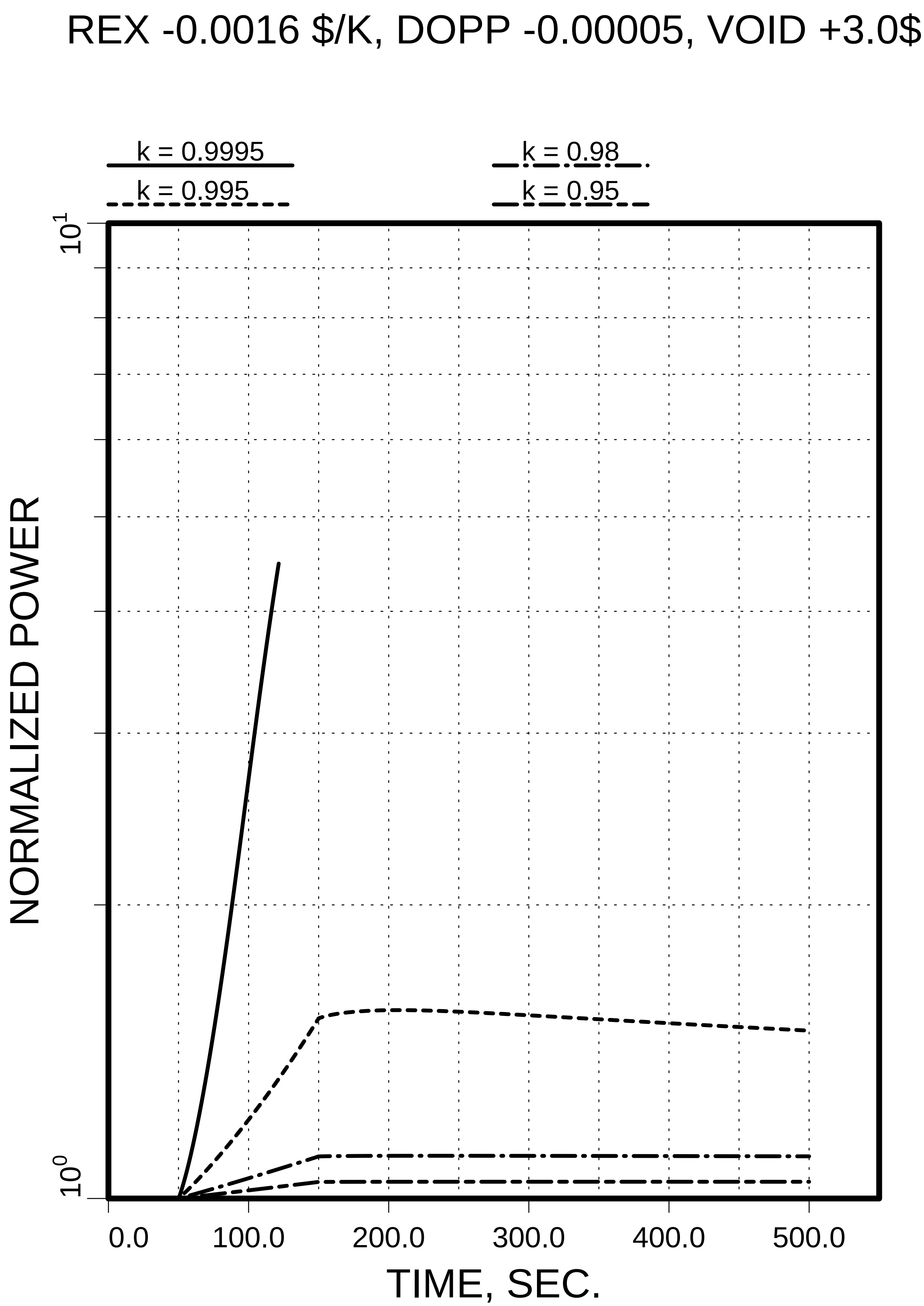

Fig. 7. Reactivity Insertion Analysis Results for Positive Void and Small Doppler.

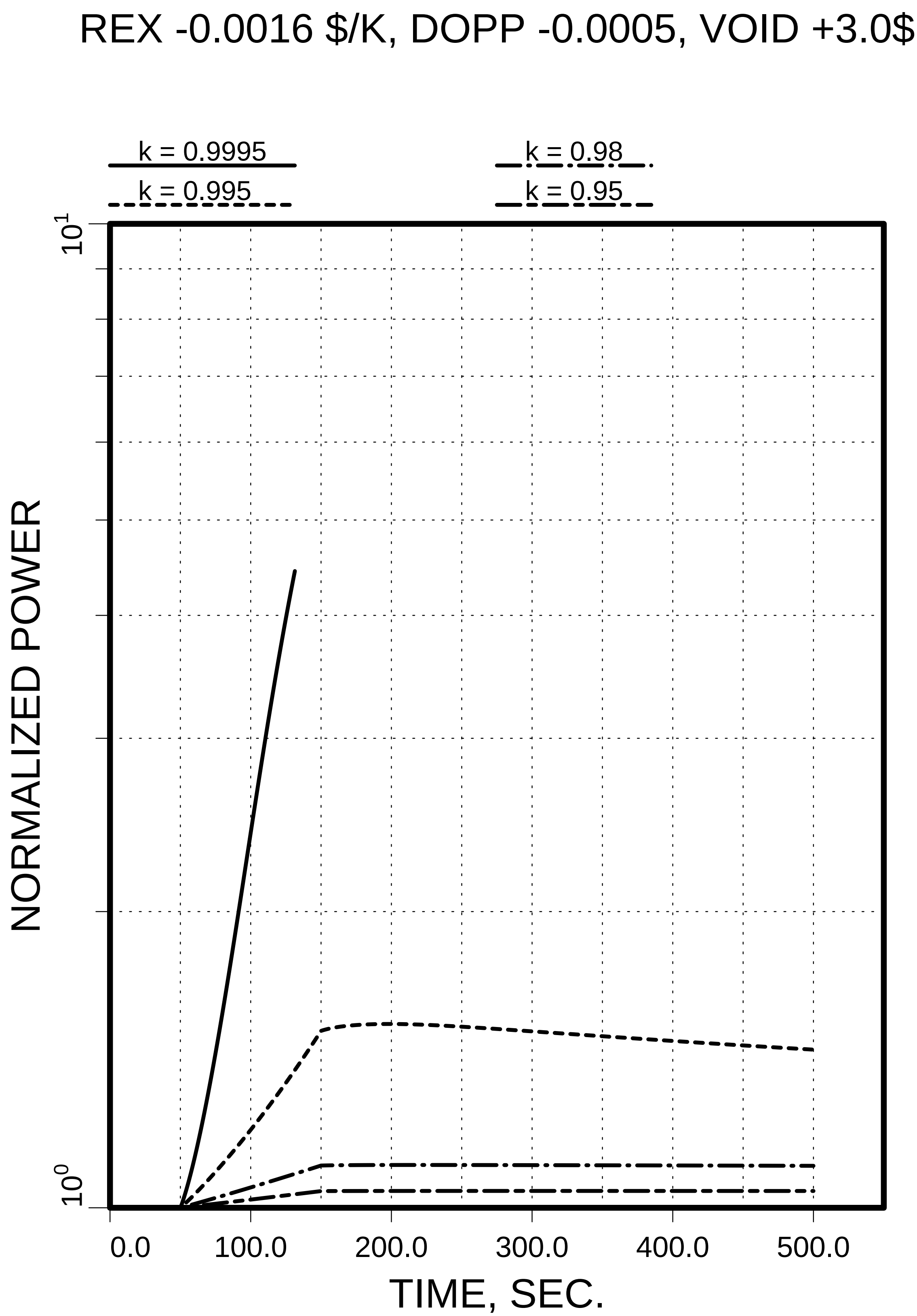

Fig. 8. Reactivity Insertion Analysis Results for Positive Void and Large Doppler.

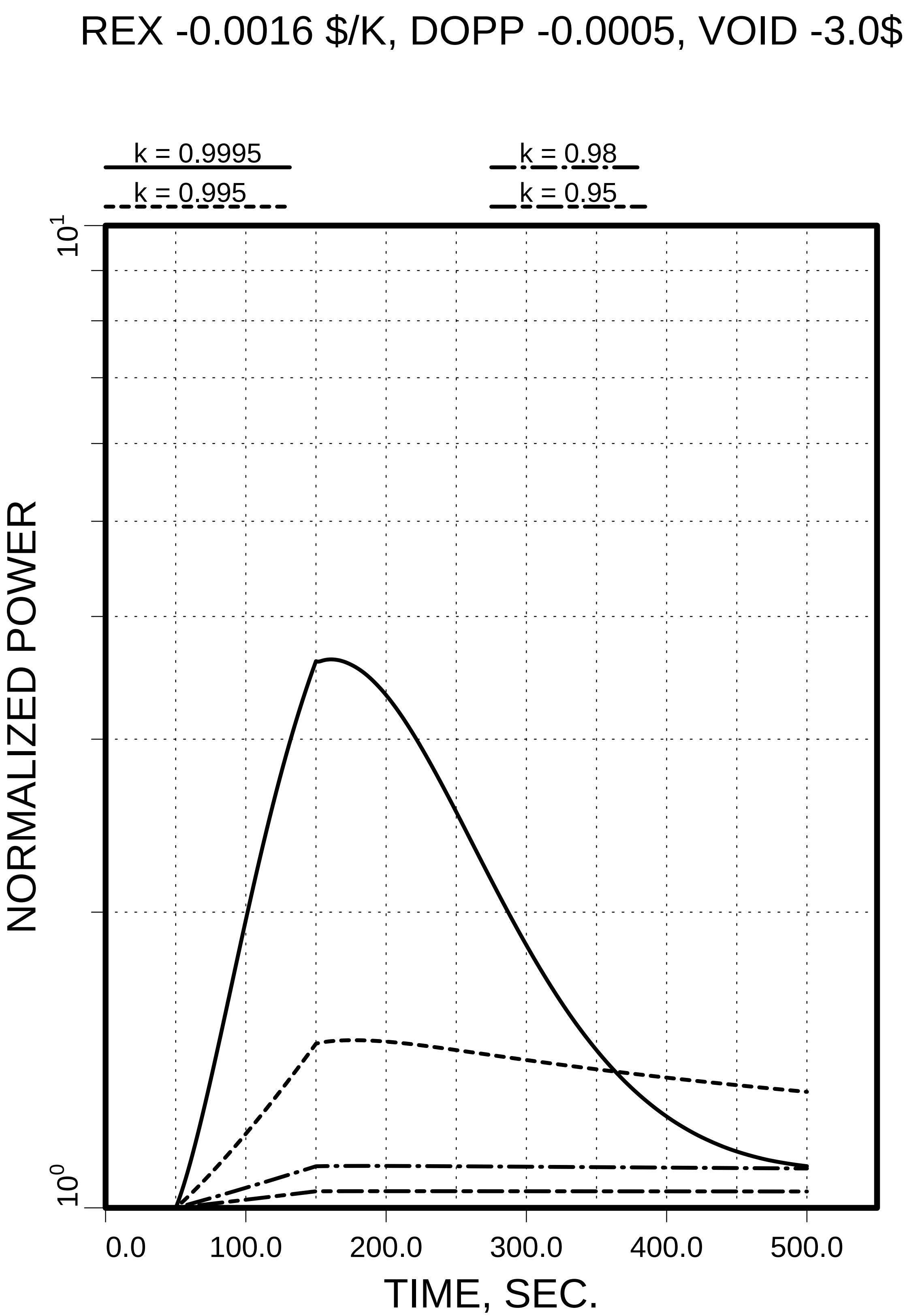

Fig. 9. Reactivity Insertion Analysis Results for Negative Void and Large Doppler.

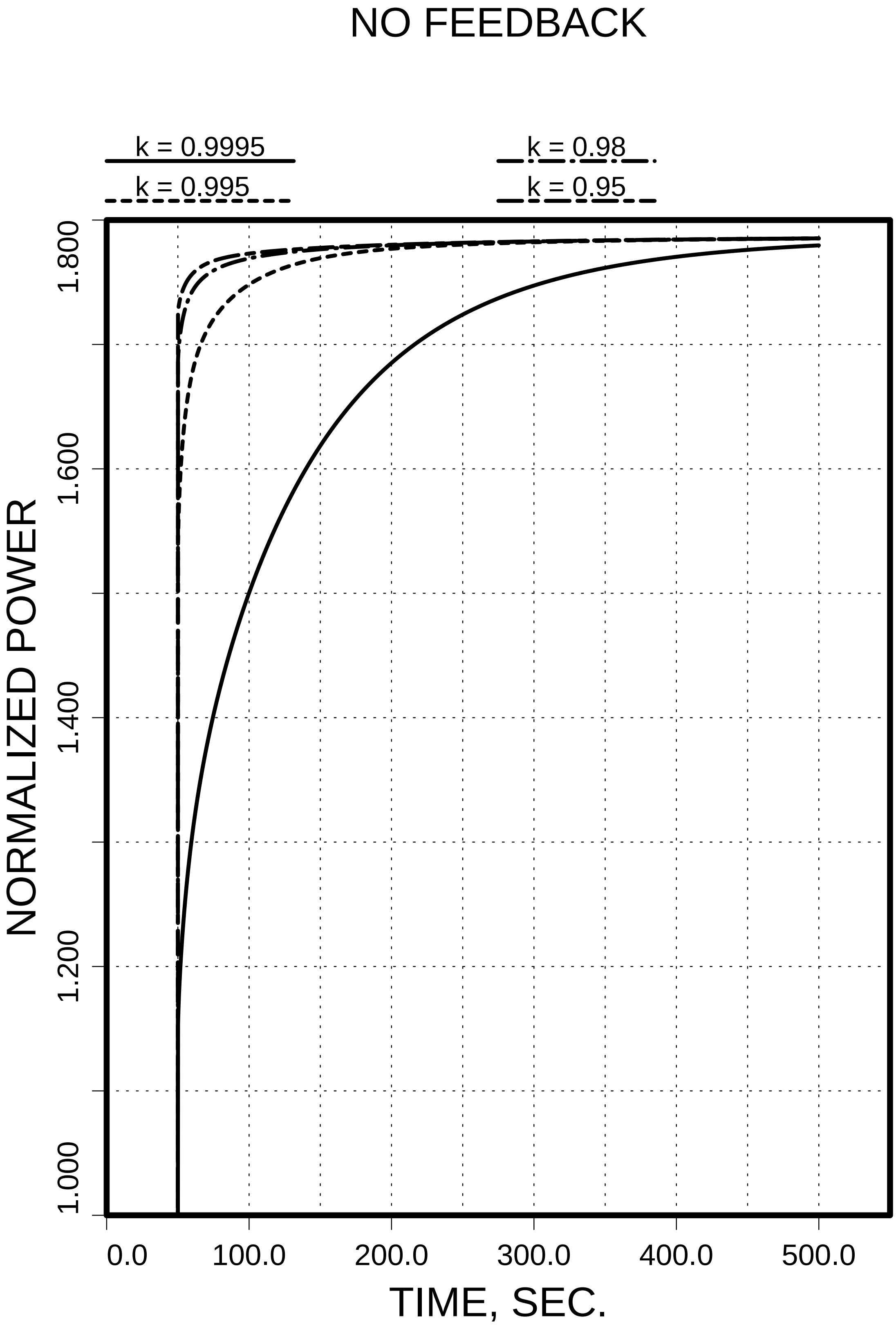

Fig. 10. Beam Excursion Analysis Results for No Feedbacks.

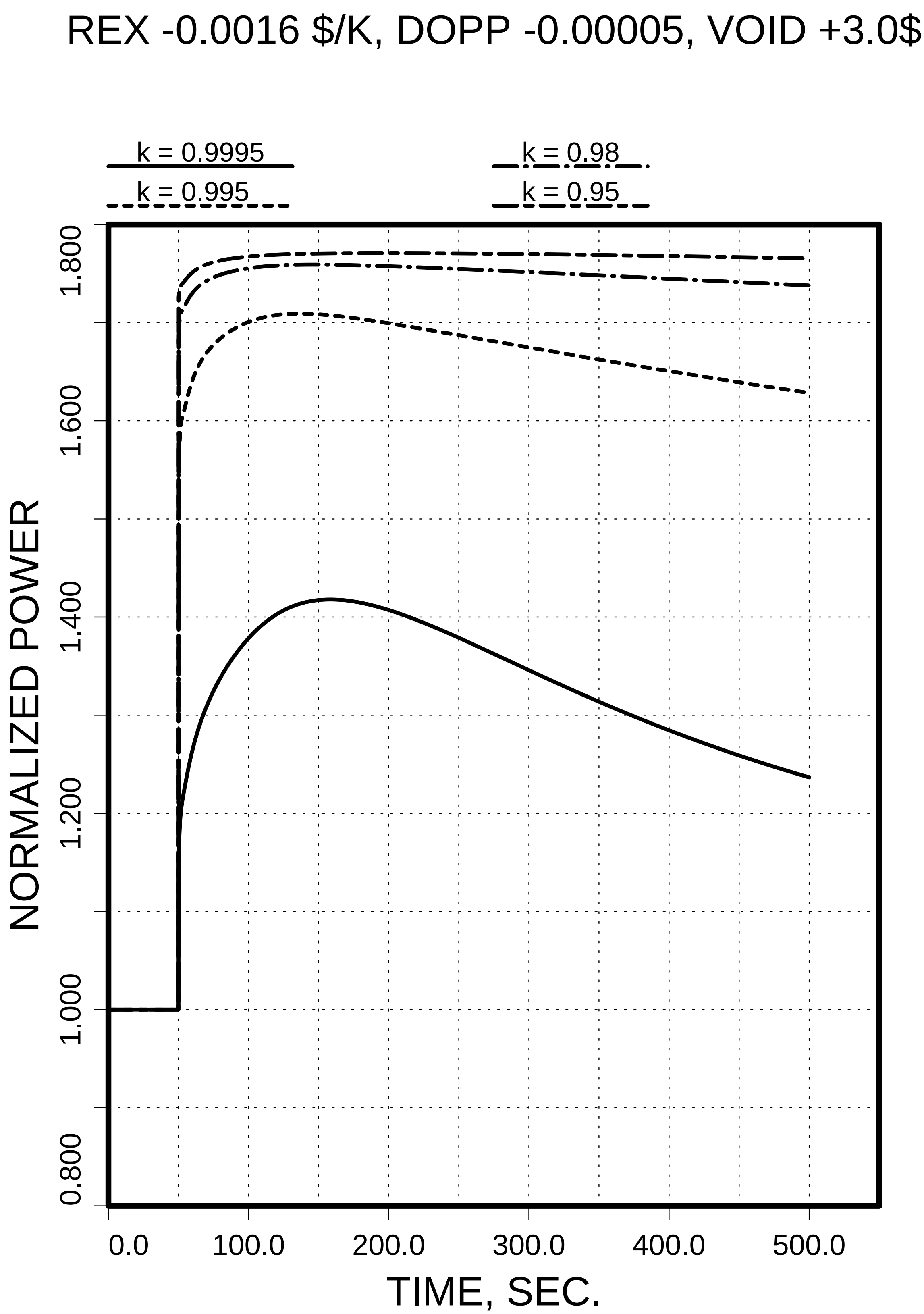

Fig. 11. Beam Excursion Analysis Results for Positive Void and Small Doppler.

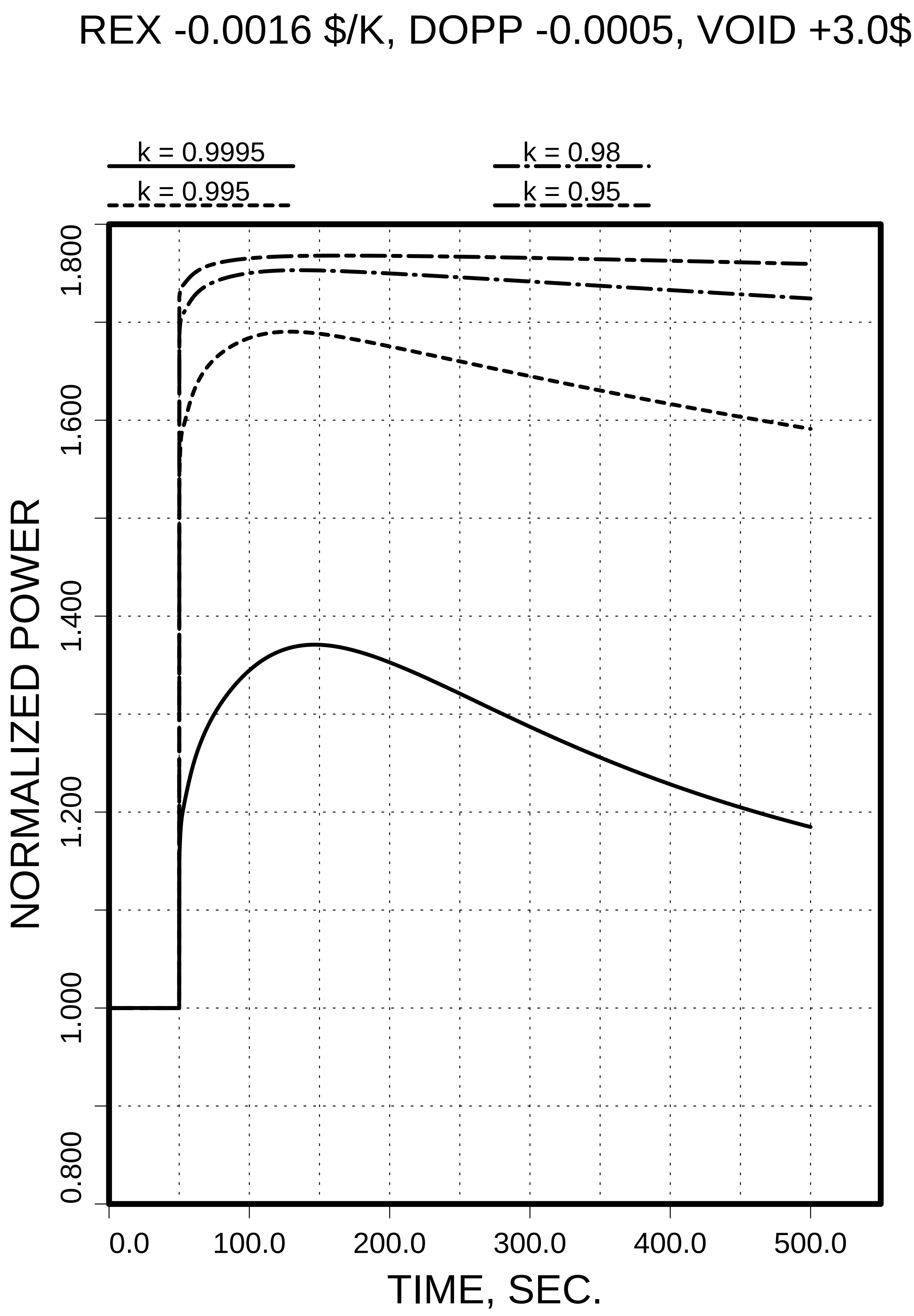

Fig. 12. Beam Excursion Analysis Results for Positive Void and Large Doppler.

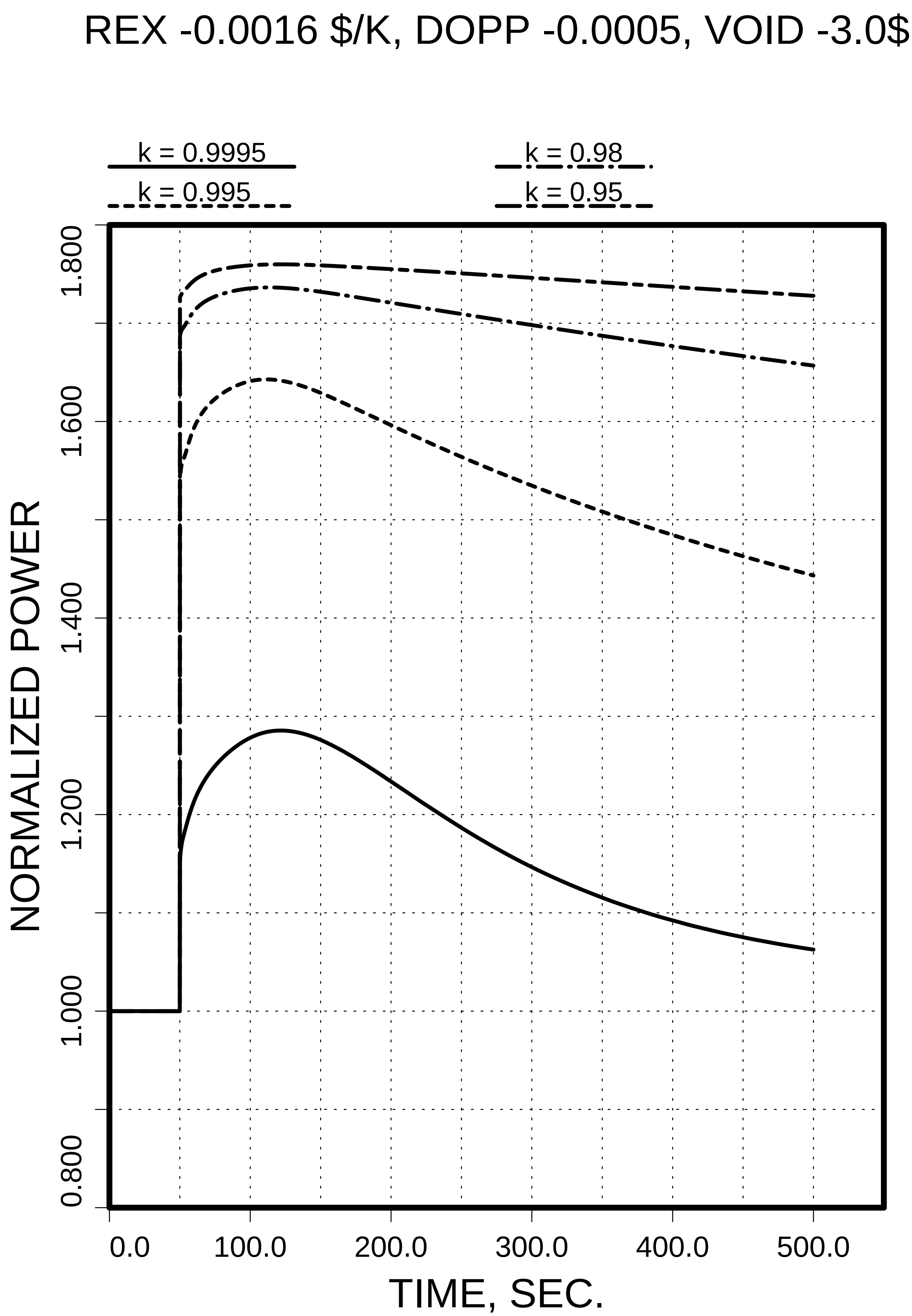

Fig. 13. Beam Excursion Analysis Results for Negative Void and Large Doppler.