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A Burst Mode, Ultrahigh Temperature UF_4 Vapor Core Reactor Rankine Cycle Space Power System Concept

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ABSTRACT

Static and dynamic neutronic analyses have been performed on an innovative burst mode (100's of MW output for a few thousand seconds) Ultrahigh Temperature Vapor Core Reactor (UTVR) space nuclear power system. The NVTR employs multiple, neutronically-coupled fissioning cores and operates on a direct, closed Rankine cycle using a disk Magnetohydrodynamic (MHD) generator for energy conversion. The UTVR includes two types of fissioning core regions: (1) the central Ultrahigh Temperature Vapor Core (UTVC) which contains a vapor mixture of highly enriched UF_4 fuel and a metal fluoride working fluid and (2) the UF_4 boiler column cores located in the BeO moderator/reflector region. The gaseous nature of the fuel, the fact that the fuel is circulating, the multiple coupled fissioning cores, and the use of a two phase fissioning fuel lead to unique static and dynamic neutronic characteristics.

Static neutronic analysis was conducted using two-dimensional S_n transport theory calculations and three-dimensional Monte Carlo transport theory calculations. Circulating-fuel, coupled-core point reactor kinetics equations were used for analyzing the dynamic behavior of the UTVR. In addition to including reactivity feedback phenomena associated with the individual fissioning cores, the effects of core-to-core neutronic and mass flow coupling between the UTVC and the surrounding boiler cores were also included in the dynamic model.

The dynamic analysis of the UTVR reveals the existence of some very effective inherent reactivity feedback effects that are capable of quickly stabilizing this system, within a few seconds, even when large positive reactivity insertions are imposed. If the UTVC vapor fuel density feedback is suppressed, the UTVR is still inherently stable because of the boiler core liquid-fuel volume feedback; in contrast, suppression of the vapor fuel density feedback in "conventional" gas core cavity reactors causes them to become inherently unstable. Due to the strength of the negative reactivity feedback in the UTVR, it is found that external reactivity insertions alone are inadequate for bringing about significant power level changes during normal reactor operations. Additional methods of reactivity control, such as variations in the gaseous fuel mass flow rate, are needed to achieve the desired power level control.

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1.0 INTRODUCTION

The Ultrahigh Temperature Vapor Core Reactor (UTVR) is a highly enriched (>85%), BeO externally-moderated, circulating fuel reactor with UF_4 as the fissioning fuel. The working fluid is in the form of a metal fluoride such as NaF, KF, RbF, or ^7LiF. A side view schematic of the UTVR is shown in Fig. 1.

The UTVR includes two types of fissioning core regions: (1) the central Ultrahigh Temperature Vapor Core (UTVC) regions which contain a vapor mixture of highly-enriched UF_4 and a metal fluoride working fluid at an average temperature of ≈3000 K and a pressure of ≈5×10^6 Pa, and (2) the boiler column (BCOL) or boiler core regions which contain highly enriched UF_4 fuel. This reactor has symmetry about the midplane with identical top and bottom vapor cores and boiler columns separated by the mid-plane BeO (MBEO) slab region and the MHD ducts where power is extracted.

The UTVC is surrounded in the radial direction by the wall and wall cooling region. The wall cooling region contains a liquid metal fluoride. By tangentially injecting the metal fluoride working fluid into the UTVC, the UTVC walls are maintained at the desired low temperatures (≈2000 K). As the metal fluoride is injected into the UTVC, an annular buffer zone is obtained which aids in maintaining the UF_4 away from the UTVC walls. This reduces the possibility of condensation of uranium or uranium compounds on the UTVC walls. Beyond this buffer zone, the metal fluoride vaporizes and mixes with the UF_4 in the UTVC.

The boiler region, which includes a number of boiler columns, is connected to the UTVC via the UTVC inlet plenum, as shown in Fig. 1. The UF_4 liquid is supplied to the boiler columns by means of feedlines. Each boiler column consists of three distinct regions: the subcooled liquid region, the saturated liquid-vapor region, and the superheated vapor region. The UF_4 fluid is vaporized in the boiler columns prior to its entrance to the UTVC.

A top view schematic of a six-boiler column UTVR in Fig. 2 shows three distinct BeO regions. The first region is the inner BeO (IBEO) region which separates the UTVC walls from the boiler columns in the radial direction. The second region is the annular boiler BeO (BBEO) region with a radial thickness equal to the diameter of the boiler columns. The third region is the outer BeO (OBEO) region surrounding the boiler columns and the BBEO region. Three other BeO regions are shown in Fig. 1. These are the MBEO region mentioned previously, the lower BeO (LBEO) region separating the boiler feedlines from the MHD duct, and the top BeO (TBEO) region above the UTVC.

By configuring the disk MHD generator as an integral part of the reactor (as shown in Fig. 1), a significant amount of fissioning occurs throughout the disk MHD generator region; this helps to maintain the required electrical conductivity, despite the relatively low fluid temperatures (<2500 K) in the duct. The combination of the following three features differentiates the UTVR from other nuclear reactor concepts: 1) the multi-core configuration resulting in a coupled core system by means of direct neutron transport through the media; 2) the circulating fuel and the associated neutronic and mass flow coupling between the UTVC and boiler core; and 3) the employment of two-phase (liquid-vapor) fissioning fuel.

Reactivity changes associated with changes in the volume of the liquid fuel/working fluid mixture in the boiler columns tend to stabilize the system. If the power level of the system should rise, the amount of liquid in the boiler regions is reduced and more vapor or void is present. This causes a negative reactivity insertion and a drop in the power level. The amount of this negative reactivity feedback depends strongly on the neutronic coupling between the UF_4 boiler columns and the UTVC.

For space power systems, size and mass are significant constraints. Hence a vital goal is to obtain a UTVR reactor power system that is optimized for minimum mass and size. In addition to the total power requirement, an important design parameter for this system is the power sharing or power distribution between the vapor core and the UF_4 boiler regions (i.e., the ratio P_{UTVC}/P_{BCOL}). The system design must assure that the P_{UTVC}/P_{BCOL} value obtained from the neutronic analysis agrees with the value required by thermodynamic and flow considerations. One method of controlling P_{UTVC}/P_{BCOL} is to divert part of the metal fluoride from the wall cooling region to the boiler region. For example, when all the NaF flow is used for cooling the UTVC walls, thermodynamic and flow considerations require $P_{UTVC}/P_{BCOL} \approx 20$. However, if ≈30% of the NaF is diverted to- and vaporized in the boiler columns, the required P_{UTVC}/P_{BCOL} is reduced to ≈3.

Both static and dynamic neutronics analyses have been performed on the UTVR in order to: (1) establish its basic neutronic characteristics, such as the extent of the neutronic coupling between the vapor core and the surrounding boiler columns; (2) determine its scientific feasibility, e.g., show that the P_{UTVC}/P_{BCOL} value predicted from neutronic analysis can be made to match the P_{UTVC}/P_{BCOL} required on the basis of thermodynamic considerations while still satisfying thermal hydraulic requirements; and (3) characterize it with respect to stability and dynamic response. This report summarizes results from these analyses. A detailed presentation of the static and dynamic neutronic analyses can be found in Reference 1.

2.0 STATIC NEUTRONICS ANALYSIS

Two-dimensional static neutronic calculations were performed with the 2-D S_n transport theory code, DOT4[2]. Results obtained from these calculations were used to obtain basic neutronic characteristics and reference configurations for the three-dimensional analysis of the UTVR. Three-dimensional static neutronic analysis was performed using MCNP[3], a 3-D Monte Carlo transport theory code. UTVR parameters needed for the dynamic neutronic studies such as core reactivities, neutron generation times, and core-to-core coupling probabilities were obtained from the 3-D MCNP calculations.

2-D S_n Analysis

Fig. 3 shows the neutron multiplication factor (k_{eff}) and the ratio of the UTVC-to-Boiler Column power (P_{UTVC}/P_{BCOL}) as a function of the IBEO region thickness. A maximum value in k_{eff} is obtained at an IBEO thickness of ≈15 cm. At this thickness, the combined boiler-to-boiler, boiler-to-UTVC, and UTVC-to-boiler neutronic coupling is optimum. Similar calculations have been performed on the other BeO regions. The optimum thicknesses of these regions are listed in Table 1. Although not shown, if the thicknesses of the BeO regions are fixed at the optimum values presented in Table 1, a plot of k_{eff} versus the UTVC radius indicates that a maximum in k_{eff} occurs at a UTVC radius of ≈80 cm. For UTVC radii above ≈80 cm, no appreciable increase in k_{eff} is observed.

Shown in Fig. 4 is a plot of k_{eff} and P_{UTVC}/P_{BCOL} versus the UF_4 partial pressure in the UTVC at different NaF partial pressures. Fig. 4 demonstrates that while the UF_4 partial pressure in the UTVC can have a significant effect on k_{eff}, the NaF partial pressure has very little effect on k_{eff}. Thus, the UTVC can be operated with a fuel/working fluid mixture that is selected to enhance MHD generator performance for efficient energy extraction. Preliminary analysis of the MHD generator indicates good performance at a mole fraction of ≈10% for UF_4 and ≈90% for NaF[4]. Although not shown, it is also found that the choice of metal fluoride vapor (NaF, KF, ^{7}LiF, and RbF) in the UTVC has very little effect on k_{eff}. The behavior of k_{eff} versus the vapor fuel density illustrates an important feature of externally-moderated vapor core reactors. As the UTVC gas density is increased, a "saturation point" is reached where the core becomes "black" to neutrons. Further increases in the UTVC gas density above this "saturation point" yield diminishingly small increases in k_{eff}. From a control standpoint, it is desirable to operate in a region well below this "saturation point," where changes in the vapor-fuel density yield significant changes in k_{eff}; operation in this region provides a prompt and effective method for inherent power and reactivity control of the UTVR.

The effect of the average UF_4 density in the boiler region on k_{eff} and P_{UTVC}/P_{BCOL} is shown in Fig. 5 which indicates that a "saturation point" also exists for the boiler region. Table 2 lists k_{eff} and P_{UTVC}/P_{BCOL} as a function of the number of boiler columns (the total volume of the boiler column region is fixed). The results indicate that as the number of UF_4 boiler columns increases, k_{eff} increases while P_{UTVC}/P_{BCOL} decreases. This behavior is due primarily to the increase in the boiler's fission rate as a result of a decrease in the thermal neutron flux depression in the (smaller) boiler columns and also to enhanced boiler-to-boiler and UTVC-to-boiler neutronic coupling.

3-D Monte Carlo Analysis

Until vapor core reactor experimental data are available, Monte Carlo neutron transport calculations are essential for benchmarking UTVR neutronic calculations. Additionally, since 1- and 2-D S_n calculations are unable to properly model the UTVR due to its complex geometry, 3-D Monte Carlo calculations are crucial for accurately treating and reliably estimating essential parameters such as reactivity worths of liquid volume variations in the UF_4 boiler zones and neutronic coupling coefficients among the UTVR fissioning core regions.

Table 3 lists some results obtained from a 30 minute, MCNP calculation performed on a reference UTVR configuration using the Cray X-MP/48 at the San Diego Supercomputer Center. Due to the relatively small size of the boiler region compared to the size of the UTVC, neutrons have a much smaller probability of entering the UF_4 boiler columns than entering the UTVC. Consequently, the uncertainty of Φ_{BCOL} is ≈8 times greater than the uncertainty of Φ_{UTVC}. Table 3 also indicates that the uncertainty for the boiler core-to-boiler core coupling probabilities, $\varepsilon^{B\rightarrow Bn}$ and $\varepsilon^{B\rightarrow Bo}$, is quite large (>80%). The coupling probability, $\varepsilon^{i\rightarrow j}$, is the probability that neutrons born in core i will be transported through the media to core j where they cause fission. Since a primary objective of performing 3-D Monte Carlo calculations is to obtain reliable neutronic coupling probabilities and reactivity worths of the UF_4 boiler columns, the uncertainty of parameters associated with the boiler regions needs to be reduced. Reliable confidence intervals are generated when the uncertainty is ≈10%

or less[3]. A reduction in the uncertainty can be achieved by increasing the number of neutron histories examined (i.e., by increasing the computation time) and/or by the use of variance reduction techniques. Unless variance reduction techniques are employed, a reduction in the uncertainty of $\varepsilon^{B\rightarrow Bn}$ or $\varepsilon^{B\rightarrow Bo}$ from ≈80% to ≈10% would require an increase in computer time by a factor of ≈60, (each problem would require ≈1,800 minutes or ≈30 hours of CRAY X-MP/48 computer time) which is prohibitive.

The MCNP code employs a variety of variance reduction techniques[5] which include geometry splitting and Russian Roulette, implicit capture and weight cutoff, time and energy cutoffs, forced collision, and weight windows. These variance reduction methods were selectively employed to reduce the large uncertainties associated with UTVR boiler column parameters. Results presented in Table 4 (Method B) indicate that the uncertainties of Φ_{BCOL}, $\varepsilon^{U\rightarrow B}$, $\varepsilon^{B\rightarrow Bo}$, and $\varepsilon^{B\rightarrow Bn}$ have been decreased by factors of ≈1.4, ≈1.5, ≈1.5 and ≈1.7, respectively. This translates to a factor of ≈2.5 savings in computer time. The cost of reducing the variance of certain parameters is an increase in the variance of other parameters. This is also shown in Table 4 where the uncertainties of k_{eff}, Φ_{UTVC}, and $\varepsilon^{B\rightarrow U}$ have been increased by factors of ≈1.5, ≈2.5, and ≈1.4, respectively. Shown in Table 4 are the modified uncertainties when tallies are properly selected (Method C). That is, by taking advantage of the symmetric alignment of the UF_4 boiler columns around the UTVC, the uncertainties in Φ_{BCOL}, $\varepsilon^{B\rightarrow Bn}$, $\varepsilon^{B\rightarrow Bo}$, $\varepsilon^{B\rightarrow U}$, and $\varepsilon^{U\rightarrow B}$ have been further reduced by factors of ≈2, ≈2.8, ≈2, ≈2, and ≈2, respectively. Thus, to achieve uncertainties of less than 10% for $\varepsilon^{B\rightarrow Bn}$ and $\varepsilon^{B\rightarrow Bo}$ the required CRAY X-MP/48 computer time is reduced from ≈1800 to ≈120 minutes when variance reduction techniques and tally selection according to Method C in Table 4 are employed (the required computer time is reduced by a factor of ≈15). The uncertainties in $\varepsilon^{B\rightarrow U}$ and $\varepsilon^{U\rightarrow B}$ for these 2 hour runs are 4.5% and 1.6%, respectively. The uncertainty for all other parameters of interest (fluxes, reaction rates, k_{eff} etc.) is now less than 1% for these two hour runs.

Listed in Table 5 are the coupling probabilities and reactivities of the UTVC and boiler columns as a function of UF_4 partial pressure in the UTVC for U^{235} fuel loadings of 0.9 kg and 2.96 kg per boiler column. Table 5 indicates that as the UF_4 partial pressure increases, ρ_{UTVC} and $\varepsilon^{B\rightarrow U}$ increase. As the UTVC vapor fuel density increases, the neutron mean free path in the UTVC decreases (i.e., the probability that neutrons will have an interaction with the UTVC increases). Thus, neutrons entering the UTVC will more likely be absorbed in the UTVC causing both ρ_{UTVC} and $\varepsilon^{B\rightarrow U}$ to increase. With respect to the boiler regions, the increased UTVC density acts as a poison to the boiler columns since neutrons born in a given boiler column will more likely be absorbed in the UTVC rather than be reflected back to that boiler column or transported to other boiler columns. This is seen in Table 5 where ρ_{boiler}, $\varepsilon^{U\rightarrow B}$, $\varepsilon^{B\rightarrow Bo}$, and $\varepsilon^{B\rightarrow Bn}$ all decrease as the UF_4 partial pressure increases.

Table 5 also indicates that ρ_{boiler}, $\varepsilon^{U\rightarrow B}$, $\varepsilon^{B\rightarrow Bo}$, and $\varepsilon^{B\rightarrow Bn}$ all increase as the UF_4 loading in the boiler columns increases from 0.9 kg to 2.96 kg. As the UF_4 loading increases in the boiler columns, the neutron mean free path in the boiler columns decreases causing the probability of neutron absorption in the boiler columns to increase. The results also indicate that ρ_{UTVC} and $\varepsilon^{B\rightarrow U}$ decrease since neutrons are more likely to be absorbed in the boiler columns than be reflected back to the UTVC.

Results from the static neutronic analysis[1] show that: 1) about 30% of the metal fluoride needs to be diverted from the wall cooling region to the boiler region so that the power sharing between the vapor cores and boiler cores (P_{UTVC}/P_{BCOL}) calculated on the basis of thermodynamic considerations matches the value obtained from neutronics calculations; 2) the optimum P_{UTVC}/P_{BCOL}

ratio is about 3- or 4-to-1; and 3) the optimum number of boilers is four. Results from the MCNP three-dimensional calculations were used to select a reference UTVR for the dynamic neutronic analysis. Table 6 presents specifications for this reference UTVR. The UTVR parameters needed for the dynamic neutronic analysis such as the UTVC and boiler column reactivities, neutron generation time, and core-to-core neutronic coupling coefficients were all obtained from the MCNP calculations.

3.0 DYNAMIC MODELLING

Circulating-fuel, coupled-core point reactor kinetics equations (lumped parameter models) were used for analyzing the dynamic behavior of the UTVR. The dynamic model treats each fissioning core region (the UTVC and boiler columns) as a point reactor. In addition to including unique reactivity feedback phenomena associated with the individual fissioning cores (such as gas fuel density feedback of the UTVC and liquid fuel volume feedback of the boiler columns), the effects of core-to-core neutronic and mass flow coupling between the UTVC and the surrounding boiler columns are also included in the dynamic model. The core-to-core neutronic coupling among the fissioning core regions arises both indirectly as a result of the fuel circulating between the two types of fissioning core regions (delayed neutron emission from the decay of the delayed neutron precursors which are carried in the fuel that circulates between the UTVC and boiler columns) and directly by the transport of neutrons through the IBEO region separating the UTVC and the surrounding UF_4 boiler columns.

For the dynamic analysis of the UTVR, four identical boiler columns were symmetrically deployed around the central UTVC. It was assumed that each boiler column receives 1/4 of the fuel/working fluid mixture from the UTVC and that the UTVC receives the fuel/working fluid mixture from all four boiler columns. It was also assumed that all boiler columns are at the same power level and are behaving and have behaved in an identical manner. Because of this assumption, the model employed cannot handle any imbalance among the boiler columns. As a consequence, and due to the symmetric alignment of the boiler columns around the UTVC, the boiler-to-UTVC neutronic coupling coefficients appearing in the coupled core, point reactor kinetics (PRK) equations are identical, at any given time, for all four boilers. The employed circulating fuel, coupled core PRK equations also assume that: 1) delayed neutron precursor transport through the core-to-core connecting loops is pure time delay-no fissioning occurs in the fuel outside the UTVC and boiler columns; and 2) the fuel undergoes slug flow outside the cores.

In addition to the PRK equations, energetics equations for the central UTVC and boiler cores were required. In obtaining the UTVR energetics equations, the following assumptions were made:

1. Pressure losses due to friction, boiling, and shock (flow area contractions and expansions and restrictions) are neglected.

2. Fuel/working fluid inlet pressure and temperature to the boiler columns are fixed.

The energetics equations dictate how power fluctuations in the UTVC or boiler cores affect system variables like pressure, temperature and fuel mass. Changes in these variables affect the UTVC and boiler column reactivities and changes in the reactivities in turn affect the power levels.

Considering the boiler columns, power fluctuations here induce the following:

1. The mass of fuel/working fluid in the boiler column fluctuates due to changes in the volumes (heights) of the subcooled liquid, saturated liquid and vapor regions and due to changes in the density of the fuel in the vapor region.

2. The outlet and average fuel temperatures fluctuate.

3. The temperature of the moderator-reflector region surrounding the boiler core fluctuates.

For the examined transients, reactivity effects arising from changes in either the fuel temperature (Doppler effect) or moderator temperature were found to be negligible compared to reactivity effects arising from changes in the mass of fissioning fuel present in the boiler.

Considering the UTVC, power fluctuations here induce the following:

1. The mass of the UF_4 vapor fuel/metal fluoride working fluid mixture in the UTVC fluctuates due to changes in the average density of the vapor fuel in the UTVC.

2. The average temperature of the vapor fuel fluctuates.

3. The temperature of the moderator/reflector region surrounding the UTVC fluctuates.

4. The mass of the wall coolant in the UTVC fluctuates due to changes in the density and volume occupied by the liquid wall coolant.

As for the boiler core regions, it was found that reactivity feedback associated with both fuel (Doppler) temperature and moderator temperature variations can be neglected. The reactivity effects of wall coolant density variations were also found to be very small compared to vapor fuel/working fluid density variations in the UTVC and these too can be neglected. Thus, the inherent reactivity feedback in the UTVC due to power fluctuations is almost completely a result of fuel mass variations in the UTVC. The vapor fuel density coefficient of reactivity, $\alpha^{U}_{Mf'}$, relates the reactivity effect in the UTVC to fuel mass variation in the UTVC. In deriving the energy balance on the UTVC, the following assumptions and restrictions were made:

1. Heat transferred out of the UTVC is assumed to be deposited into the wall cooling region, and is removed by the wall coolant prior to its mixing with the vapor fuel/working fluid mixture component.

2. Effects of kinetic energy changes are neglected since the ratio of kinetic energy changes to internal energy changes is less than $\approx 0.1\%$.

3. Perfect mixing of the vapor fuel/working fluid mixture with the vaporized wall coolant is assumed to occur in the UTVC. This assumes that both the fuel/working fluid mixture and wall coolant exit the UTVC at the same temperature.

4. The liquid coolant inlet temperature to the wall coolant region is fixed.

Finally, due to the restriction of constant pressure in the boiler columns, a surge tank for the boiler columns was required in order to make the system dynamically stable. By employing a surge tank, the fuel/working fluid mixture inlet mass flow rate to the boiler columns is kept constant and the inlet mass flow rate to the UTVC is determined on the basis of the pressure in the UTVC and temperature of the fuel/working fluid mixture exiting the boiler columns. A complete development of the coupled core, circulating fuel point reactor kinetics equations and of all the energetics equations employed in the UTVR dynamic modelling can be found in Ref. 1.

4.0 DYNAMIC ANALYSIS

The lumped parameter models were incorporated into COUPL, a special code developed for the dynamic analysis of the UTVR. COUPL is constructed in a format suitable for dynamic simulation by the engineering analysis program, EASY5[6]. EASY5 is an interactive program that has the capability to model, analyze, and design large complex dynamic systems defined by algebraic, differential, and/or difference equations. By integrating the differential-difference equations for a period of time and resolving the algebraic equations, EASY5 effectively simulates the behavior of the non-linear UTVR system. Behavior of core power levels, core reactivities, delayed neutron precursor concentrations, fuel loadings or fuel densities, pressure, temperature, and mass flow rates during full power transients was investigated using COUPL with EASY5. Specifications for the reference, four-boiler UTVR are given in Table 6. Additional specifications at the initial, full power steady state condition are presented in Table 7.

The behavior of the UTVC power level (P^U) and the boiler column region power level (P^B) following a \$1 positive step reactivity addition to the boiler column region are shown in Fig. 6. The reactivity insertion in the boiler region leads to an initial power increase that yields a decrease in the liquid level in the boiler due to increased vaporization. The decrease in the mass of fuel in the boiler (see Fig. 7) then leads to a reactivity decrease and a power decrease in the boiler at t=0.075 seconds. In the UTVC, the reactivity insertion also leads to an initial power increase; the higher pressure and temperature in the UTVC yield an increased mass flow rate for fuel exiting the UTVC and a decreased mass flow rate for fuel entering the UTVC (see Fig. 8). This fuel decrease then yields a reactivity decrease and a power level decrease in the UTVC at t=0.1 second. The decreased power levels in the boiler region and UTVC eventually lead to increased fuel loadings in both the UTVC and boiler region that lead to power increases and a series of damped oscillations ensues. The UTVR system, which was initially at steady state, is seen to rapidly self-stabilize, in about 3 seconds, without any external reactivity control. The results show that the UTVC power level response lags the boiler column's power response by about 0.025 seconds and that the UTVC and boiler column power levels oscillate with a ≈0.4 second period. Once the oscillations die out, the boiler column power level has increased by about 10kW (0.009%) or about 2.5 kW per boiler column and the UTVC power level has increased by about 500 kW (0.15%). Although the insertion is imposed on the boiler columns, the effect of the perturbation is much greater on the UTVC.

The UTVC and boiler column region power level behavior following a 20¢ positive reactivity step insertion in the UTVC are shown in Fig. 9. Once again, the system is seen to rapidly self-stabilize, within about 3 seconds, without any external reactivity control. Initially, the power response of the boiler column lags that of the UTVC by a time delay of approximately 10^{-4}s. However, by the time the third oscillation occurs, the UTVC power level response again lags that of the boiler column by about 0.025 seconds. The periods of oscillation for the UTVC and boiler column power levels are again about 0.4 seconds. The final equilibrium condition shows that the power level of the boiler columns has increased by about 30 kW (0.026%) while the UTVC power level has increased by about 3.2 MW (0.9%).

Figure 10 shows the UTVC and boiler region power level behavior for the same 20¢ positive step reactivity addition to the UTVC when the core-to-core neutronic coupling coefficients are artificially reduced by one order of magnitude. The consequence of this variation is to almost double the time required for the system to self-stabilize. The period of oscillation of the UTVC power level is increased to 0.45 seconds while the period of power oscillation for the boiler columns remains at 0.4 seconds. This causes the time by which the UTVC power response lags that of boiler column to increase with time. At 0.1 second the UTVC response lags the boiler response by 0.04 seconds; at 0.4 seconds, the lag time has increased to 0.08 seconds. At the final equilibrium condition the UTVC power level has increased by about 4.5 MW (1.3%) while the boiler column power level has increased by 28 kW (0.024%). It is apparent that stability of the UTVR is enhanced by the core-to-core neutronic coupling.

Fig. 11 shows the UTVC and boiler column power response for a 20¢ step insertion in the UTVC when the vapor fuel density coefficient of reactivity, α^{U}_{Mf}, is artificially reduced by a factor of five. Because the fuel reactivity worth of the UTVC is reduced, more fuel is required to be discharged from the core following the reactivity insertion and this causes the period and, thus, the amplitudes of oscillations to increase relative to those shown in Figure 10. However, because the boiler column fuel mass coefficient is now the dominant feedback mechanism and because the boiler columns have a larger damping effect due to their liquid fuel, the damping of the oscillations also increases and the time required for the system to self-stabilize is reduced from about 3 seconds to around 1.2 seconds. At the final equilibrium condition, the UTVC power level has increased by 6.75 MW (2%) while the boiler column power level has increased by 50 kW (0.04%).

Shown in Fig. 12 are the UTVC and boiler column power levels in response to a 20¢ reactivity step insertion to the UTVC when the UTVC fuel mass coefficient of reactivity is increased by a factor of two from its reference value. The results show undamped oscillations and an unstable system. From Figs. 9, 11, and 12 it is apparent that the dynamic response and stability of the UTVR can be highly dependent on the value of α^{U}_{Mf}, the gaseous fuel density coefficient of reactivity. (The coefficient α^{U}_{Mf}, is obtained from the slope of the k_{eff} versus UTVC fuel loading curve (Fig. 4). The value of α^{U}_{Mf}, can thus be changed by operating the UTVC at a different fuel mass loading or fuel gas pressure.) This conclusion is similar to that of research performed on other gas core reactor concepts. For example, Kutikkad[7] investigated a "conventional" single-core, externally-moderated GCR with circulating fuel. He found that there exists a desirable range of values for α^{U}_{Mf} for good dynamic response and stability and that if α^{U}_{Mf} is made too large, the system becomes unstable, just as is the case for the UTVR. However, Kutikkad also found that if α_{Mf} is made too small, the system again becomes unstable. This behavior is not observed with the UTVR due to the presence of the strong boiler column feedback. As a consequence of this boiler column feedback, even when the vapor fuel density reactivity feedback is suppressed, the UTVR remains inherently stable.

5.0 SUMMARY AND CONCLUSIONS

Static and dynamic neutronic analysis of the conceptual burst mode UTVR reveal the existence of unique neutronic behavior. The static neutronic analysis identified optimum reflector thicknesses, optimum core sizes and desirable gas pressures for operation. These studies showed that about 30% of the metal fluoride wall coolant must be diverted to the boiler region so that the P_{UTVC}/P_{BCOL} power sharing predicted from neutronic analysis matches the split required by thermodynamic calculations. The static results also showed that the optimum number of boiler columns is four, that the UTVC-to-boiler core neutronic coupling is large, that the boiler core-to-UTVC neutronic coupling is less but still significant, and that the boiler core-to-boiler core neutronic coupling is small.

UTVR parameters needed for the dynamic neutronic analysis such as core reactivities, neutron generation time and core-to-core neutronic coupling coefficients were obtained from static, 3-D Monte Carlo neutron transport calculations performed with MCNP. Circulating fuel, coupled core point reactor kinetics equations were used for analyzing the dynamic behavior of the UTVR. The dynamic model treats each fissioning core region as a point reactor and includes reactivity feedback due to vapor fuel density variations in the UTVC and liquid fuel volume variations in the boiler cores. The effects of core-to-core neutronic and mass flow coupling between the UTVC and the surrounding boiler cores were also included. Doppler fuel temperature and moderator temperature feedbacks were found to be insignificant, compared to the other feedbacks, for the examined UTVR transients.

The dynamic analysis indicates that the strong feedbacks of the UTVR lead to a system that quickly self-stabilizes, within a few seconds, even when large positive reactivity insertions are imposed. When the vapor fuel density coefficient of reactivity, α^{U}_{Mf}, , is large, it is found to dictate system dynamic performance and stability. As α^{U}_{Mf} becomes small, the boiler column fuel mass variation becomes the dominant feedback mechanism and is capable of rapidly self-stabilizing the UTVR even in the absence of the gas density feedback effect. Due to the strengths of the negative reactivity feedbacks of the UTVR, external reactivity insertions alone are generally inadequate for bringing about significant power level changes during normal reactor operations. Additional methods of reactivity control, such as variations in the gaseous fuel mass flow rate, are needed to achieve the desired power level control.

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Table 1. Optimum BeO Reflector Region Thicknesses

BeO Region	Optimum Thickness (cm)
IBEO	15
MBEO	7.5
OBEO	40
TBEO	50
LBEO	55

Table 2. k_{eff} and P_{UTVC}/P_{BCOL} as a Function of The Number of UF_4 Boiler Columns

Number of Boiler Columns	k_{eff}	P_{UTVC}/P_{BCOL}
2	1.032	4.32
4	1.048	3.11
6	1.068	2.32
8	1.087	1.90

Table 3. Selected Results From MCNP Monte Carlo Calculation[a]

k_{eff} = 1.046 (≈1.2%)		P_{UTVC}/P_{BCOL} = 3.68
Fissile Region	Φ_{th} (n/cm^2-sec)	Fission Rate (fissions/sec)
UTVC	400 (0.8%)	0.28 (1.4%)
Any Boiler Column	1.5 (6.8%)	0.019 (9.5%)
Coupling Probabilities[b]		
$\varepsilon^{U\rightarrow B}$ = ≈1x10^{-02} (≈10%)		$\varepsilon^{B\rightarrow Bo}$ = ≈3x10^{-03} (≈80%)
$\varepsilon^{B\rightarrow U}$ = ≈2x10^{-01} (≈12%)		$\varepsilon^{B\rightarrow Bn}$ = ≈2x10^{-03} (≈85%)

[a]
- Results normalized to one-fission neutron/sec
- 30 minutes on Cray X-MP/48
- 26,000 source particles examined
- Uncertainty in percent given in parentheses

[b] $\varepsilon^{i\rightarrow j}$: probability that neutrons born in core i will be transported through the media to core j where they cause fission; B: any boiler, Bn: adjacent boiler, U: UTVC, B_o: opposite boiler

Table 4. Effect of Employing Variance Reduction Techniques and Utilizing Boiler-to-UTVC Symmetry on MCNP Monte Carlo Calculations[a]

Parameter	Uncertainty		
	Method A	Method B	Method C
k_{eff}	≈1.2%	≈1.8%	≈1.8%
Φ_{UTVC}	≈0.8%	≈2.0%	≈2.0%
Φ_{BCOL}	≈6.8%	≈4.8%	≈2.4%
$\varepsilon^{U\rightarrow B}$	≈10%	≈6.5%	≈3.3%
$\varepsilon^{B\rightarrow U}$	≈12%	≈17%	≈9%
$\varepsilon^{B\rightarrow Bo}$	≈80%	≈55%	≈28%
$\varepsilon^{B\rightarrow Bn}$	≈85%	≈50%	≈18%

[a] 30 minutes on Cray X-MP/48

Method A: No Variance Reduction Technique Employed (Analog Treatment)
Method B: Energy and Weight Cutoff, Implicit Capture, and Weight Windows Employed
Method C: Same as Method B plus use of symmetry in Tally Selection

Table 5. The Effect of UF_4 Vapor Pressure in the UTVC and the U^{235} Loading in the Boiler Region[a]

	U_{235} = 0.9 kg/boiler		U^{235} = 2.96 kg/boiler	
	2.5 atm	7.5 atm	2.5 atm	7.5 atm
ρ_{UTVC}	-0.162	0.138	-0.194	0.112
ρ_{BCOL}	-1.37	-1.528	-0.598	-0.624
$\varepsilon^{U\rightarrow B}$	1.1%	0.9%	1.7%	1.3%
$\varepsilon^{B\rightarrow U}$	20.3%	26.2%	16.6%	22.6%
$\varepsilon^{B\rightarrow Bo}$	0.32%	0.17%	0.44%	0.22%
$\varepsilon^{B\rightarrow Bn}$	0.27%	0.14%	0.41%	0.21%

[a] Results from MCNP calculation with values normalized to one fission neutron/sec.

Table 6. Specifications for the Reference UTVR

UTVC Characteristics		Boiler Column Characteristics	
Core Radius	80 cm	Average Radius	7 cm
Core Height	200 cm	Height	60 cm
T_{in}/T_{out}	2350 K/4000 K	T_{in}/T_{out}	1800 K/2350 K
Core Pressure	5×10^6 Pa	Pressure	5×10^6 Pa
UF_4 Partial Pressure	5×10^5 to 1×10^6 Pa	Number of Columns	4
^{235}U Loading	≈15 to 20 kg	^{235}U Loading	≈7 to 20 kg
$\bar{\Phi}_{th}$	10^{16} n/cm^2 s	$\bar{\Phi}_{th}$	4×10^{13} n/cm^2 s

UTVR Fission Power Fraction By Region	
Vapor Core (UTVC)	72%
Boiler Columns	20%
MHD Duct	5%
Boiler Feedlines	2%
UTVC Inlet Plenum	1%

Table 7. Values of Selected Parameters for the Reference UTVR at the Initial, Full Power Steady State Condition

UTVC		Each Boiler Column	
Power Level	339.15 MW	Total Power Level	29.06 MW
		Subcooled liquid region	6.33 MW
		Saturated liquid region	21.75 MW
		Vapor Cone region	0.98 MW
UF_4/NaF inlet temperature from boilers	2700 K	UF_4/NaF inlet temperature	2014 K
NaF inlet temperature to wall region	2090 K	UF_4/NaF saturation temperature	2602 K
NaF saturation temperature (wall region)	2692 K	UF_4/NaF outlet temperature	2700 K
UTVC fluid outlet temperature	4000 K		
^{235}U Loading	6.800 kg	Total ^{235}U Loading	1.932 kg
UF_4 Partial Pressure	5×10^5 Pa	Subcooled liquid region (H^{SUB}=8.0 cm)	1.39 kg
NaF Partial Pressure	4.55×10^6 Pa	Saturated liquid region (H^{SAT}=40.0 cm)	0.48 kg
Total Pressure	5.05×10^6 Pa	Vapor Cone region	0.06 kg
UF_4 mass flow rate (from boilers)	31.0 kg/s	UF_4 mass flow rate	7.75 kg/s
NaF mass flow rate (from boilers)	23.7 kg/s	NaF mass flow rate	5.93 kg/s
NaF mass flow rate (from wall region)	55.3 kg/s		

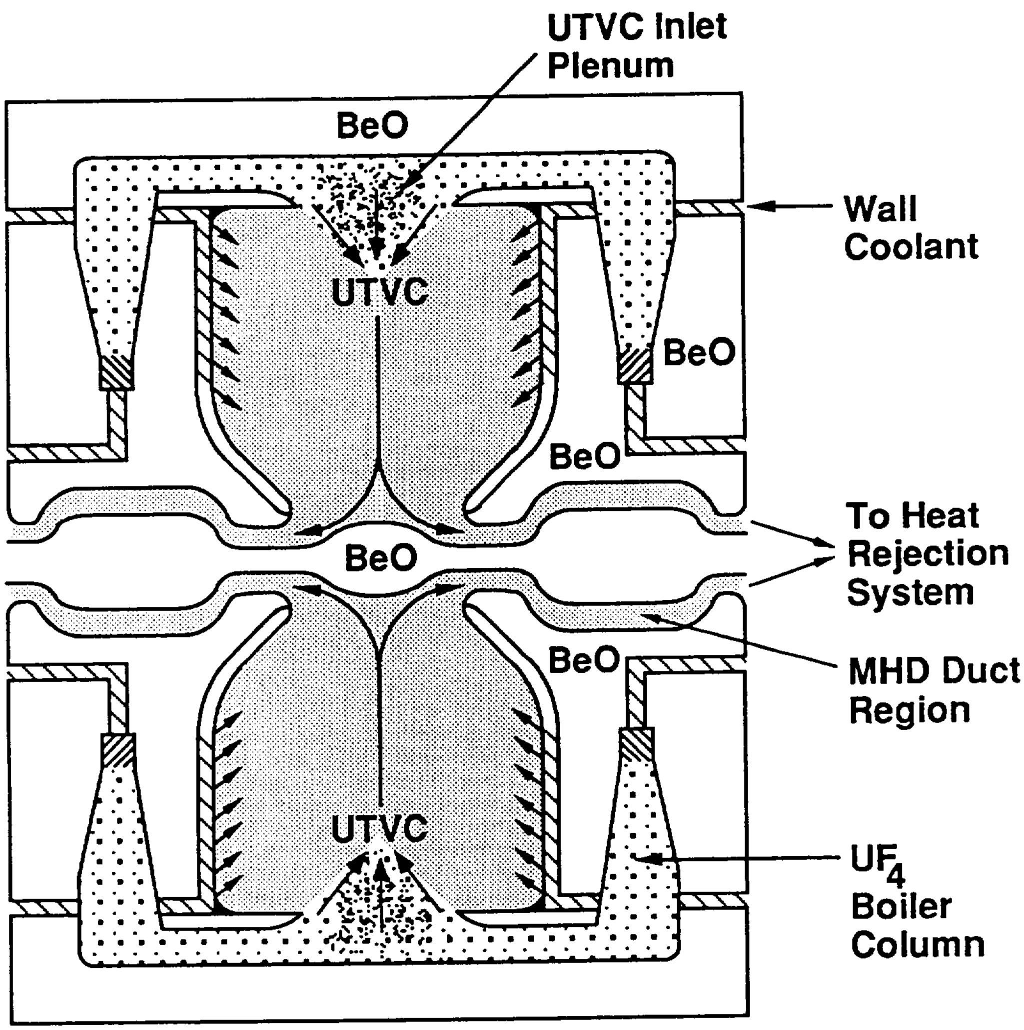


Fig. 1. Side view schematic of the UTVR.

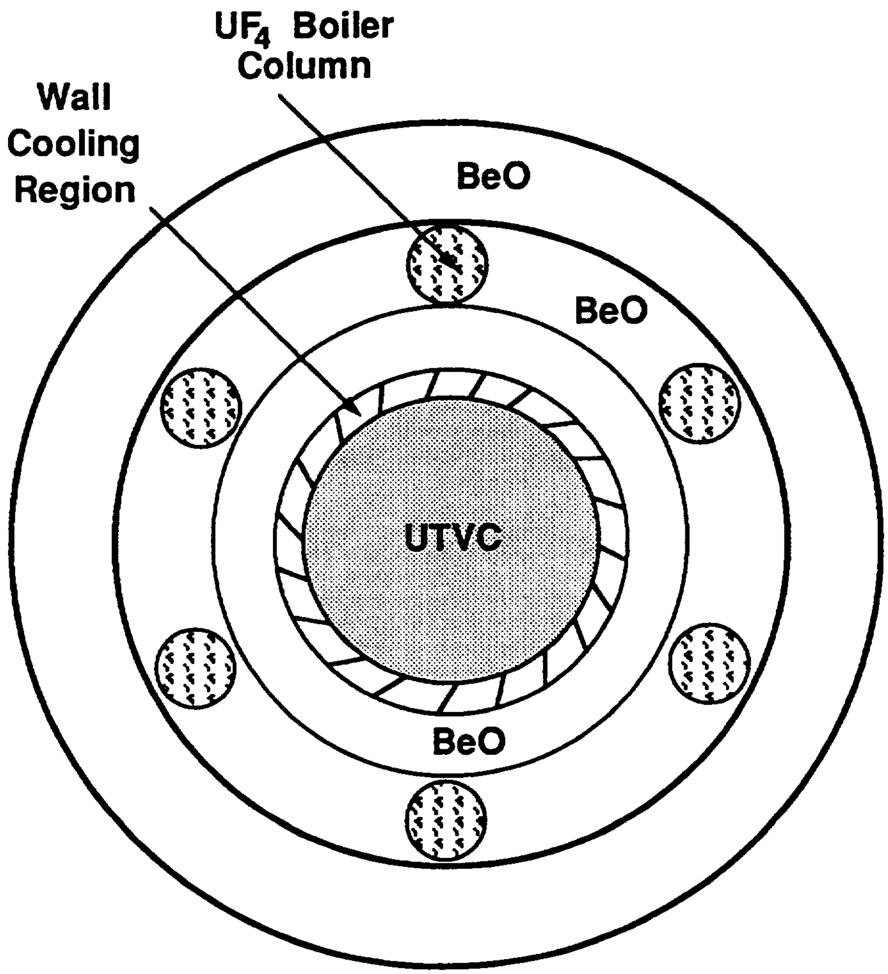


Fig. 2. Top view schematic of a six boiler column UTVR.

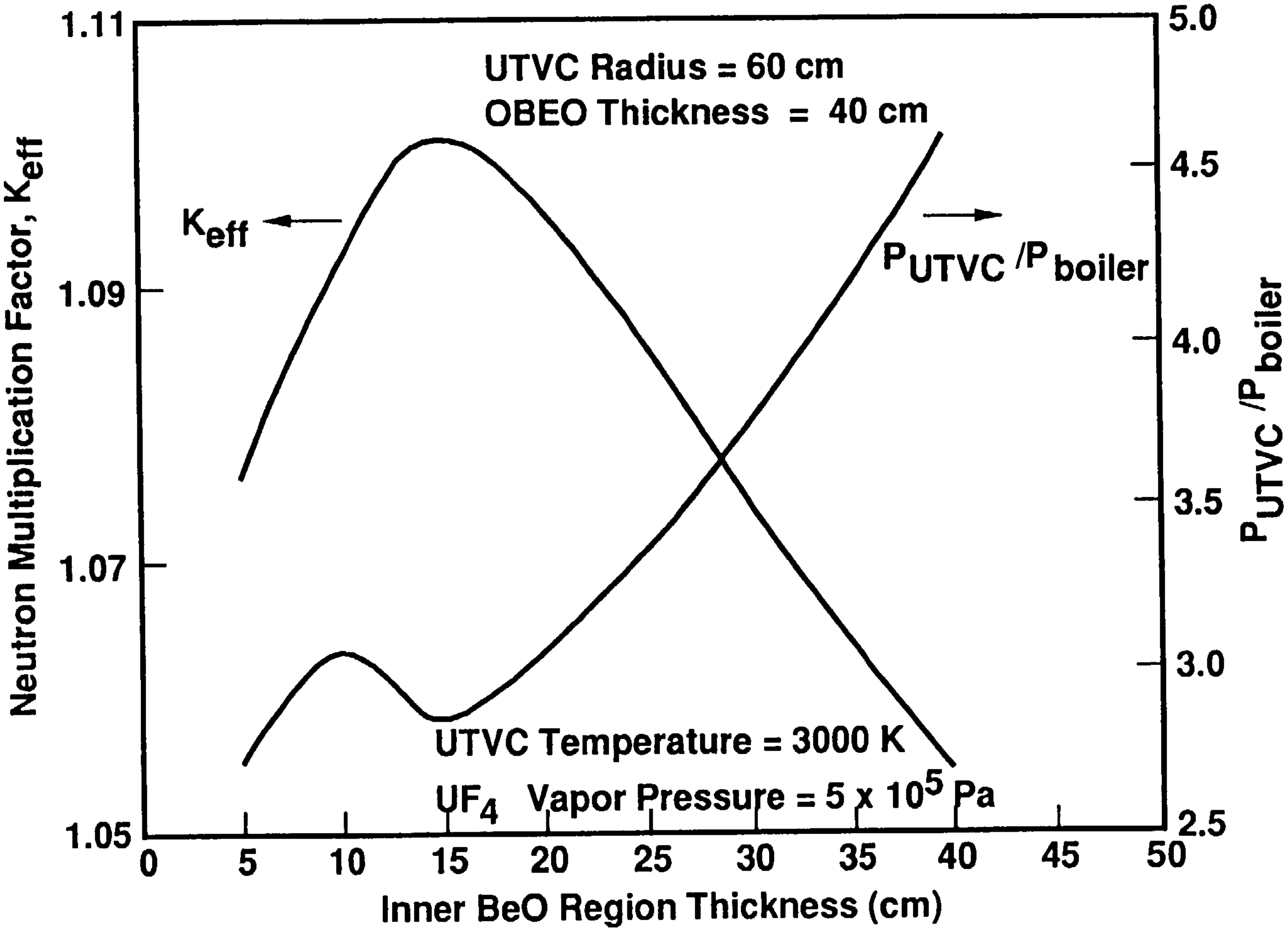


Fig. 3. K_{eff} and P_{UTVC}/P_{boiler} versus inner BeO moderator-reflector region thickness.

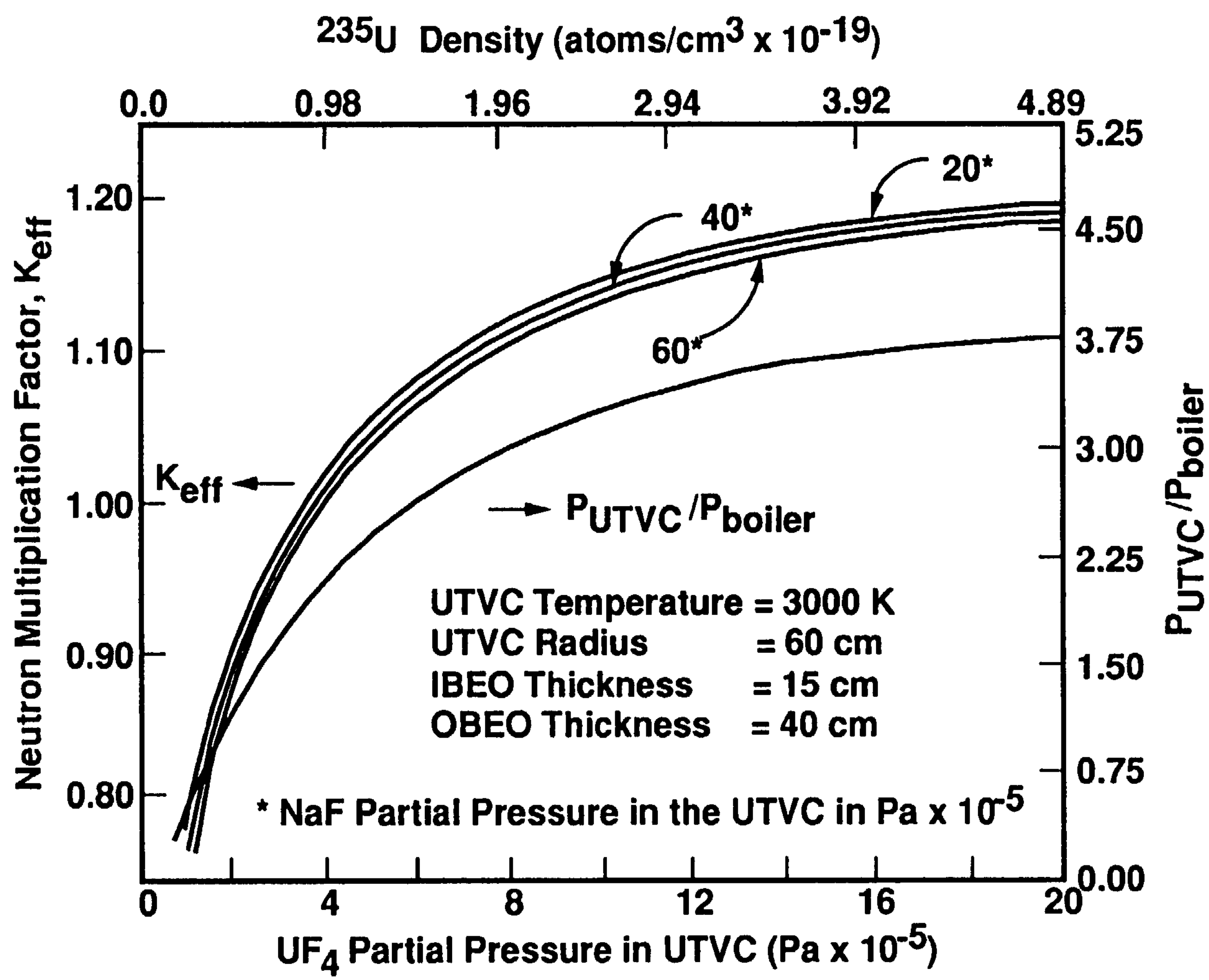


Fig. 4. K_{eff} and P_{UTVC}/P_{boiler} versus the UF_4 partial pressure in the UTVC.

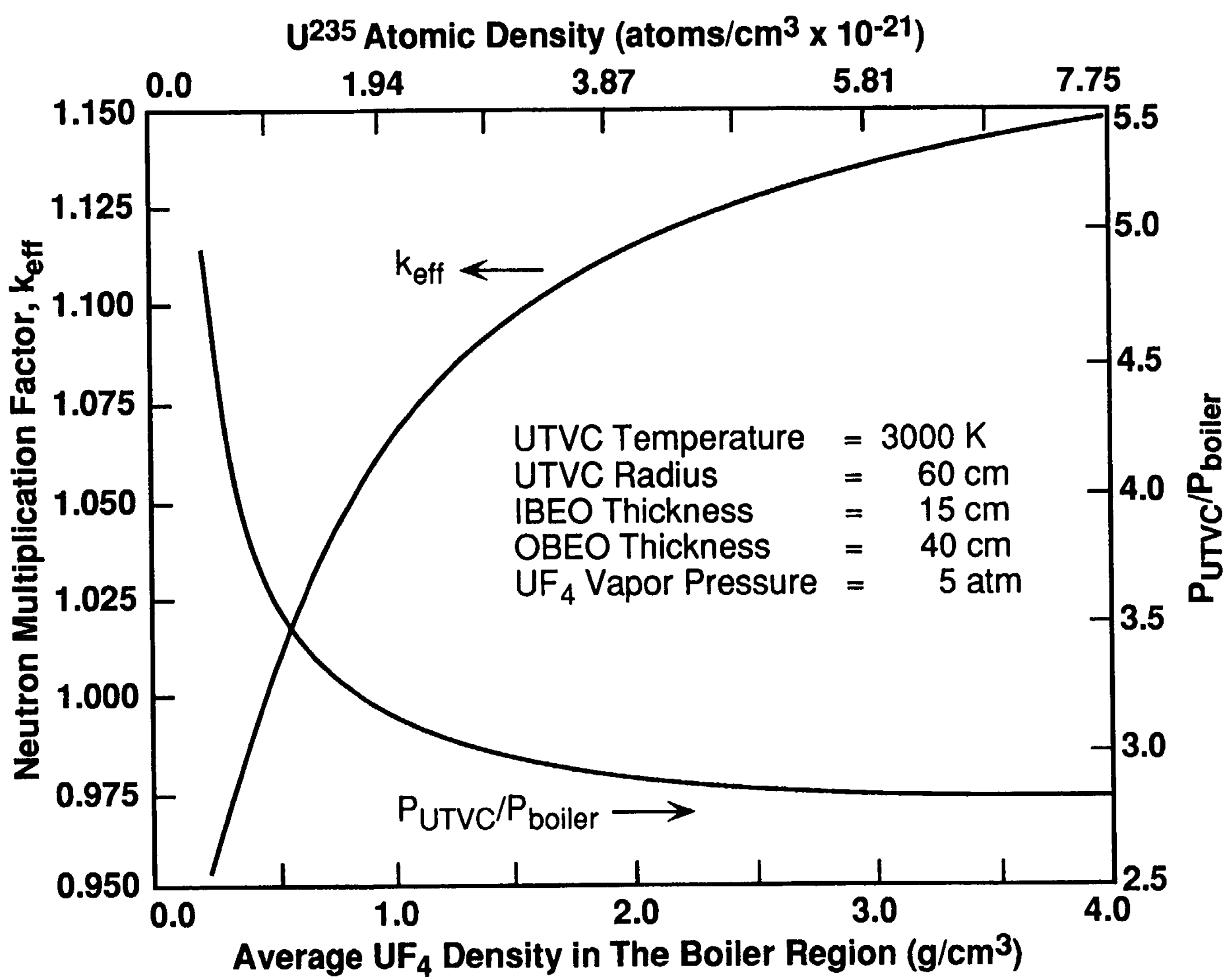


Fig.5. K_{eff} and $P_{UTVC/boiler}$ versus UF_4 density in the boiler columns.

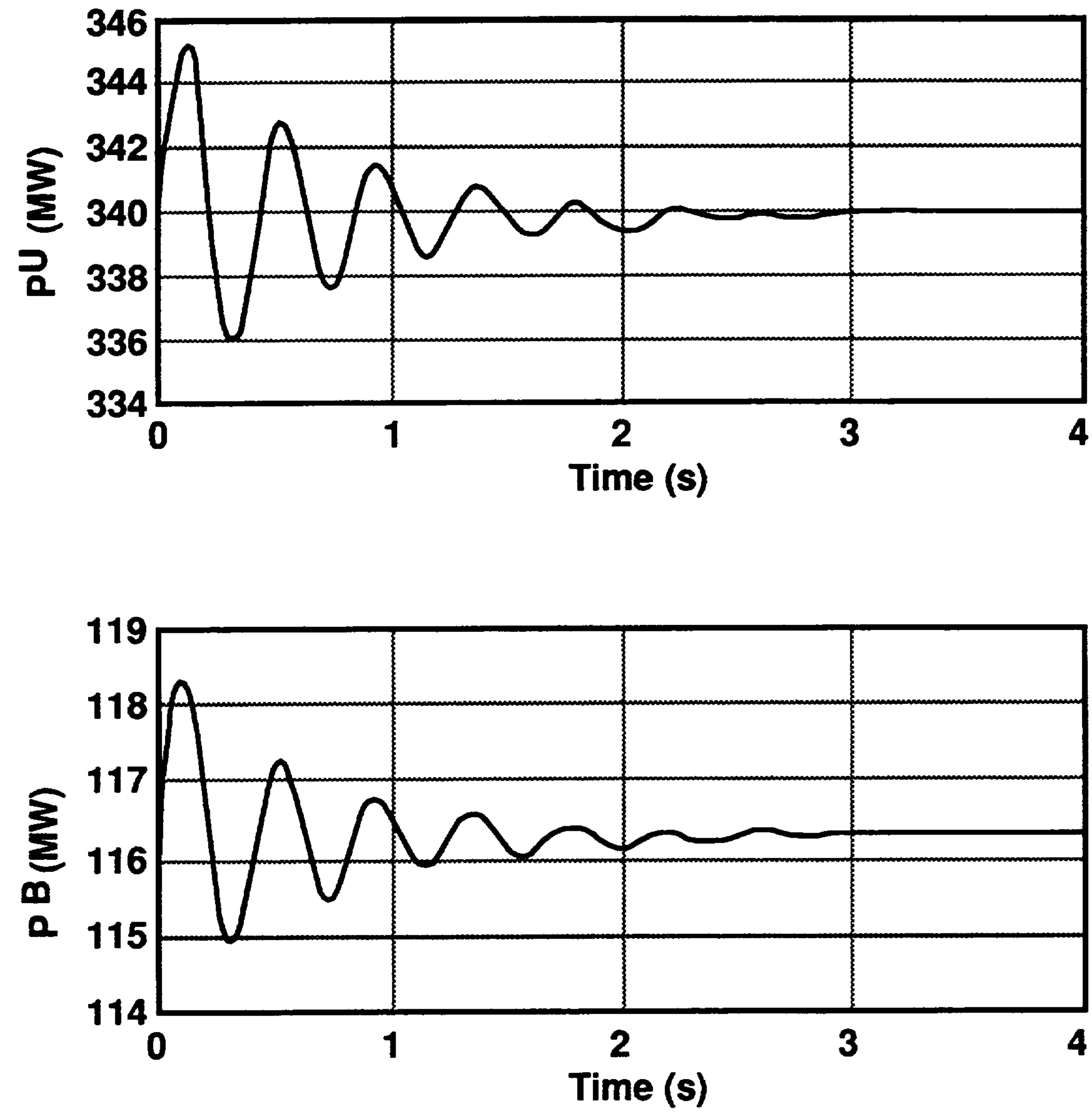


Fig. 6. UTVC and boiler column power levels following a $ 1.00 positive reactivity step insertion imposed on the boiler columns.

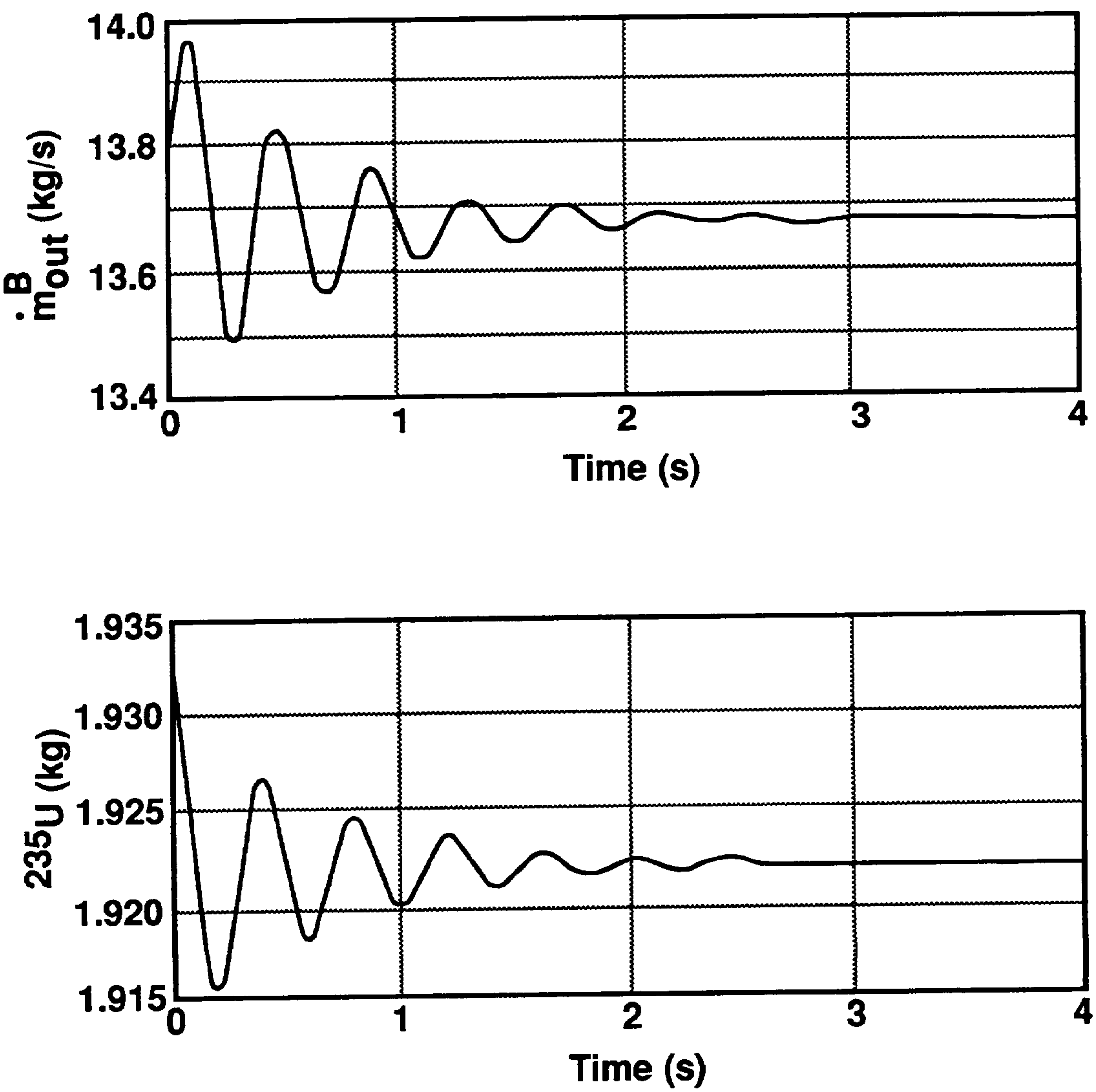


Fig. 7. Boiler column outlet mass flow rate and ^{235}U loading following a \$1.00 positive reactivity step insertion imposed on the boiler columns.

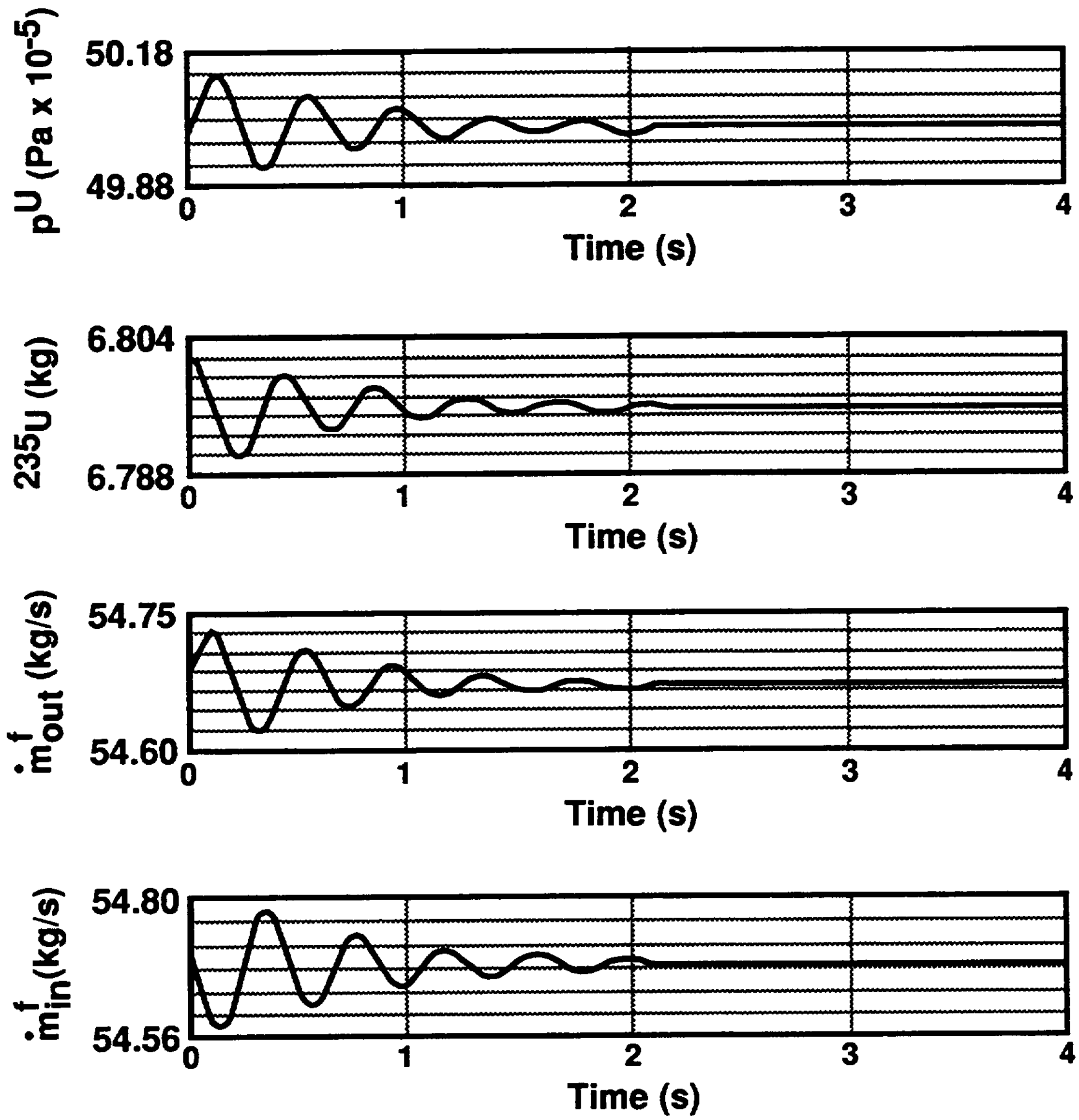


Fig. 8. UTVC pressure, ^{235}U loading, and UF_4/NaF inlet and outlet mass flow rates, following a $1.00 positive reactivity step insertion imposed on the boiler columns.

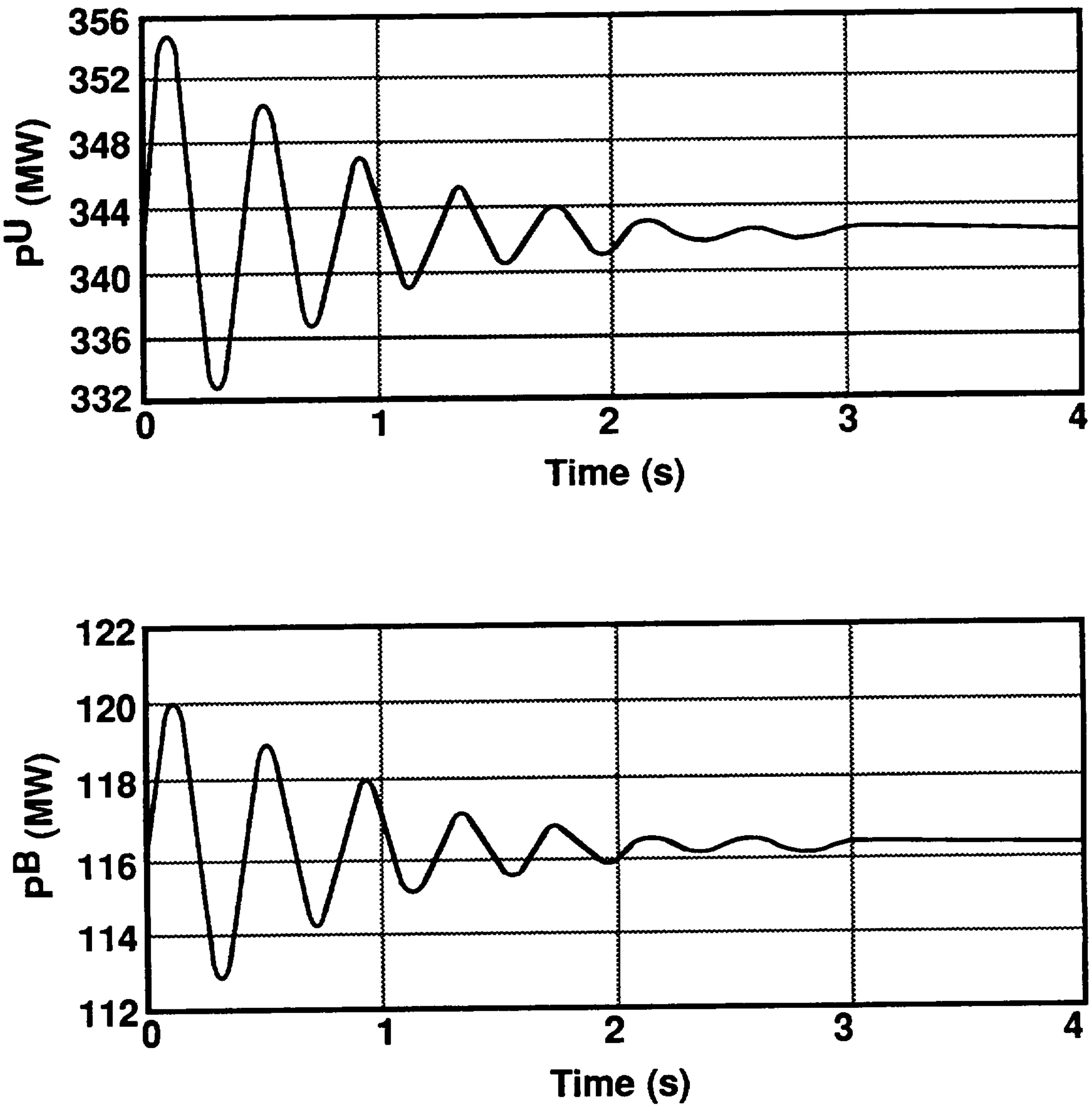
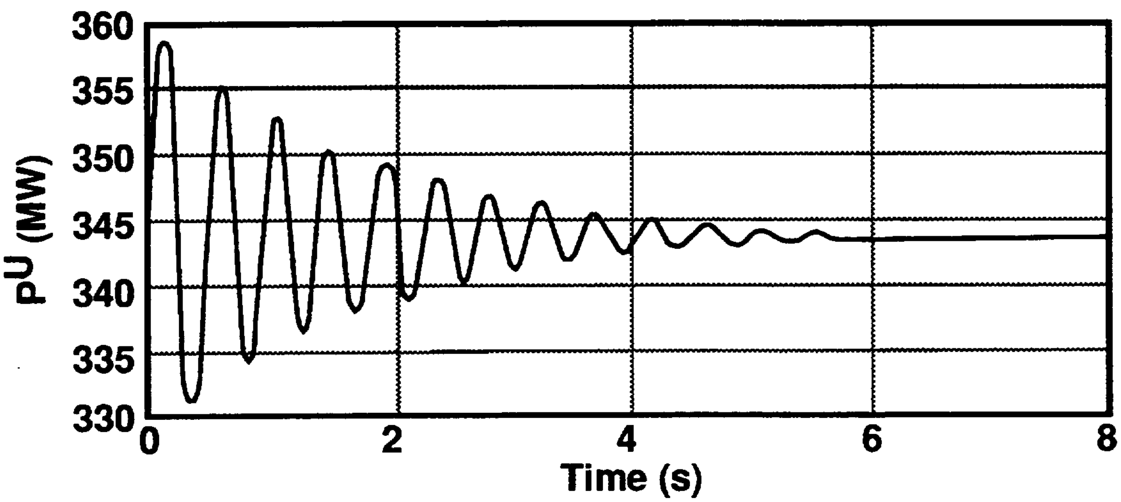


Fig. 9. UTVC and boiler column power levels following a $ 0.20 positive reactivity step insertion imposed on the UTVC.



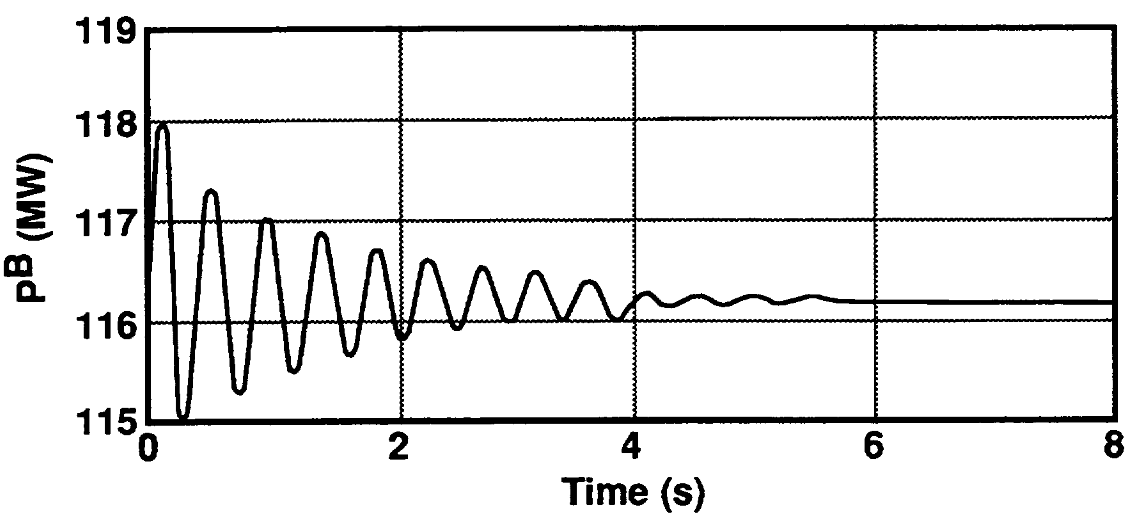


Fig. 10. UTVC and boiler column power levels following a \$ 0.20 positive reactivity step insertion imposed on the UTVC with the coupling coefficients reduced by one order in magnitude.

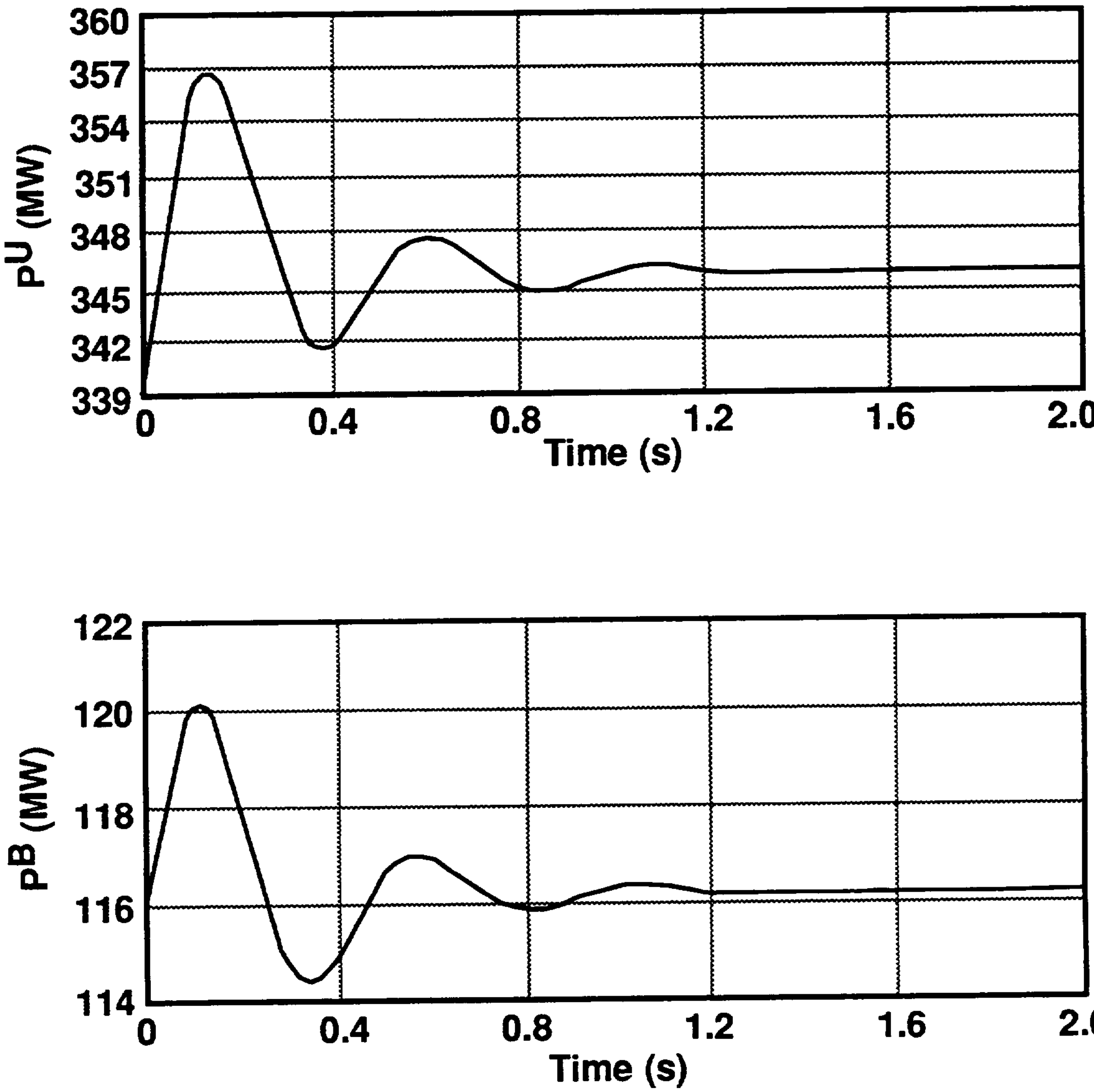


Fig. 11. UTVC and boiler column power levels following a \$ 0.20 positive reactivity step insertion imposed on the UTVC with the UTVC fuel mass reactivity feed-back coefficient reduced by a factor of five.

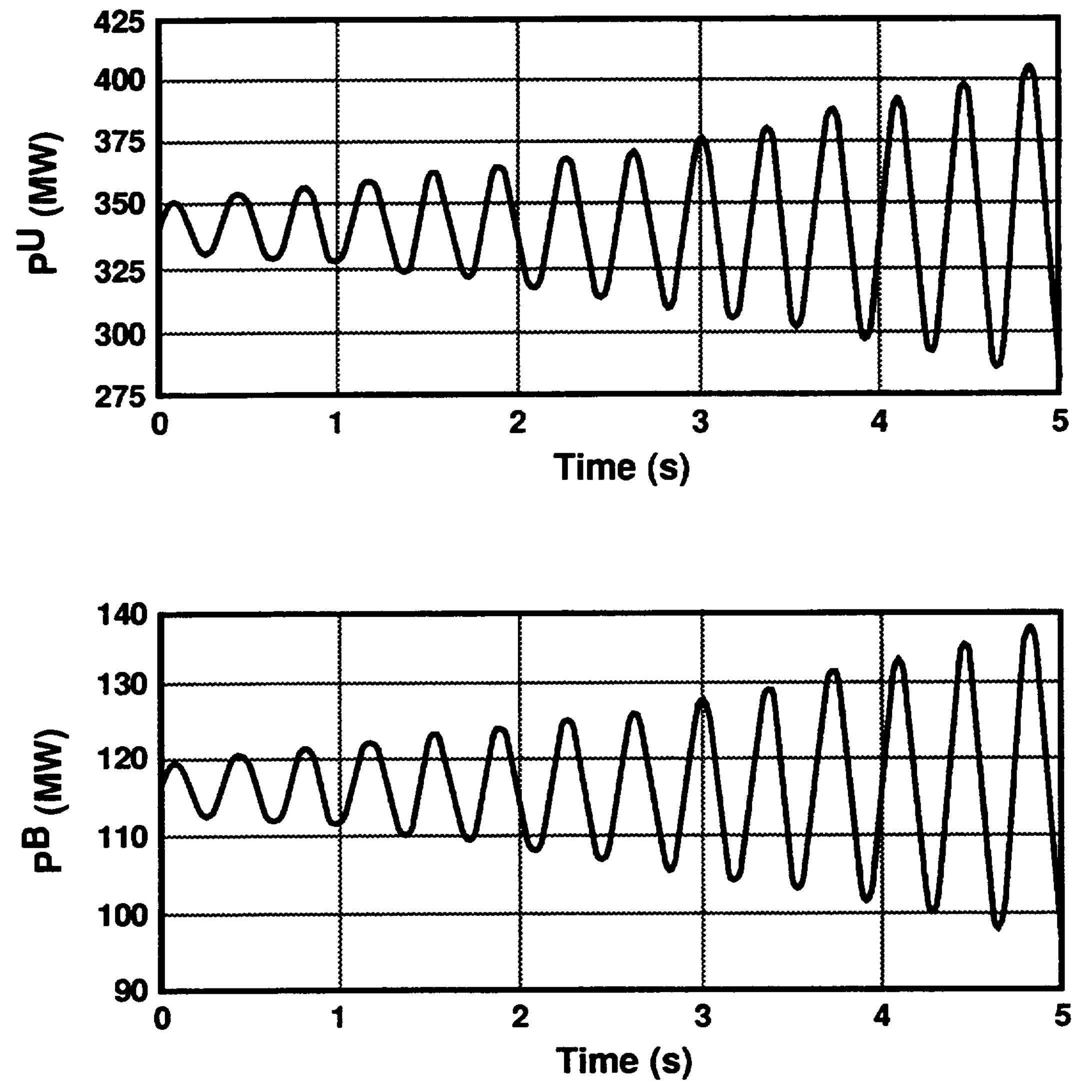


Fig. 12. UTVC and boiler column power levels following a \$0.20 positive reactivity step insertion imposed on the UTVC at t=0 sec with the UTVC fuel mass reactivity feedback coefficient increased by a factor of two.

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13. ABSTRACT ***(Maximum 200 words)***

Static and dynamic neutronic analyses have been performed on an innovative burst mode (100's of MW output for a few thousand seconds) Ultrahigh Temperature Vapor Core Reactor (UTVR) space nuclear power system. The NVTR employs multiple, neutronically-coupled fissioning cores and operates on a direct, closed Rankine cycle using a disk Magnetohydrodynamic (MHD) generator for energy conversion. The UTVR includes two types of fissioning core regions: (1) the central Ultrahigh Temperature Vapor Core (UTVC) which contains a vapor mixture of highly enriched UF_4 fuel and a metal fluoride working fluid and (2) the UF_4 boiler column cores located in the BeO moderator/reflector region. The gaseous nature of the fuel, the fact that the fuel is circulating, the multiple coupled fissioning cores, and the use of a two phase fissioning fuel lead to unique static and dynamic neutronic characteristics. Static neutronic analysis was conducted using two-dimensional S_n transport theory calculations and three-dimensional Monte Carlo transport theory calculations. Circulating-fuel, coupled-core point reactor kinetics equations were used for analyzing the dynamic behavior of the UTVR. In addition to including reactivity feedback phenomena associated with the individual fissioning cores, the effects of core-to-core neutronic and mass flow coupling between the UTVC and the surrounding boiler cores were also included in the dynamic model. The dynamic analysis of the UTVR reveals the existence of some very effective inherent reactivity feedback effects that are capable of quickly stabilizing this system, within a few seconds, even when large positive reactivity insertions are imposed. If the UTVC vapor fuel density feedback is suppressed, the UTVR is still inherently stable because of the boiler core liquid-fuel volume feedback; in contrast, suppression of the vapor fuel density feedback in "conventional" gas core cavity reactors causes them to become inherently unstable. Due to the strength of the negative reactivity feedback in the UTVR, it is found that external reactivity insertions alone are inadequate for bringing about significant power level changes during normal reactor operations. Additional methods of reactivity control, such as variations in the gaseous fuel mass flow rate, are needed to achieve the desired power level control.

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