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A SPLIT-CORE HEAT-PIPE REACTOR FOR SPACE POWER APPLICATIONS

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A SPLIT-CORE HEAT PIPE REACTOR CONCEPT FOR AN OUT-OF-CORE THERMIONIC POWER SYSTEM

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Abstract

The design and operation of small $U^{235}C$- and $U^{233}C$- fueled cores with axial heat pipes for a 350 kWe out-of-core thermionic power system has been investigated. A split in the core at midplane is used for reactivity control. Each half core is built up from modules, each of which consists of a fuel element with a central heat pipe that extends beyond the axial reflector. With 1cm-diameter heat pipes a typical U^{235} core has a 30cm diameter and contains 123kg of U^{235} and a typical U^{233} core has a 24cm diameter and contains 55kg of U^{233}. The physics of the design concept are presented for both $U^{235}C$ and $U^{233}C$ systems. A study of the startup dynamics of the reactor and heat pipes shows that ramp reactivity inputs should be limited to less than 2cents/sec for the U^{233} reactor and less than 8 cents/sec for the U^{235} reactor.

Introduction

The demands of future long-lived space power systems require reliable nuclear heat sources. The Lewis Research Center is engaged in technology studies of compact fast reactors which are built of refractory metals and use liquid metals for cooling. The split-core, heat-pipe reactor, which supplies heat to an out-of-core thermionic converter system, is one concept under study.

Development efforts in thermionic energy conversion have almost completely focused on the use of thermionic converters located in the core of reactor, but recently several technological advances in thermionic converters, refractory metals and heat pipes have stimulated new interest in out-of-core thermionics. The scope and impact of these advances are reviewed in references 1 and 2.

The reactor concept of a 350kWe power system is described here. The out-of-core thermionic converter system is discussed in reference 1. A smaller reactor of the same concept is utilized in a 150kWe out-of-core thermionic converter system described in reference 2.

Reactor Description

For space missions it is important to keep the size and weight of shielded reactors as low as possible. Since the weight savings of a reactor and shield is a function of the cube of the reactor diameter, reactor sizing is a prime factor in the design of a new system. The reactors under consideration are fueled with $U^{235}C$ or $U^{233}C$, and the core volume fractions for void and tungsten are 0.3 and 0.1, respectively, of the fuel volume fraction. The remaining volume fraction is due to the 1cm diameter heat pipes, which number 241 in each half of the core. Under these conditions the fuel loading curves for reactor cores with the ratio of length to diameter equal to unity are plotted in Figure 1 against the diameter for several fuel volume fractions. These curves arise from the geometric and physical constraints given above. On top of these curves is plotted a bolder curve which is the locus of reactors with about 9 percent excess reactivity in the core, which is presumed to be sufficient to meet control and lifetime requirements. This curve was determined for both the U^{235}- and U^{233}- fueled cores from two-dimensional neutron transport calculations with consideration for the reflectors and plenum as described later in this report. The lower limit on the reactor diameter is dictated by the minimum heat pipe diameter and system power requirements. The reference reactors selected for this study are a 30cm diameter core containing 123kg of U^{235} and a 24cm diameter core containing 55kg of U^{233}. A summary of some physical characteristics of these designs is given in Table 1.

The basic design philosophy is compactness and reliability through modularity. The basic module for this design is the reactor heat pipe module, which contains the axial reflector as an integral part, as shown in Figure 2, and is based on a heat exchanger design study by Breitwieser (reference 3). The cylindrical heat pipe evaporator makes a transition in the upper part of the axial reflector region to the rectangular box of the condenser section. Advantages and redundancy are obtained by using modular heat pipes so they alleviate many of the problems of the pump and loop designs. For example, no auxiliary heating system is required for melting a liquid metal coolant prior to reactor startup, no backup cooling system is needed for loss-of-coolant and loss-of-flow accidents, no auxiliary cooling system need be provided to remove afterheat, and no pumps are used for coolant circulation. Reliability is also gained through the redundancy of heat pipes; for example, in the event of failure of isolated heat pipes the adjacent heat pipes help cool the affected fuel regions and allows the reactor to operate and deliver useful power. In this design 241 modules are joined together to form a nearly circular axial reflector. (This is for a 350kWe power level. At a lower level of 150kWe 163 pipes are used; cf. reference 2.) This also sets the grids for the heat exchanger and the core.

The uranium carbide-tungsten fuel slugs are designed to fit between the heat pipes and not around them, several possibilities of which are shown in Figure 3. With only fuel and heat pipes in the core high fuel volume fractions (0.50 for the U^{235} design) are achieved, resulting in compact cores. By maintaining contact with more than one heat pipe the fuel can transfer heat out if a heat pipe fails. The contact between fuel and heat pipe is accomplished by pressure from the radial reflector or from a girdle at the core radial surface. Axially the fuel rests against a plenum at the core midplane and is allowed to expand into a gap between the core and axial

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reflector. Clearance between the fuel slugs allows for fuel expansion and fuel growth. This clearance and possibly holes in the fuel slugs allow the fission gases to escape from the core through the midplane plenum (Figure 4) and through passageways in the control rods to collectors at the ends of the control rods.

The schematic of the split-core, heat-pipe reactor shown in Figure 4 is an axial cut through the reactor. Looking down the line of the axis one would see the radial reflector as an annulus surrounding a nearly circular core cross section. The reactor consists of two identical halves separated in the middle by a variable gap used for reactivity control. The tungsten-lithium reactor heat pipes carry the heat to the two heat-pipe heat exchangers immediately outside of the axial reflectors. From here long heat pipes (reference 4) wind through the shield surrounding the reactor to the thermionic converters (reference 5) which lie beyond the shield in a manner which prevents direct radiation streaming from the core. The result is a compact reactor with an inherent reliability due to the redundancy of modularity.

Reactivity Control

Reactivity control is by two modes: one active, the other passive. The first is by axial translation of the two halves by a set of control drives around the periphery of the reactor. The second is by stepped shims for excess reactivity control. These are stepped mechanical stops which limit the inward travel of the core halves. The size of the steps determines the maximum reactivity available to the core in a single insertion. The active control is nonlinear until the gap decreases to about 2 or 3cm; then it becomes nearly linear, as shown in Figure 5. In the graph on the left the U^{233} reactor is more sensitive than the U^{235} because of the enhanced leakage due to its smaller size. The sensitivity is further amplified by the smaller delayed neutron fraction in the U^{233} reactor, as shown by the curves on the right, plotted in units of $, in Figure 5. A characteristic of this type of reactivity control is that it only requires separating the core halves a short distance to obtain a large shutdown reactivity.

Startup Kinetics

Parallel studies of the reactor kinetics of both the U^{233} and U^{235} reactors have been made. Since the heat pipe is noted for its ability to transport large quantities of heat and to react promptly to temperature transients, a study of the startup mode dynamics is presumed to lead to greater operating restrictions than a study with the heat pipe in the normal operating condition. The effort was directed to finding limiting operating ranges of reactivity input and determining the effects of ambient temperature, axial fuel expansion and Doppler doefficients on the limiting transients through parametric studies of the reactivity ramp input rate and level. These studies are preliminary in nature and therefore do not necessarily reflect the final set of limits on the system. The reactor was modeled by nodes which represent an average cell in the core, an average heat pipe, the reflectors and the plenum. The heat pipe startup formulas, as written by Sockol (reference 6), describe a pressure front initially in the axial reflector zone until the lithium temperature in that zone reaches that in the core zone. Then the front advances to the heat exchanger. The heat pipe does not proceed beyond this stage in startup as far as the core is concerned. The calculations were done with a version of the AIROS (reference 7) reactor dynamics code modified to take into consideration Brehm's formulas for Doppler effects (reference 8), radiative heat transfer between zones, and the heat pipe startup equations. The expansion reactivity coefficients were calculated with the aid of the TDSN (reference 9) and PERTRAN (reference 10) programs. The Doppler and expansion reactivity coefficients are listed in Table 2.

Typical characteristics of startup transients are shown through the illustration of a single transient in Figure 6; this is for a ramp at 1$/sec to a 1$ level in a U^{235} reactor. The reference reactor for both the U^{233} and U^{235} systems had a 300K initial temperature everywhere, Doppler coefficients calculated according to Brehm's formulas and free axial expansion of the fuel. The reactivity curve in certain cases may peak out slightly above one dollar for a short period of time without an excursion occurring. The fuel temperature here shows two peaks, an initial sharper one and a second one which rolls over more gradually. It is the height of the first which is the limiting factor. In general the heat flux displays sharp peaks for transients in which the fuel does not melt. In certain cases the heat flux rises and stays at a high level, but in these cases the fuel also melts so that the fuel temperature is the more limiting factor.

The reference case parametric analysis of the U^{233} and U^{235} reactors is shown in Figure 7. Also shown is the case where the Doppler coefficients are taken to be one-fourth of the value predicted by Brehm. In the latter case the fuel Doppler values are then in agreement with those reported in ref. 11. The U^{233} Doppler coefficient is three times the U^{235} Doppler coefficient in terms of $\delta k/k$, but in terms of dollars of reactivity the factor is seven, which is reflected in the greater sensitivity of the U^{233} reactor to the faster transients. The transition zone between about 0.02 $/sec and 0.1 $/sec in Figure 6 and 7 separate the slower transients, in which the system thermodynamics keeps up with the neutronics, from the faster transients. It is not yet known what values of surface heat flux peaks will damage the heat pipe by causing a burnout. It is known that lithium heat pipes have been able to sustain 300 W/cm^2. Peaks reaching this point are marked in the graph to form a conservative upper limit on reactivity inputs. Actually the pipes can probably withstand larger peaks without burning out, and the transients are really fuel-temperature limited rather than heat-flux limited.

The positive fuel Doppler coefficient is overwhelmed by the magnitude of the negative fuel expansion coefficient. However, the radial component of the fuel expansion is constrained by the reflector or other radial component which holds the core together. The promptness of the axial fuel expansion depends on slippage between the fuel and heat pipes, which is not likely to be present if the core is held tightly together, especially later in core life when wall and fuel bond together. The effect of removing the axial fuel expansion effect to the heat pipe with which it expands is shown in Figure 8. Whereas in the preceding Figure a 1$/sec ramp to the 1$ level was safe, here it is not. There is a definite critical rate above which reactivity input rates can be catastrophic. It is about 2 cents/sec for the U^{233} and 8 cents/sec for the U^{235} reactor. Below this rate the U^{233} reactor is less sensitive to transients than the U-235. If the magnitude of the Doppler coefficients are taken to be one-fourth of that predicted by Brehm's formulas so that the fuel coefficients match those reported in reference 11, then the 5$ plateaus appear at about 800K for U^{233} and 2000K for 235 (cf. Figure 7). Although it appears that even a level of 5$ is a safe input at low rates, the peak temperatures shown are only for the average temperature in an average cell. There may well be several hundred degrees separating the peak fuel temperature from the core averaged fuel temperature in a transient. Both systems, however, are inherently safe for reactivity inputs which reach less than 1$ and at rates less than 2 cents/sec. The upper limit for the level may be raised as more information becomes available.

Concluding Remarks

The split-core heat-pipe reactor concept presented here has many inherent features for safety and reliability. It requires no auxiliary system for melting a liquid metal coolant prior to startup, no backup system for loss-of-coolant or loss-of-flow accidents, no auxiliary system to remove afterheat and no pumps for coolant circulation. It could provide a light-weight, compact, reliable, constant high-temperature heat source adaptable to many forms of external conversion techniques.

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TABLE 1

Physical Characteristics of U^{233} and U^{235}
Split-Core, Heat-Pipe Reactors

	U^{233}	U^{235}
Length and diameter of core, cm	24.0	29.6
Fuel volume fraction in core	0.39	0.50
Mass of metallic fuel, kg	55	123
Average energy of neutrons, Mev	0.879	0.803
Delayed neutron fraction	0.00286	0.00670
Prompt neutron lifetime, nsec	26.5	31.9

TABLE 2

Reactivity Coefficients of U^{233} and U^{235}
Split-Core, Heat-Pipe Reactors

Doppler coefficients are 1/4 of the values predicted by Brehm's formulas at 2000K.

	U^{233}		U^{235}	
	$10^{-6}\ \delta k/k/K$	10^{-4} $/K	$10^{-6}\ \delta k/k/K$	10^{-4} $/K
1. Expansion				
Axial Fuel	- 3.20	- 11.19	- 3.02	- 4.51
Radial Fuel	- 5.24	- 18.30	- 2.01	- 3.00
Axial Reflector	- 1.26	- 4.41	- 0.89	- 1.33
Radial Reflector	- 8.24	- 28.81	- 7.25	- 10.82
Plenum	- 0.26	- 0.91	- 0.18	- 0.26
Heat Pipe	- 0.18	- 0.61	- 0.12	- 0.18
2. Doppler				
Fuel	0.326	1.139	0.109	0.162
Core Tungsten	- 0.059	- 0.205	- 0.063	- 0.094
Heat Pipe	- 0.202	- 0.705	- 0.112	- 0.167
Plenum	- 0.038	- 0.132	- 0.031	- 0.046

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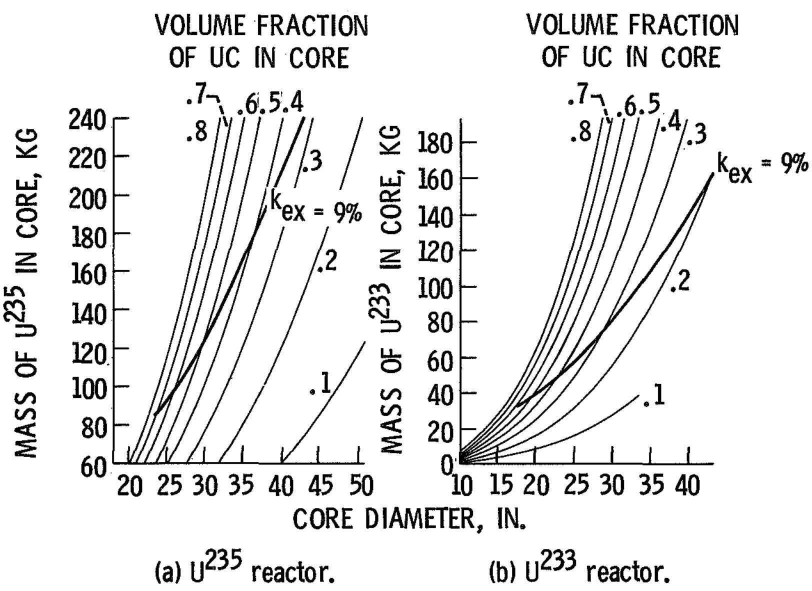

Figure 1. - Fuel loading curve for two reactors with about 9 percent excess reactivity.

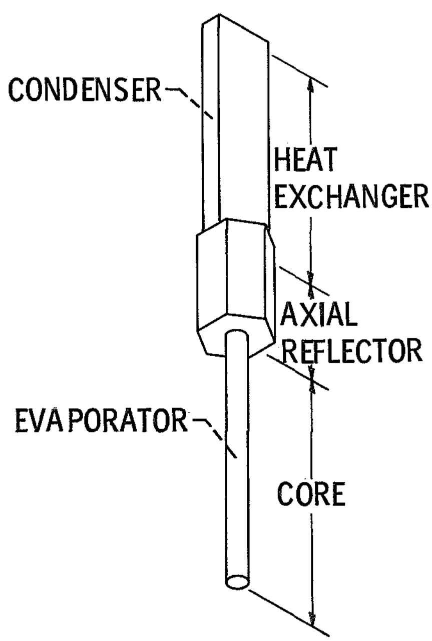

Figure 2. - Heat pipe module.

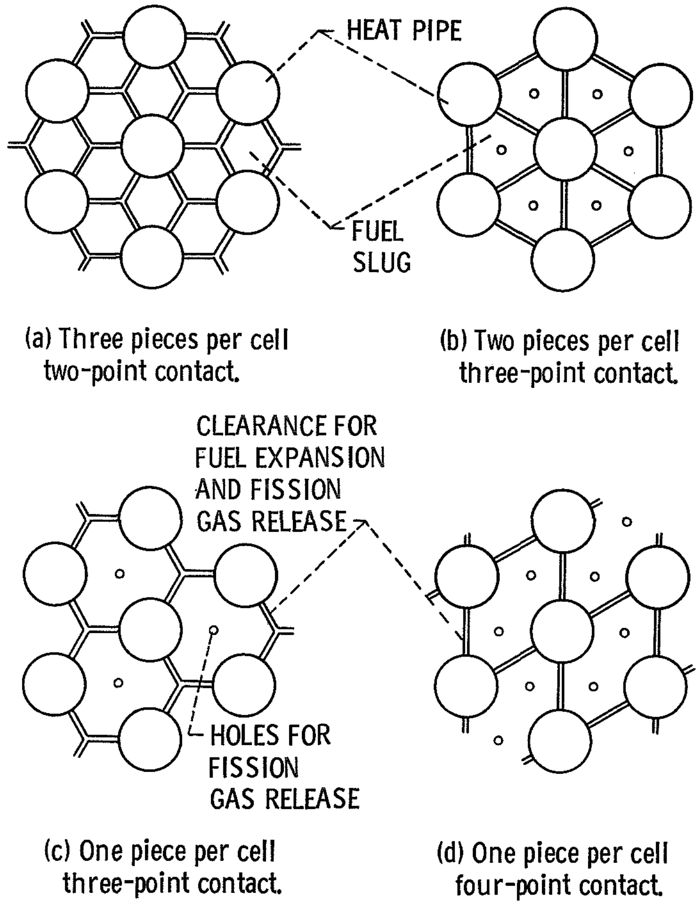

Figure 3. - Fuel slug configurations.

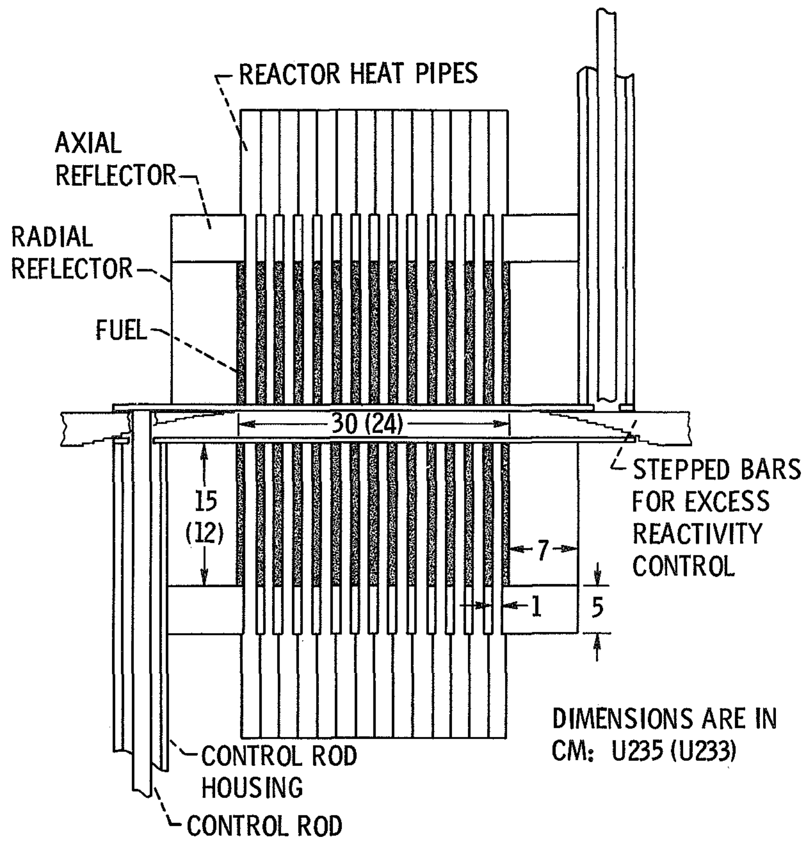

Figure 4. - Split-core, heat-pipe reactor concept.

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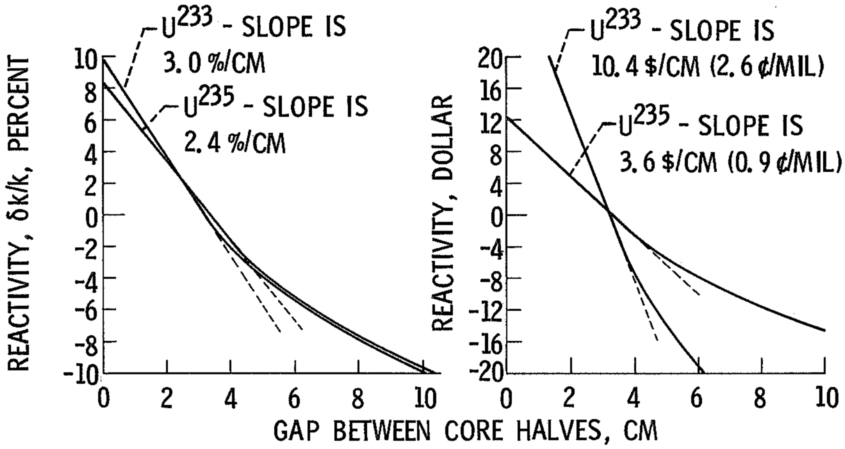

(a) Reactivity in percent. (b) Reactivity in dollars.

Figure 5. - Control rod worths.

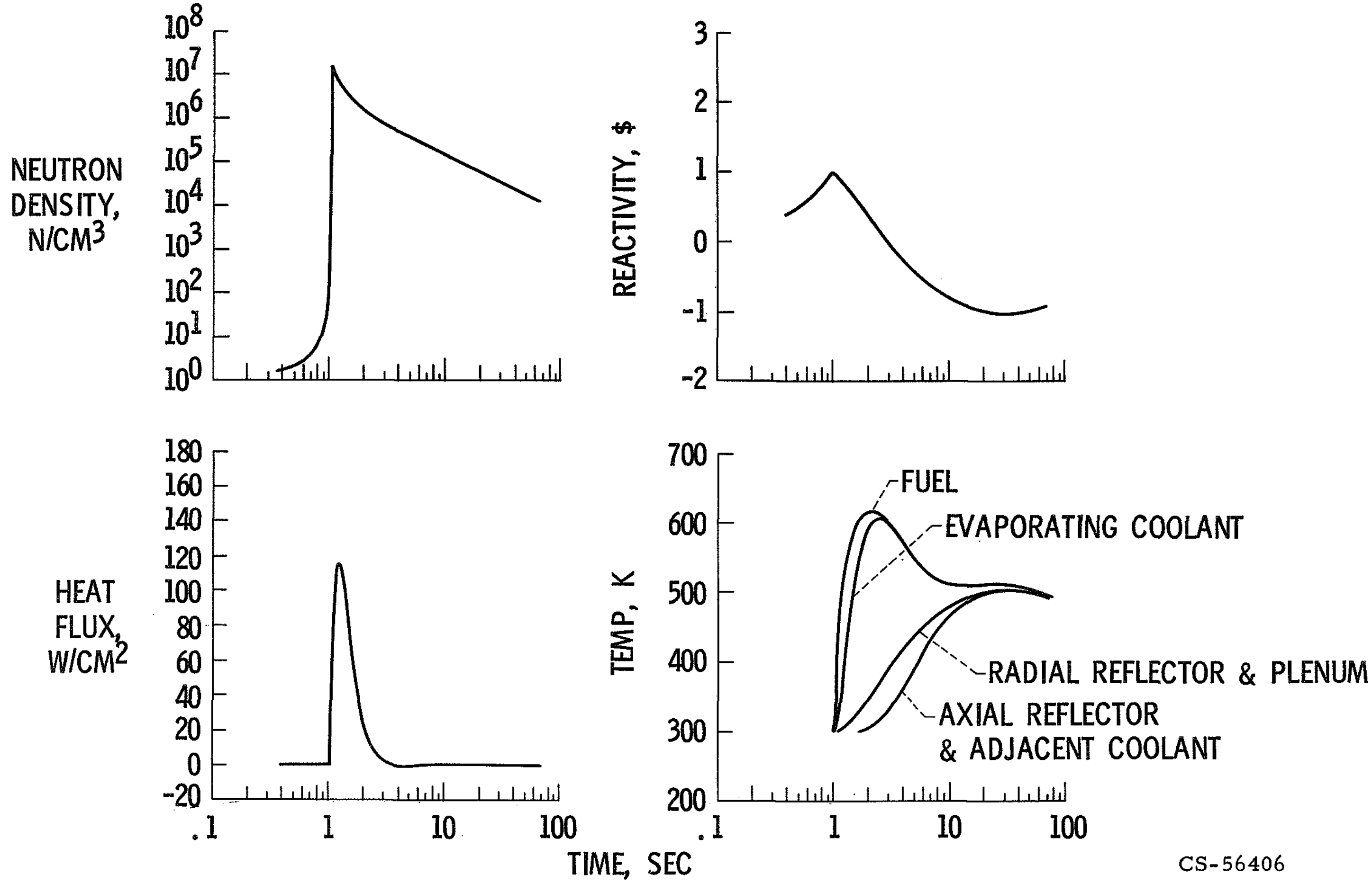

Figure 6. - U235 reactor transients for 1$/ sec to 1$ reactivity ramp input.

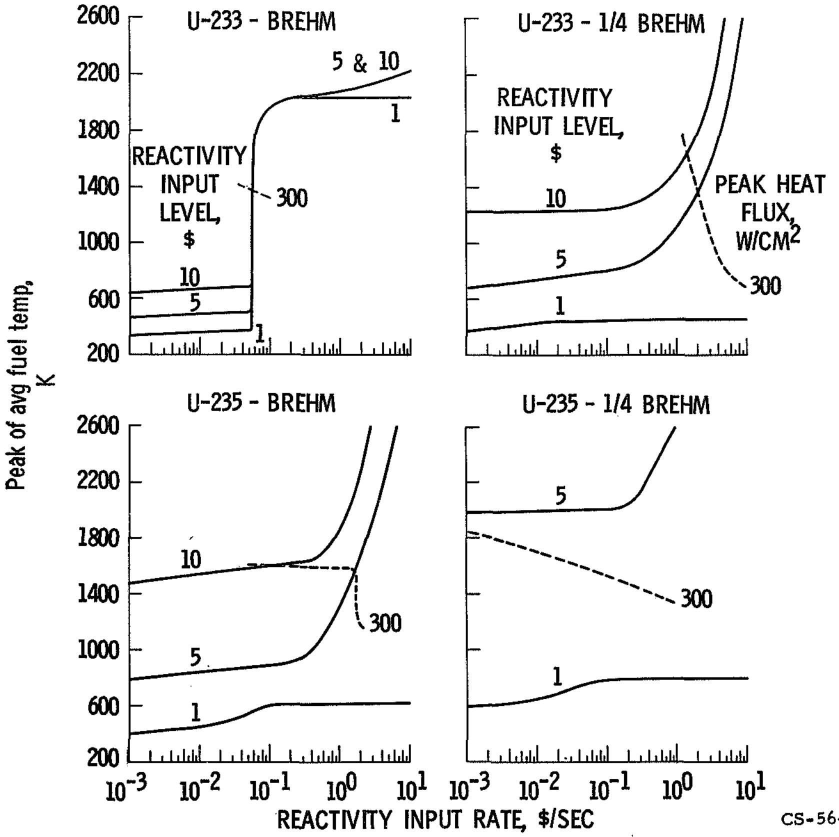

Figure 7. - Fuel temperature transients vs ramp reactivity inputs.

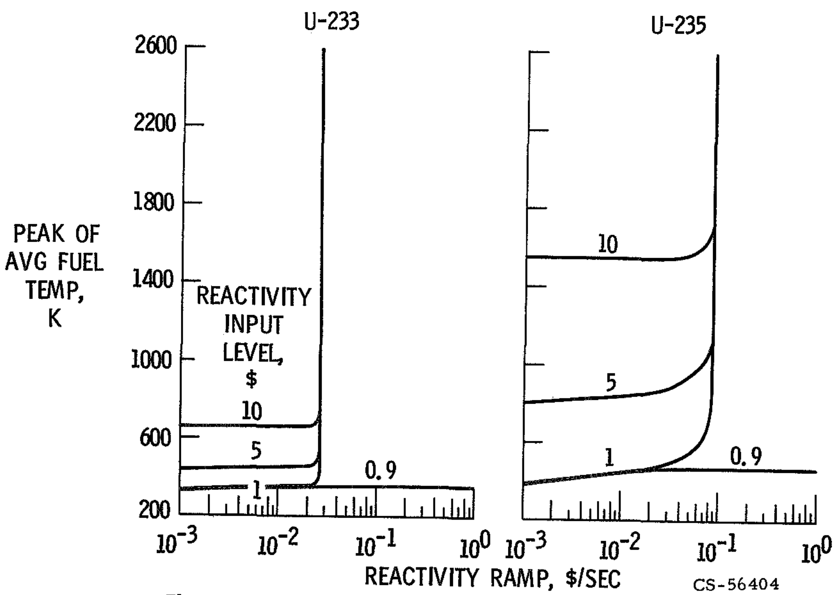

Figure 8. - Fuel temperature transients for fuel expanding axially with heat pipe.