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POWER COUPLING ALTERNATIVES FOR THE NEP THERMIONIC POWER SYSTEM

FINAL REPORT

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ABSTRACT

Three output power coupling methods which can eliminate the high temperature insulator from the NEP power system are described and estimates of their effects on the NEP system masses and cooling requirements are presented. Nominal 400 kWe power systems using push-pull and flux reset inductive output coupling are shown to have specific masses of 22.2 kg/kWe and 18.8 kg/kWe, respectively. Series connected heat pipe systems, which use the heat pipe-to-heat pipe resistance to isolate converters on adjacent heat pipes, are shown to have specific masses 0.5 to 1.4 kg/kWe lower than the NEP baseline system. Increasing the number and temperature of the heat pipes in the system without changing the electric output reduces the calculated system specific mass only slightly, whereas increasing the output power significantly reduces the specific mass. Estimates of cooling requirements indicate that 11-45 m^2 of power conditioning radiator are needed. A possible location for the power conditioning radiator may be in the present location of the kapton sputter shield.

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1.0 INTRODUCTION

The current design for a nuclear electric propulsion (NEP) spacecraft relies on a matrix array of individual thermionic converters to act as the power conversion system. Since the thermionic converters have series-parallel electrical connections in the matrix approach, high temperature electrical insulators (Sialon) are required to isolate adjacent converters on the same molybdenum heat pipe. These insulators, in addition to possessing the necessary thermal conductivity required to couple the thermionic emitters to the reactor, must match the thermal expansion of the molybdenum heat pipes, resist solid state electrolysis and arcing, and be stable in vacuum. These extreme requirements make it attractive to investigate alternate types of power conditioning which could completely eliminate this insulator from the power conversion system design.

The purpose of this study was to evaluate inductive and other output power coupling methods in light of the desire to eliminate the high temperature insulators from the power module design. Three power conditioning alternatives were considered in this report: push-pull, flux reset, and series connected heat pipes. Push-pull and flux reset are characteristic converter operating modes associated with inductive output power coupling. The series connected heat pipe concept utilizes the heat pipe-to-heat pipe resistance to electrically isolate the converters on one heat pipe from the converters on other heat pipes.

Incorporation of these power conditioning alternatives into the NEP spacecraft design may allow the elimination of the Sialon insulator with some alterations in the present system design. Performance and weight penalties must be considered in the utilization of inductive output coupling. Electrical connections and cooling requirements are different from the baseline design for both inductive output coupling and series connected heat pipes. These deviations from the baseline design were investigated in this study. The estimates of the mass, volume, and cooling requirements for each of the proposed power conversion schemes were generated from anticipated performance characteristics by perturbing the baseline figures.

2.0 POWER CONVERSION SYSTEM DESCRIPTION

2.1 90 Heat Pipe Baseline System

A cutaway view of the proposed NEP spacecraft and power conversion system designed by the Jet Propulsion Laboratory[1,2,3] is shown in Fig. 1. Ninety molybdenum heat pipes are used to transfer heat from a compact cylindrical reactor to an array of thermionic converters. The 540 converters produce 6 watts/cm^2 at an emitter temperature of 1650°K and a collector temperature of 925°K. A detailed listing of the system characteristics can be found in Table 1. This represents the baseline system and it is the basis for all calculations involving inductive output coupling. Some calculations are also performed for the series connected heat pipe case using baseline converter performance.

2.2 162 Heat Pipe Configuration

The 90 heat pipe baseline design exhibits thermal problems in the event of an isolated heat pipe failure.[3] This is especially true at the periphery of the core. An acceptable solution to this problem involves the use of a larger number of heat pipes whose diameter is smaller than the diameter of the baseline heat pipes. The current proposed configuration specifies a core containing 162 heat pipes 2.0 cm in diameter.[3,4] These heat pipes interface with the 90 converter supporting heat pipes through a heat exhanger located near the LiH shield. This presents no particular problem to the inductive output coupling concepts, since the converter emitters are at a common potential. However the length of the heat pipes from the converters to the heat exchanger is shorter than from the converters to the reactor. This reduces the standoff resistance between heat pipes and is undesirable for the series connected heat pipe power coupling alternative. Consequently, it was decided to eliminate the heat exchanger for this alternative and consider 162 heat pipes which were continuous from the reactor to the converter array.

The effects of a 162 heat pipe configuration on the series connected heat pipe output coupling scheme were investigated for emitter/heat pipe temperatures of 1650°K and 1800°K. This required knowledge of converter operating parameters. These parameters, however, have not been specifically

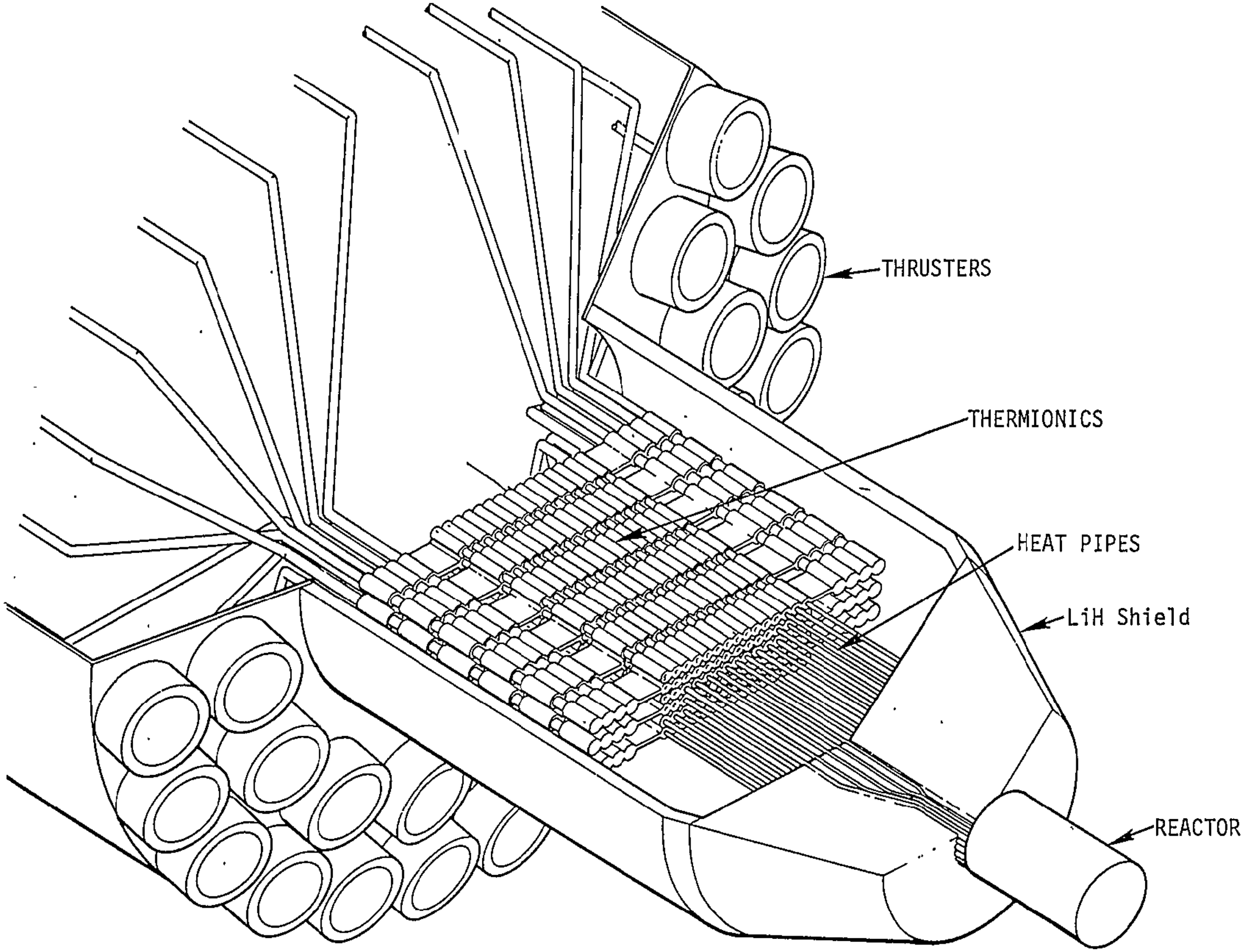


Fig. 1 Cutaway of All-Heat-Pipe System

Table 1

CONVERTER OPERATING PARAMETERS

		Modified Baseline Systems			
	Baseline System	162 Heat Pipe 1650°K	162 Heat Pipe 1650°K	162 Heat Pipe 1800°K	162 Heat Pipe 1800°K
Heat Pipes	90	162	162	162	162
Converters/Heat Pipe	6	6	5	5	4
Efficiency η(%)	15	15.6	15.3	17.3	16.8
Lead Power (W/cm^2) (BOL)	6	6.3	6.2	8.4	8.2
Emitter Temperature T_E(°K)	1650	1650	1650	1800	1800
Collector Temperature T_C(°K)	925	925	925	925	925
Converter Volts @ 10 A/cm^2 (V)(BOL)	0.6	0.63	0.62	0.84	0.82
Emitter Area/Converter (cm^2)	163.7	87.2	105.5	77.9	99.4
Converter Length (cm)	15.1	10.8	13.3	9.7	12.4
Emitter Diameter (mm)	34.5	25.5	25.5	25.5	25.5
Gross Output (BOL) (amps)	9815	5232*	5274*	3897*	3975*
Gross Output (BOL) (volts)	54	102*	100*	136*	133*
Gross Output (BOL) (kWe)	530	534*	530*	530*	528*
Nominal Operating Power (kWe)	443	446	443	443	441
Nominal Operating Current (amps)	8205	4370	4408	3257	3320

*Tabulated Gross Output (amps, volts) are values which would be achieved with series-parallel converter electrical connections reported for baseline system.

defined for the 162 heat pipe reactor. A number of design alternatives are possible (i.e. vary the number and/or the size of the converters to compensate for a larger number of heat pipes); but determination of the optimum system is beyond the intended source of this study.

Two converter design alternatives with 162 heat pipes were considered for each of the proposed emitter/heat pipe temperatures. The four cases are:

1. T_E = 1650°K, 6 converters/heat pipe, $P_{out} = P_{baseline}$
2. T_E = 1650°K, 5 converters/heat pipe, $P_{out} = P_{baseline}$
3. T_E = 1800°K, 5 converters/heat pipe, $P_{out} = P_{baseline}$
4. T_E = 1800°K, 4 converters/heat pipe, $P_{out} = P_{baseline}$

where: P_{out} = output power from thermionics for proposed system

$P_{baseline}$ = output power from thermionics for baseline system = 443 kWe (EOL)

The details of these design alternatives are listed in Table 1.

3.0 INDUCTIVE OUTPUT COUPLING

3.1 Concept Description

Inductive output coupling refers to the connection of the thermionic converters to their load through the windings of a transformer. Two modes of inductive output coupling, push-pull and flux reset, were investigated in this study. Both of these methods couple the converters to their load inductively by switching the converters between two characteristic operating states (high current, low impedance ignited mode and low current, high impedance unignited mode).

The emitters of converters operating in an inductive output coupling system are usually at the same electrical potential. This eliminates the requirement that individual converters be isolated from each other and thus allows the high temperature Sialon insulator to be removed from the NEP system.

The connection of the converters in series-parallel is not required when using inductive output coupling, because voltage transformation is attained by adjusting the transformer turns ratio. However both push-pull and flux reset systems operate at less than 100% duty cycle and less than baseline efficiency.

3.2 Push-Pull Inductive Output Power Coupling

The simplest inductive output coupling method is push-pull, where two converters are connected to the center-tapped primary winding of a transformer as shown in Fig. 2. The characteristic operating points for the converters are also shown in Fig. 2. While one converter is producing power, the other converter is operating in its high impedance state. To reverse the flux in the transformer core, the converters are switched simultaneously between operating states by means of a pulse generator connected to the transformer secondary. The output using this coupling method is square wave ac, with the voltage determined by the transformer turns ratio.

PUSH-PULL

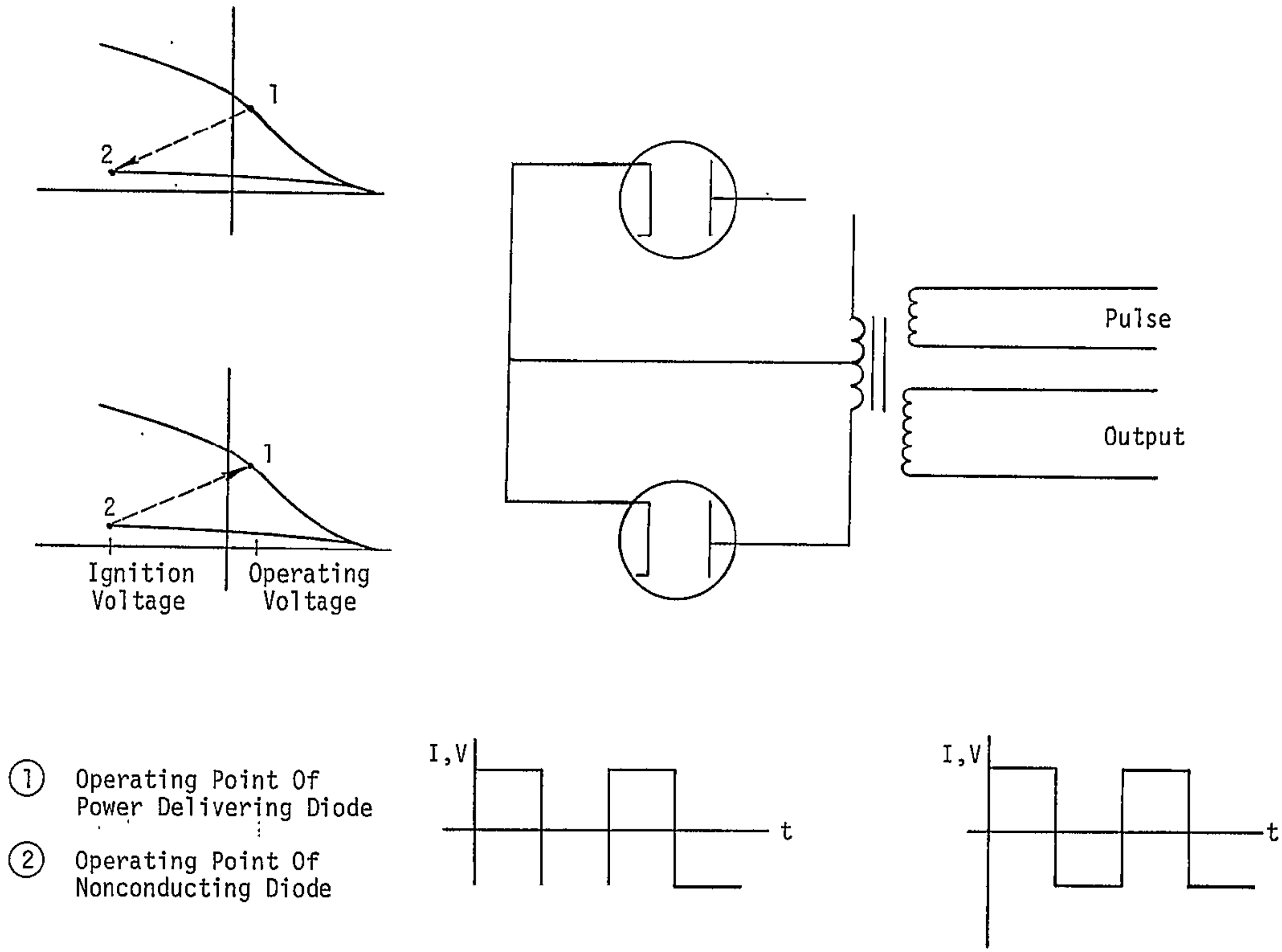


Fig. 2 Push-Pull Operating Characteristics

The duty cycle of each converter in a push-pull power conditioning system is 50%. Thus, twice as many converters as the baseline design are required to produce the same output power. It is not necessary, however to double the reactor power to compensate for the loss in output power (i.e. the system efficiency does not drop by a factor of two with a 50% duty cycle).

Input power required at the emitter is determined by radiative heat transfer, cesium thermal conduction, conduction losses through the leads, and electron cooling of the emitter. Electron cooling and radiative heat transfer dominate over the other modes of heat transfer. A good fit to most converters is provided by the equation[5].

$$P_{in} = 1.8 \times 10^{-3} \, JT_E + 1.2 \times 10^{-12} \, (T_E^4 - T_C^4) \quad (1)$$

where P_{in} = input power density (W/cm^2)
J = converter current density (A/cm^2)
T_E = emitter temperature (°K)
T_C = collector temperature (°K).

The first term in Eq. (1) represents the electron cooling and the second term is the radiative heat transfer between the emitter and collector. Thus, the input power equation may be written

$$P_{in} = Q_{ec} + Q_{rad} \quad (2)$$

where Q_{ec} = electron cooling (W/cm^2)
Q_{rad} = radiation heat transfer (W/cm^2).

For the baseline case, the efficiency of the converter is just

$$\eta = \frac{P_{out}}{Q_{ec} + Q_{rad}} , \quad (3)$$

where P_{out} = converter output power density. With push-pull, the output power is decreased by 50%. The electron cooling term also decreases by a factor of two since only half of the converters are conducting current at a given time. The radiation term does not change, however, since all the converters lose power by radiation, even when they are not conducting. Thus, the efficiency of the push-pull system, η', is described by

$$\eta' = \frac{(P_{out}/2)}{(Q_{ec}/2) + Q_{rad}}. \qquad (4)$$

Eqs. (3) and (4) combine to yield

$$\frac{\eta'}{\eta} = \frac{Q_{ec} + Q_{rad}}{Q_{ec} + 2\,Q_{rad}}. \qquad (5)$$

Q_{ec} and Q_{rad} are calculated from Eq. (1) using the appropriate values for J, T_E, and T_C. The NEP system, for example, specifies that

$$J = 10\ A/cm^2$$

$$T_E = 1650°K$$

and $$T_C = 925°K.$$

Thus,

$$Q_{ec} = 1.8 \times 10^{-3}\ J\ T_E = 29.7\ W/cm^2.$$

Similarly, $Q_{rad} = 1.2 \times 10^{-12}(T_C{}^4 - T_C{}^4) = 8\ W/cm^2$ and

$$\frac{\eta'}{\eta} = .83$$

Push-pull operation, then, is capable of achieving a maximum efficiency about 83% that of baseline efficiency. To obtain the same output power as the baseline system, the reactor power must be increased by $1/(\eta'/\eta)$. This implies that the reactor power must be increased by 20% with push-pull operation.

Operational restrictions on the utilization of push-pull inductive output coupling are dictated by operating characteristics of the thermionic converters. In particular, the magnitude of the diode ignition voltage should be no less than the desired output voltage.

The ignition voltage of a cesium diode converter is a function of cesium pressure, emitter temperature, and interelectrode gap. Fig. 3 shows the behavior of the ignition voltage as a function of emitter temperature and cesium pressure for constant interelectrode gap.[6]

As shown in the figure, the ignition voltage decreases with increasing emitter temperature. The emitter temperature at which the ignition voltage moves into the power quadrant represents an upper limit for operation of a system with inductive output coupling. For the converter characterized in Fig. 3, the ignition voltage moves into the power quadrant for $T_E \gtrsim 1675°K$. However, cylindrical devices have been operated above this temperature with ignition voltages >0.6 volts out of the power quadrant.[+] Also, the temperature limitation may be removed by addition of small amounts of inert gas to the converter plasma, since this increases the ignition voltage. However, experiments with converters used as switches have shown that at least 10 to 20 Torr of argon must be added to the plasma to affect the ignition voltage.[7] This amount of gas in the interelectrode space would cause significant thermal conduction between the emitter and collector, and thus would reduce the converter efficiency.

Further constraints are imposed on the system by the converter turn-off time. Turn-off time places an upper limit on the switching frequency and thus impacts the size of the transformer used in the power conditioning schemes. Transformer weight decreases with increasing frequency. High frequency operation may be possible if a large amount of power is used to turn off the converters at a faster rate. This requires a large magnitude auxiliary pulse to field drift the ions out of the interelectrode space rapidly. An optimum may be found by trading off the increase in auxiliary power for the decrease in transformer weight with higher frequency operation.

[+]Rasor Associates, Inc. mini system converter, 1975

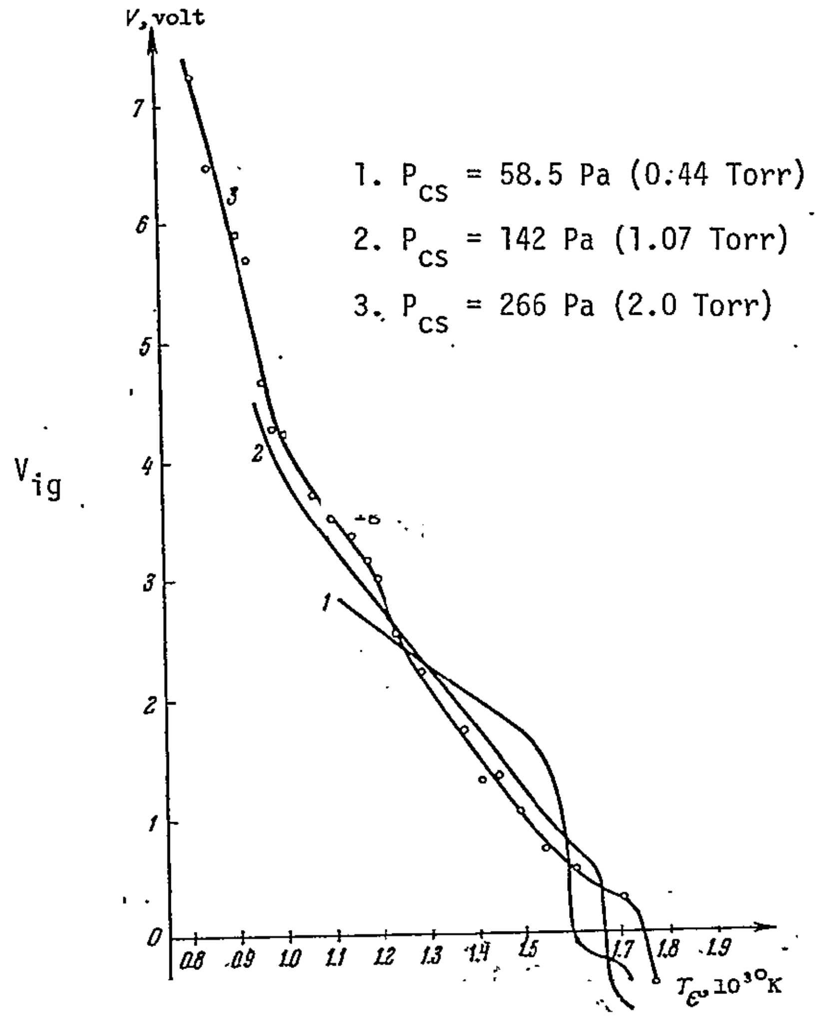


Fig. 3 Dependence of Ignition Voltage V_{ig} on Emitter Temperature, T_E. GAP = 0.5 mm (Ref. 6)

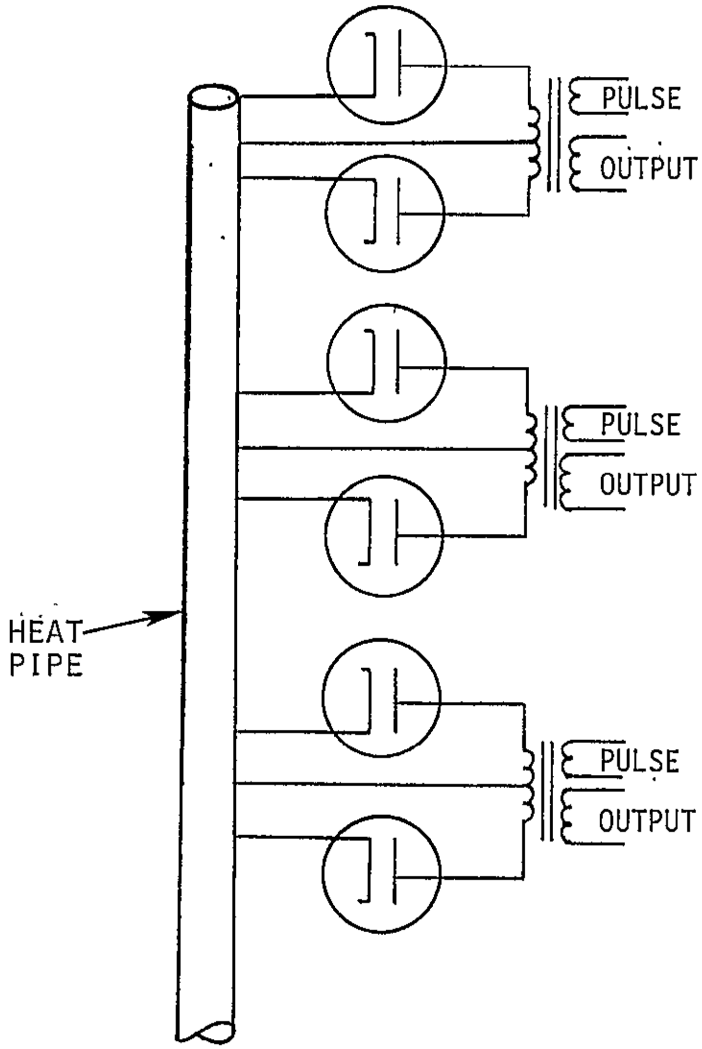
If the auxiliary turn-off power is low, typical turn-off times for operating converters are about .1 msec, and output waveforms should thus have a half period around 10 msec. The cycle frequency, then, should be near 50 Hz. The specific mass of 60 Hz transformers proposed for terrestrial applications of flux reset systems has been estimated to be about 6.1 kg/kWe. With some design optimization it is believed that the transformer specific mass for a space power system operating at a similar frequency could be reduced to less than half this value.

Advanced mode converters with controllable auxiliary ion sources could also be used in the NEP system. The turn-off time for an auxiliary ion source converter is governed by ion decay times (100-600 μsec).[8] This can potentially increase the switching frequency to a value above 100 Hz with concurrent reductions in transformer mass.

There are a number of ways in which push-pull may be incorporated into the NEP system design. Figs. 4, 5, and 6 show three of the possible ways to connect converters to the transformers. In all cases, the transformers must be located near the converter array to minimize bus bar losses.

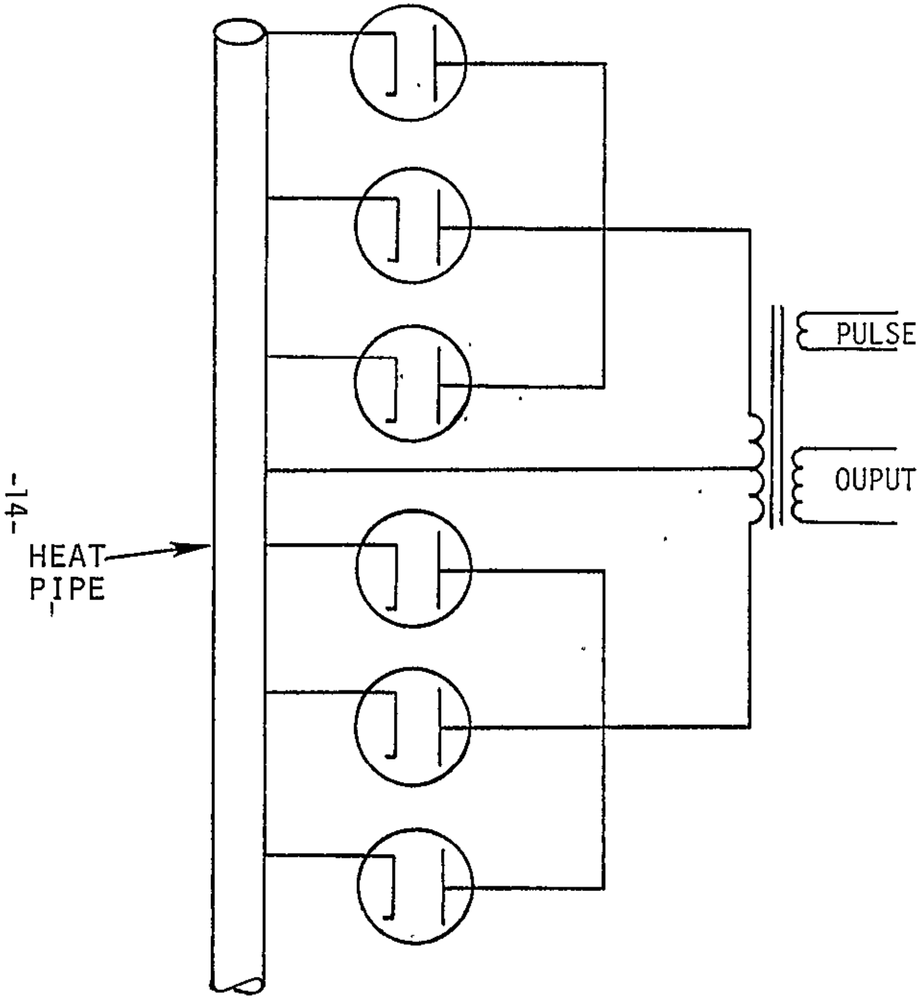
Fig. 4 shows a configuration in which many small transformers are interspersed with the converter array. It offers the desired system redundancy. However, a single converter failure (both open and short circuit) disables two converters electrically, and can adversely affect the heat pipe thermal power dissipation. An open circuit failure of one converter in a pair does not affect the thermal power dissipation capability if the remaining converter in the pair can be ignited to permit electron cooling. Failure to ignite the remaining converter, however, will result in a 19% loss in thermal power dissipation. Conversely, if a short circuited converter conducts a large amount of heat to its collector and if the good converter is ignited, then the heat pipe could dissipate more power than if the failure had not occurred.

Similar observations can be made for Figs. 5 and 6. These figures show alternate push-pull configurations and list the appropriate features of each.



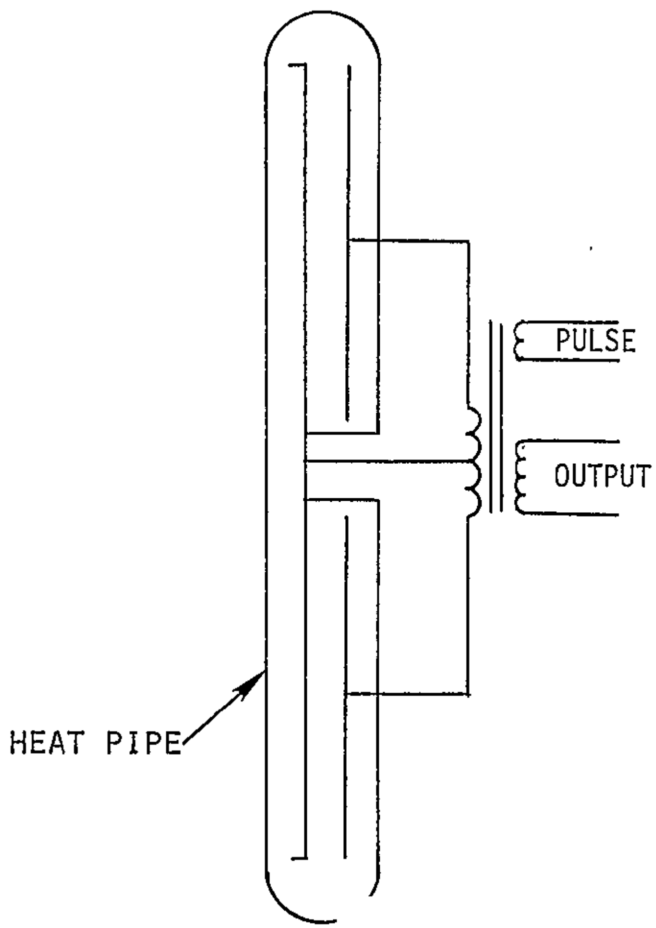
- MANY SMALL TRANSFORMERS INTERSPERSED WITH THE CONVERTER ARRAY
- A FAILURE ELECTRICALLY DISABLES 2 CONVERTERS
- SINGLE OPEN CIRCUIT FAILURE DOES NOT CHANGE TOTAL HEAT PIPE THERMAL POWER DISSIPATION IF SECOND CONVERTER IGNITES
- SINGLE OPEN CIRCUIT FAILURE REDUCES HEAT PIPE THERMAL POWER DISSIPATION BY 19% IF SECOND CONVERTER DOES NOT IGNITE
- SINGLE SHORT CIRCUIT FAILURE INCREASES THERMAL POWER DISSIPATION IF CONDUCTION LOSSES ARE HIGH AND SECOND CONVERTER IS IGNITED

Fig. 4 Push-Pull System with 3 Converter Pairs on One Heat Pipe



- FEWER TRANSFORMERS REQUIRED (LARGER CURRENT CAPACITY)
- SHORT CIRCUITED CONVERTER FAILURE DISABLES ENTIRE HEAT PIPE ELECTRICAL OUTPUT
- OPEN CIRCUIT CONVERTER FAILURE ALLOWS CONTINUED OPERATION WITH IRREGULAR WAVEFORM
- A SINGLE OPEN CIRCUIT FAILURE REDUCES THE HEAT PIPE THERMAL POWER DISSIPATION BY 9%
- SINGLE SHORT CIRCUIT FAILURE CAN INCREASE THERMAL POWER DISSIPATION IF CONDUCTION BECOMES LARGE

Fig. 5 Push-Pull System with One Transformer per Heat Pipe



- SIMPLIFIED CONSTRUCTION WITH FEWER BUSBAR INTERCONNECTIONS
- POTENTIAL TO ELIMINATE EMITTER-COLLECTOR CERAMIC SEAL WITH THIN METAL CLOSURE
- ONE CESIUM RESERVOIR FOR ENTIRE HEAT PIPE
- FAILURE DISABLES ENTIRE HEAT PIPE ELECTRIC OUTPUT
- HALF-CELL FAILURE DOES NOT CHANGE TOTAL THERMAL POWER DISSIPATION IF OTHER HALF-CELL CAN STAY IGNITED
- HALF-CELL FAILURE REDUCES TOTAL THERMAL POWER DISSIPATION BY 57% IF SECOND HALF-CELL DOES NOT IGNITE

Fig. 6 Push-Pull System with One Converter Cell per Heat Pipe

3.3 Flux Reset Inductive Output Power Coupling

In the flux reset method,[9] a single converter drives the primary of a transformer as shown in Fig. 7. The converter is alternately switched between its low-impedance power-producing state and its high-impedance state. A small amount of energy, supplied by a pulse generator in the secondary circuit, is used to reverse the flux in the transformer core while the converter is in its high impedance mode and while the load is switched out of the circuit.

Fig. 7 shows the input and output waveforms and the converter operating points for flux reset output coupling. At point 1, power is delivered to the load until the transformer core begins to saturate. A pulse at point 2 de-ignites the converter and disconnects the load from the circuit. The converter is driven out of the power quadrant at point 3 to reset the flux in the transformer. Finally, a pulse at point 4 re-ignites the converter and reconnects the load. The output from the transformer secondary is interrupted dc with a high duty cycle (80-90%). The output voltage is determined by the turns ratio used in the transformer.

Although the duty cycle is high, there are losses in efficiency associated with the amount of time the converter is not producing power. Eq. (3) was used to compare the efficiency of the flux reset power conditioning to the baseline efficiency. Again, the baseline efficiency is just

$$\eta = \frac{P_{out}}{Q_{ec} + Q_{rad}} . \qquad (6)$$

If an 85% duty cycle is assumed, the efficiency of the flux reset system, η' is

$$\eta' = \frac{.85\ P_{out}}{.85\ Q_{ec} + Q_{rad}} \qquad (7)$$

where $.85\ P_{out}$ = output power from flux reset system

$.85\ Q_{ec}$ = electron cooling term

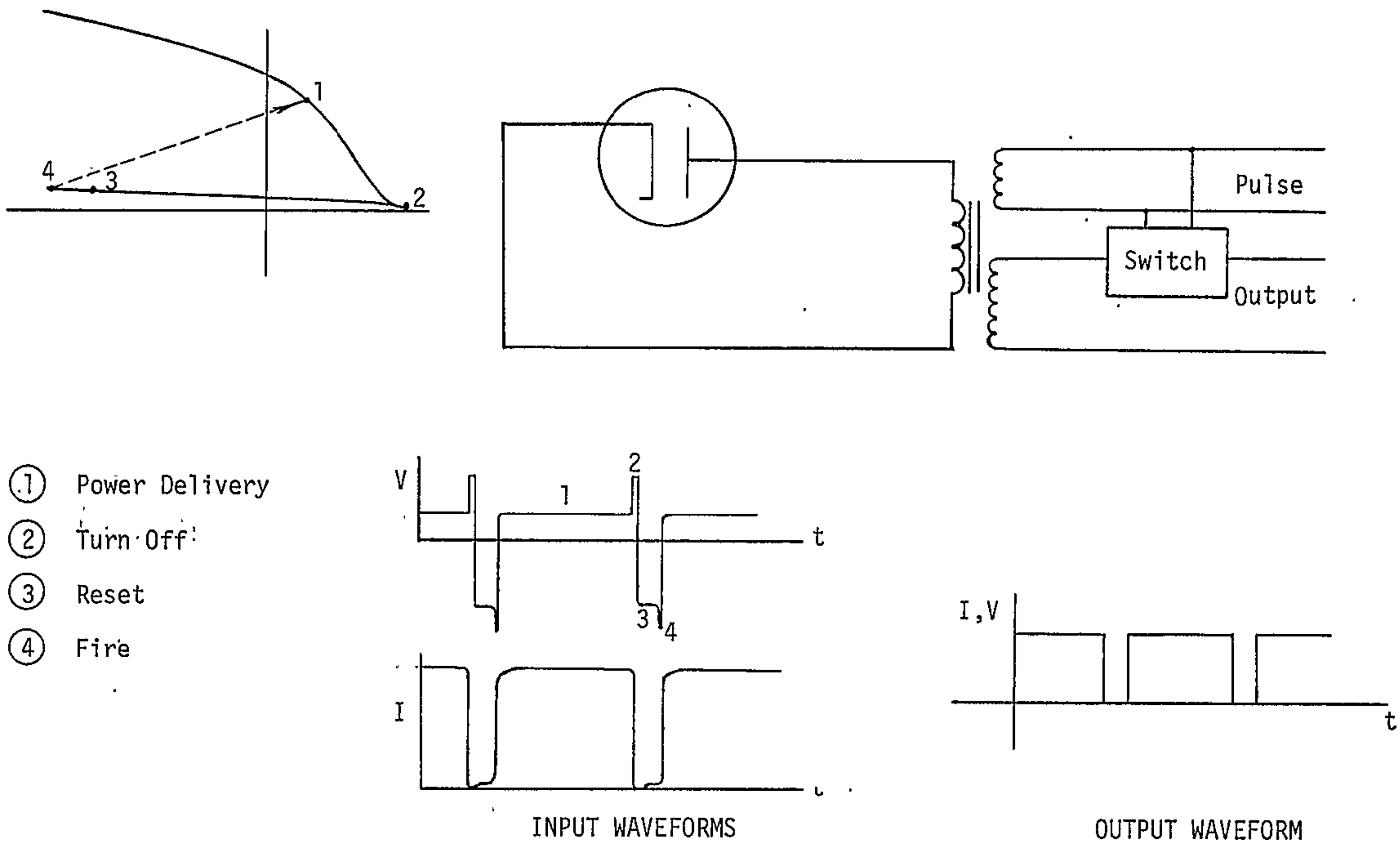


Fig. 7 Flux Reset Operating Characteristics

The ratio of the flux reset efficiency to the baseline efficiency is,

$$\frac{\eta'}{\eta} = \frac{.85\ (Q_{ec} + Q_{rad})}{.85\ Q_{ec} + Q_{rad}} = .96 \qquad (8)$$

This figure is high because some of the power must be used to generate the turn-off, reset, and ignition pulses. Since the pulse power is about 6% of the total output power,[9] the efficiency ratio η'/η becomes about .90. The reactor power, then, must increase by $1/(\eta'/\eta)$ or 1.11 to compensate for the loss of system efficiency.

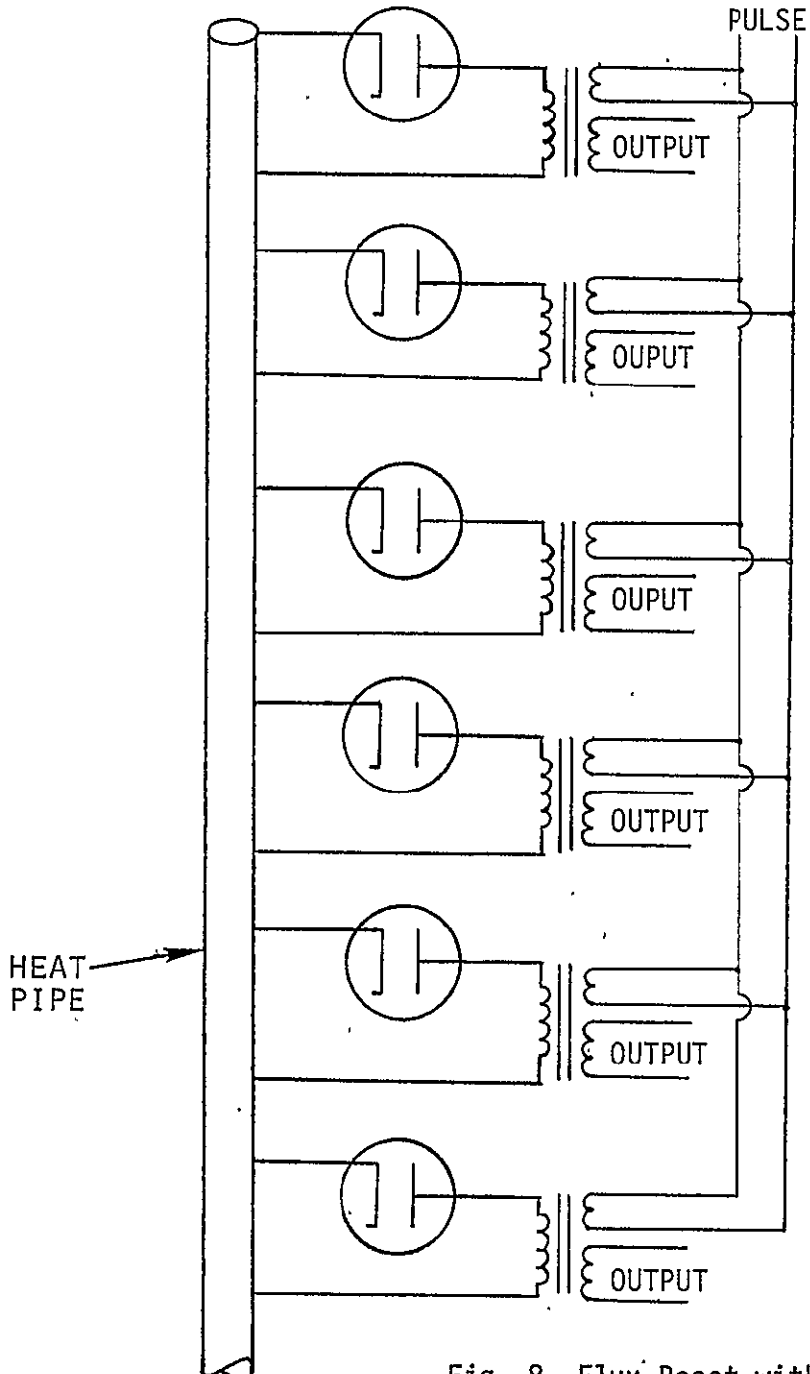
The operational limitations of flux reset are similar to those described for push-pull. Proper utilization of flux reset requires that the reset and ignition voltages extend out of the power quadrant by an amount many times the operating voltage. As the reset and ignition voltages approach a value equal to the output voltage, the duty cycle decreases to 50%, and the efficiency decreases to the value reported for push-pull. These calculations are shown in detail in Appendix A.

As shown in Appendix A, an 85% duty cycle can be obtained with the NEP system if the converter ignition voltage is above 3.4 volts. However, Fig. 3 indicates that this condition may be difficult to obtain with a conventional cesium diode. As with push-pull, additions of small amounts of inert gas could be used to increase the ignition voltages with a concurrent decrease in converter efficiency. This is significant in that the restrictions on ignition voltage place an upper limit on the emitter temperature.

There is no lower limit to the frequency at which a converter may be switched on and off. As the frequency decreases, the transformer becomes larger and hence physical size and weight introduce a practical lower limit. The upper frequency limit is controlled by the ignition and turn-off times. The turn-off time (1 msec) is much longer than the ignition time (<10 μsec) and this controls the upper frequency limit. In general, increasing the switching frequency decreases the duty cycle and, hence, the system efficiency.

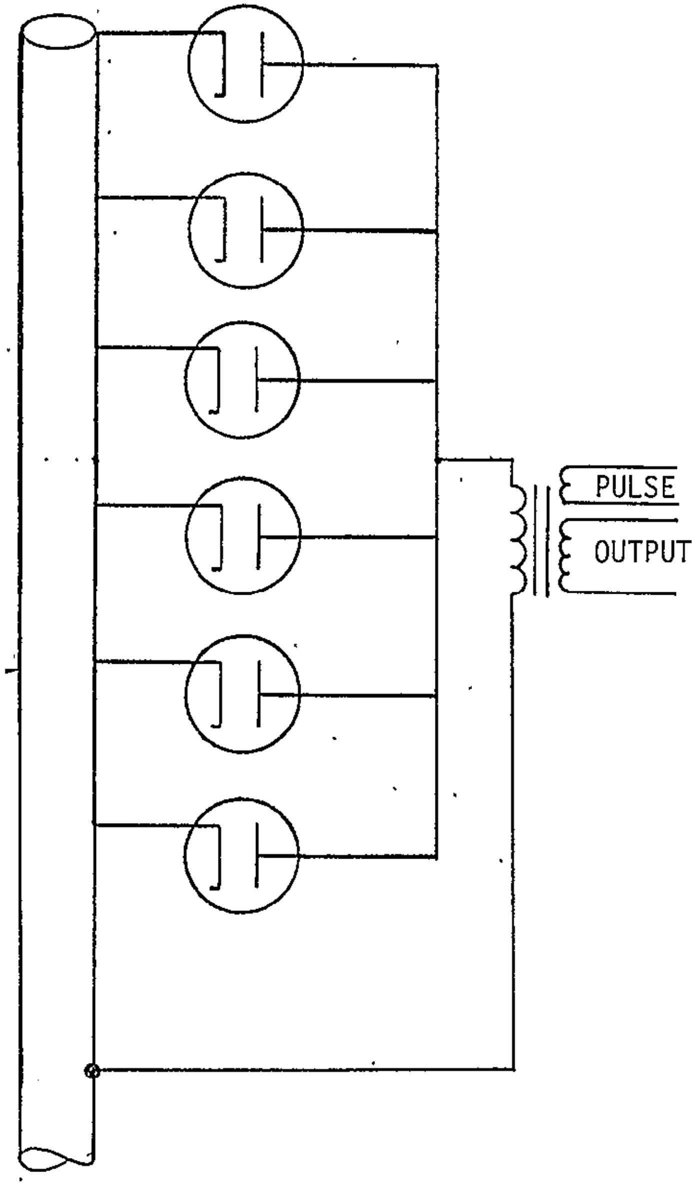
There are a number of ways in which flux reset may be incorporated into the NEP system design. Figs. 8, 9, and 10 shows three of the possible alternatives. In Fig. 8, many small transformers are interspersed with the converter array. These transformers must be located near the converter array to minimize power losses in the leads. A single converter failure in this case reduces the heat pipe electrical output power by 16% but does not affect the output from the other converters. An open circuit failure reduces the heat pipe thermal power dissipation by 13%, but a short circuit failure may slightly increase the thermal power dissipation. A de-ignition failure mode is also important. If this occurs, the transformer core saturates and the output power drops to zero. However, the heat pipe thermal power dissipation may increase slightly since the ignited converter continues to be electron and radiatively cooled with a 100% duty cycle.

Similar observations were made for Figs. 9 and 10 and listed on the figures. Of particular interest is the case in which several converters are connected in parallel across the same transformer (Fig. 9). A flux reset system will operate properly in this case only if all the converters de-ignite during each cycle. This requires that the turn-off pulse be large enough to de-ignite the converter with the highest de-ignition voltage.



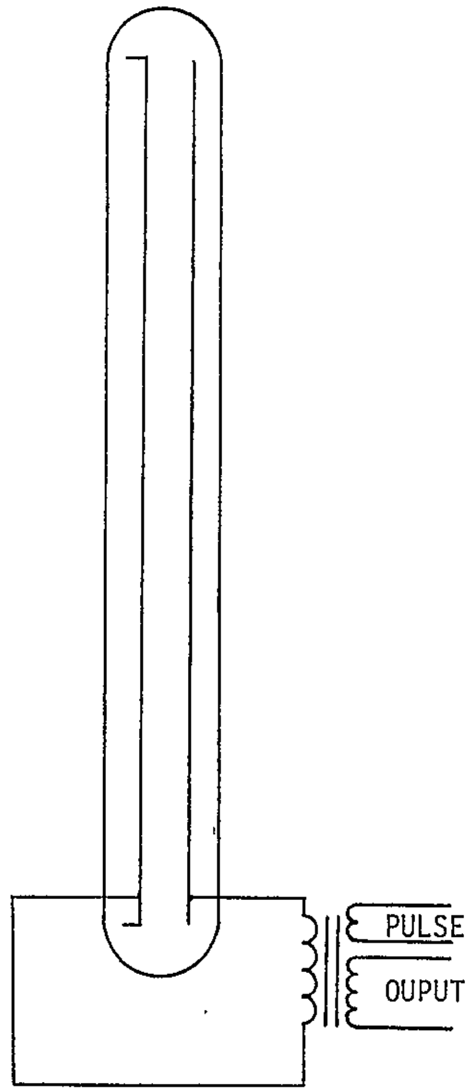
- MANY SMALL TRANSFORMERS INTERSPERSED WITH THE CONVERTER ARRAY
- FAILURE OF ONE CONVERTER DOES NOT AFFECT OUTPUT FROM THE OTHERS
- OPEN CIRCUIT FAILURE REDUCES HEAT PIPE THERMAL POWER DISSIPATION BY 13%
- SHORT CIRCUIT FAILURE CAN INCREASE THERMAL POWER DISSIPATION IF CONDUCTION HEAT TRANSFER IS LARGE
- DE-IGNITION FAILURE INCREASES THERMAL POWER DISSIPATION BY 2%

Fig. 8 Flux Reset with One Transformer per Converter



- FEWER TRANSFORMERS REQUIRED (LARGE CURRENT CAPACITY).
- SIMULTANEOUS DE-IGNITION OF ALL CONVERTERS REQUIRED
- FAILURE OF A CONVERTER BY SHORT CIRCUIT DISABLES ENTIRE ELECTRICAL OUTPUT FROM HEAT PIPE
- OPEN CIRCUIT FAILURE OF A CONVERTER ALLOWS CONTINUED OPERATION WITH REDUCED OUTPUT
- OPEN CIRCUIT FAILURE REDUCES HEAT PIPE THERMAL POWER DISSIPATION BY 13%
- DE-IGNITION OR SHORT CIRCUIT FAILURE INCREASES THERMAL POWER DISSIPATION BY 13% IF ALL CONVERTERS REMAIN IGNITED
- SINGLE DE-IGNITION OR SHORT CIRCUIT FAILURE DECREASES THERMAL POWER DISSIPATION BY 61% IF REMAINING CONVERTERS STAY UNIGINITED

Fig. 9 Flux-Reset with One Transformer per Heat Pipe



- SIMPLIFIED CONSTRUCTION WITH FEWER BUSBAR INTERCONNECTIONS
- POTENTIAL TO ELIMINATE EMITTER-COLLECTOR CERAMIC SEAL WITH THIN METAL CLOSURE
- ONE CESIUM RESERVOIR FOR ENTIRE HEAT PIPE
- FAILURE ELECTRICALLY DISABLES ENTIRE HEAT PIPE
- OPEN CIRCUIT FAILURE REDUCES HEAT PIPE THERMAL POWER DISSIPATION BY 76%
- LOCALIZED SHORT CIRCUIT FAILURE MAY NOT AFFECT THERMAL POWER DISSIPATION

Fig. 10 Flux Reset with Single Converter Cell per Heat Pipe

4.0 SERIES CONNECTED HEAT PIPE OUTPUT COUPLING

4.1 Concept Description

Another output coupling alternative which was investigated is the series connected heat pipe method. In this method, the Sialon insulators are removed and the heat pipe-to-heat pipe resistance is utilized to isolate converters on successive heat pipes. If this resistance is large enough, the output from the converters can be connected in series-parallel without appreciable power losses.

4.2 Calculation of Heat Pipe Resistance

The heat pipe resistance was estimated by considering the resistances of a grooved molybdenum heat pipe, liquid lithium filled grooves, and molybdenum inner mesh in parallel. A cross sectional view of the heat pipe model is shown in Fig. 11. The heat pipes were assumed to be electrically isolated from each other between the reactor and the converter array and short circuited at the reactor.

The resistance of the heat pipe, R is described by

$$\frac{1}{R} = \frac{1}{R_{Mo}} + \frac{1}{R_{Li}} + \frac{1}{R_{mesh}} \qquad (9)$$

where R_{Mo} = resistance of molybdenum heat pipe

R_{Li} = resistance of liquid lithium

R_{mesh} = resistance of inner molybdenum mesh.

All resistances can be calculated if the resistivity, length, and cross sectional area of each component is known. The resistance of the molybdenum heat pipe is

$$R_{Mo} \cong \rho_{Mo} L \left\{ \left[\frac{\pi}{4} (d_o^2 - d_i^2) \right] - N w_g^2 \right\}^{-1} \qquad (10)$$

where ρ_{Mo} = resistivity of molybdenum at the heat pipe temperature (Ω-cm)

L = heat pipe length from reactor to first converter (cm)

d_o = outside diameter of heat pipe (cm)

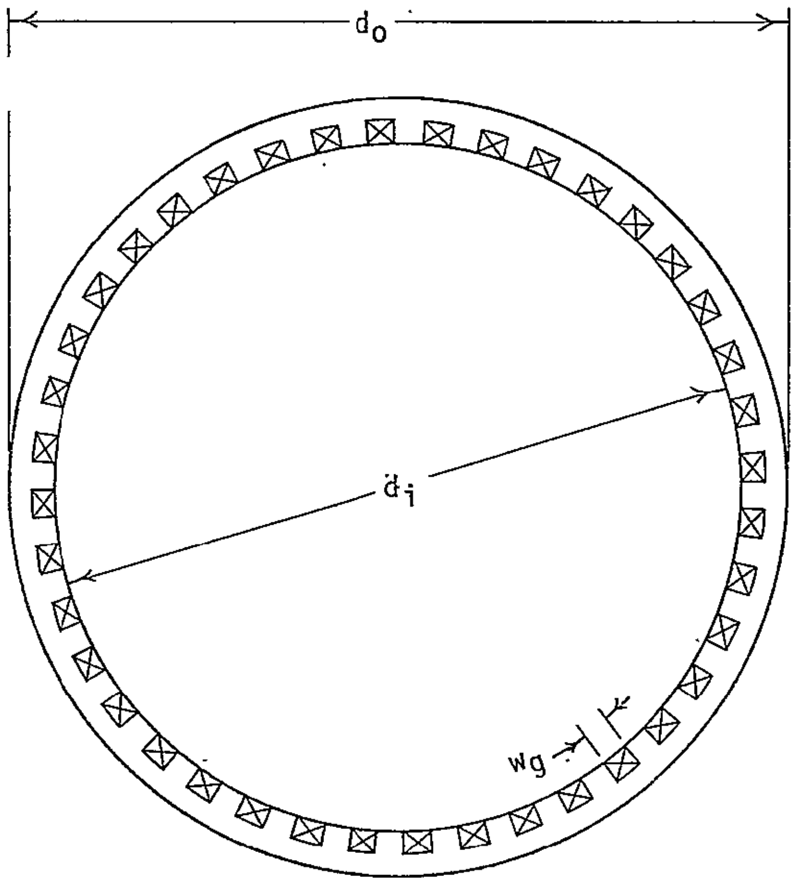


Fig. 11 Heat Pipe Cross Section

d_i = inside diameter of heat pipe (cm)

N = number of square grooves in heat pipe

w_g = width and depth of grooves (cm).

Since square grooves were assumed, the resistance of the liquid lithium in the grooves is

$$R_{Li} = \frac{\rho_{Li}\ L}{N\ w_g^{\ 2}}\ , \tag{11}$$

where ρ_{Li} = lithium resistivity at the heat pipe temperature. The resistance of the mesh was estimated by calculating the resistance of an equivalent foil and dividing by the solid fraction, S, of the mesh. The mesh resistance is described by,

$$R_{mesh} = \frac{\rho_{foil}\ L}{\pi d_i\ t\ S} \tag{12}$$

where ρ_{foil} = resistivity of molybdenum foil at the heat pipe temperature

t = thickness of the foil.

For a square mesh with nominal wire diameter, d_w, and nominal sieve openings, a, the solid fraction is

$$S \cong \frac{d_w\ (\frac{\pi}{2}\ a + d_w)}{(a + d_w)^2}\ . \tag{13}$$

A triple layer of 160 mesh was assumed for further calculations. For 160 mesh,

$a \cong .009398$ cm

$d_w \cong .0068$ cm,

and thus, $S \cong .56$.

Eqs. (9-12) combine to give an estimate of the heat pipe resistance.

The resistance of the heat pipes was calculated for the baseline system and for two proposed systems using 162 heat pipes; one operating with T_E = 1650°K and the other with T_E = 1800°K. Table 2 lists the

Table 2

PARAMETERS FOR RESISTANCE CALCULATIONS

	Baseline System	162 Heat Pipes 1650°K	162 Heat Pipes 1800°K
L	215 cm	215 cm	215 cm
d_o	2.5 cm	2.0 cm	2.0 cm
d_i	2.2 cm	1.6 cm	1.6 cm
w_g	0.08 cm	0.1 cm	0.1 cm
N	40	25	25
ρ_{Mo}	36μΩ - cm	36μΩ - cm	49μΩ - cm
ρ_{Li}	59μΩ - cm	59μΩ - cm	66μΩ - cm
ρ_{foil}	36μΩ - cm	36μΩ - cm	36μΩ - cm
t	0.02 cm	0.02 cm	0.02 cm

appropriate parameter values used in these calculations. For the baseline system it was assumed that the heat pipe diameter was increased in the converter region to compensate for the removal of the Sialon insulator. The heat pipe wall thickness and the emitter thickness were kept equal to the original baseline design. This requires a "flared" transition section in the heat pipe at the point where the converters begin. The results are as follows:

Baseline system: $R = 0.0073\Omega$

162 heat pipe, 1650°K: $R = 0.0076\Omega$

162 heat pipe, 1800°K: $R = 0.0098\Omega$.

4.3 Calculation of Output Power from Series Connected Heat Pipes

In the series connected heat pipe output coupling method, converters are connected in parallel on each heat pipe and in series across heat pipes as shown in Fig. 12. The available power, P_o, from such an array of N+1 series-parallel connected converter heat pipes in the absence of leakage currents is just

$$P_o = (N+1)\, V_o\, I_o \tag{14}$$

where V_o = nominal converter output voltage

I_o = nominal output current from all the converters on a heat pipe.

Leakage currents affect the useful output power by reducing the output current and by affecting the converter operating points.

The electrical model used to analyze the series connected heat pipe coupling method is shown in Fig. 12. Leakage currents are represented by I_1, I_2, ...I_N. The total leakage current is just the sum of all the I_N. The output voltage from N+1 heat pipes is the sum of the individual

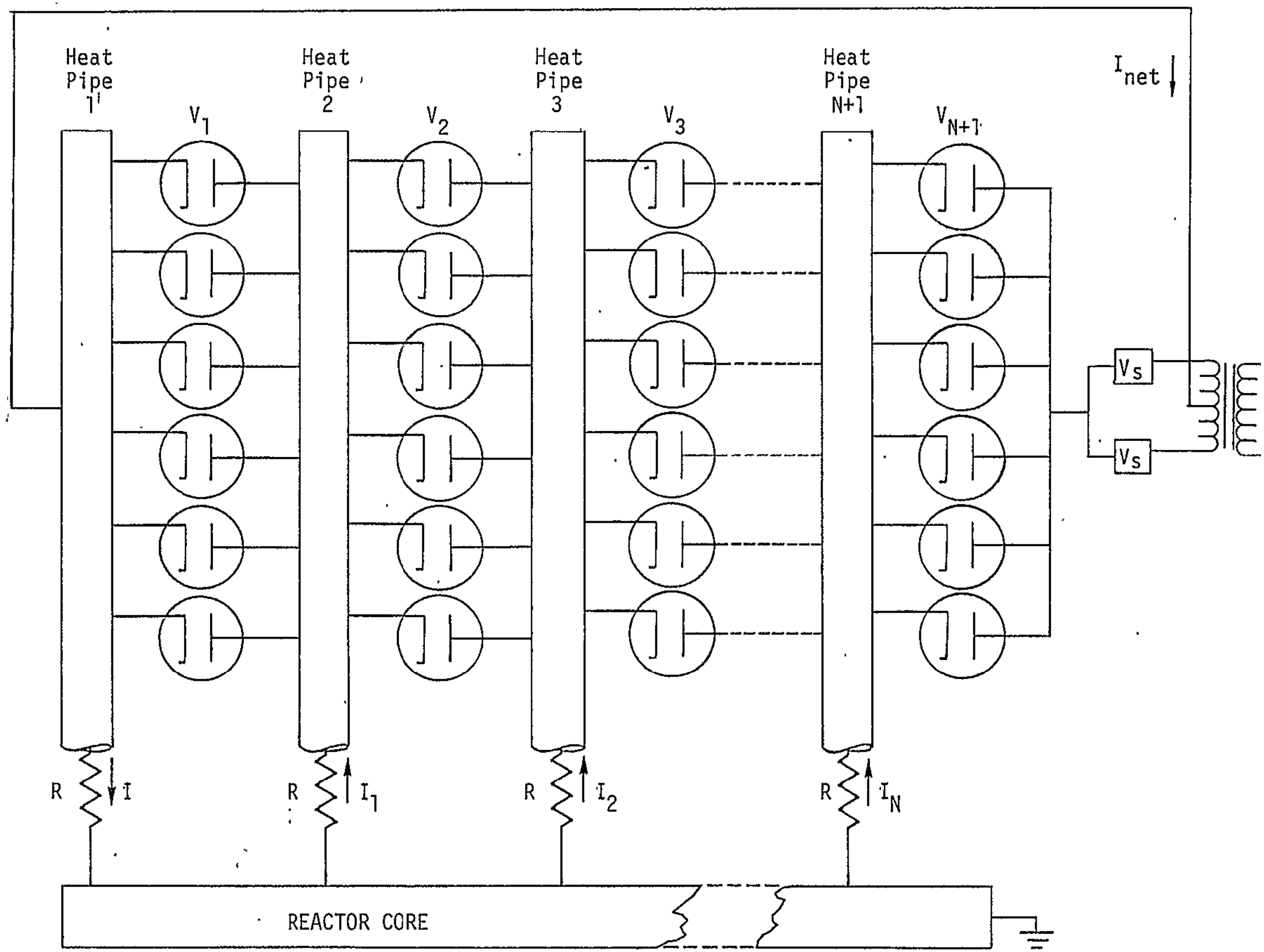


Fig. 12 Series Heat Pipe Model

heat pipe output voltage minus the voltage loss in the transistors switches, Vs. This can be written as

$$V = \sum_{k=1}^{N+1} V_k - V_s \tag{15}$$

where V_k = output voltage from converters on kth heat pipe

V_s = voltage drop in transistor switch.

In general, V_k is not equal to the nominal converter output voltage, V_o, as specified in Table 1; because of the leakage currents, the converters on adjacent heat pipes operate at different points on their I-V curves.

The current-voltage characteristics of a typical thermionic device is shown in Fig. 13a. For the purposes of this analysis, a linear approximation was used for the I-V characteristic of each heat pipe as shown in Fig. 13b. The approximate I-V characteristic is described by

$$V_k = (2\, I_o - \overline{I}_k)\, \frac{V_o}{I_o} \tag{16}$$

where $\overline{I}_k$ = average current flow through kth heat pipe.

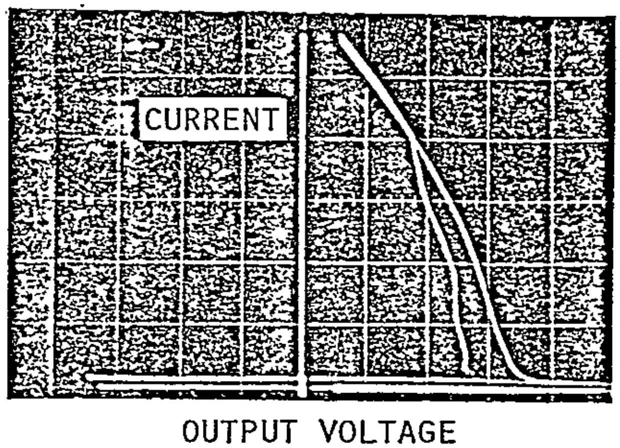
By calculating the loop currents shown in Fig. 12, it can be shown that

$$\overline{I}_k = I_o - \sum_{j=1}^{k-1} I_j$$

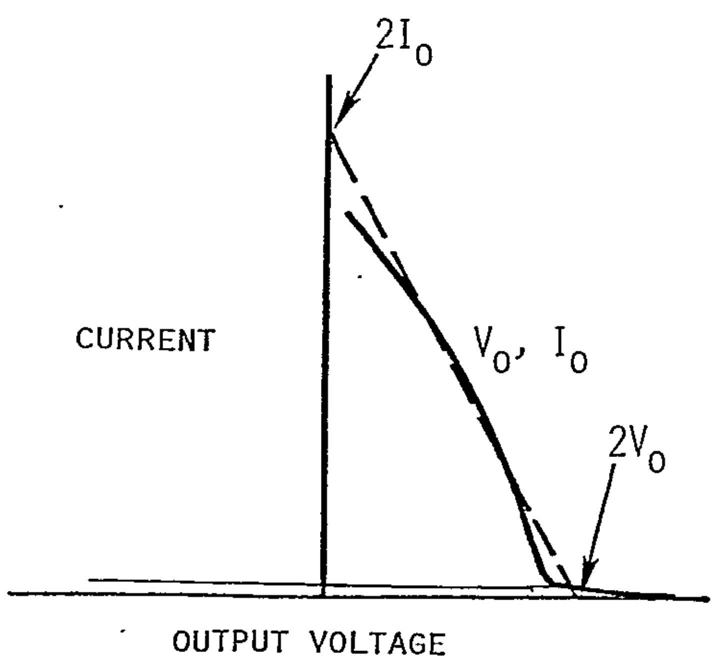
and thus $$V_k = \frac{V_o}{I_o} \sum_{j=0}^{k-1} I_j. \tag{17}$$

The net output current, I_{net}, is the difference between the nominal output current and the total leakage current: For N+1 series heat pipes,

$$I_{net} = I_o - I = I_o - \sum_{m=1}^{N} I_m. \tag{18}$$



(a)



(b)

Fig. 13 Output Characteristics of Thermionic Power Sources (a) Typical I-V Curve of Cylindrical Thermionic Converter (b) Linear Approximation Representing the Output of a Thermionic Heat Pipe

By again using loop currents, it can be shown that the individual leakage currents are described by

$$I_m = \frac{1}{R}\left[\left(\sum_{k=1}^{m} V_k\right) - IR\right]. \tag{19}$$

An expression for the output power from N+1 series connected heat pipes is derived by combining Eqs. 12-15. The result is

$$P = \left(\sum_{k=1}^{N+1} V_k - V_s\right)\left(I_o - \left\{\frac{1}{R}\sum_{m=1}^{N}\left[\frac{V_o}{I_o}\left(\sum_{k=1}^{m}\sum_{j=0}^{k-1} I_j\right) - IR\right]\right\}\right). \tag{20}$$

The percentage of power output can be optimized with respect to the number of heat pipes connected in series, because the ratio P/P_o goes through a maximum as N is varied.

The solution of Eq. (20) for known V_o, I_o, N, V_s, and R required an iterative calculation which sums the I_j and compares them to an assumed total leakage current. The computer program listed in Appendix B was used to solve Eq. (20) and to plot P/P_o versus the number of heat pipes connected in series. An example calculation the results for 5 series connected heat pipes is shown in detail in Appendix C. The results for the five proposed systems in Table 1 are shown in Figs. 14-17.

In Fig. 14, P/P_o is plotted versus the number of series connected heat pipes for the 90 heat pipe baseline configuration with the heat pipe resistance as a parameter. The inverter transistor voltage drop, V_s, is held constant (0.5 V). The optimum number of heat pipes in series for the baseline case is 8. At the optimum, the output voltage is 4.7 volts and the net output power is 84.8% of the output power which would be available with the high temperature insulators. As the heat pipe resistance increases, the leakage currents decrease, the net output power increases, and the optimum number of heat pipes in series increases. For a system of heat pipes with twice the resistance of the baseline heat pipes, the optimum occurs with 10 heat pipes in series. The net output power is 87.7% of the available output power, and the output voltage is 5.9 volts.

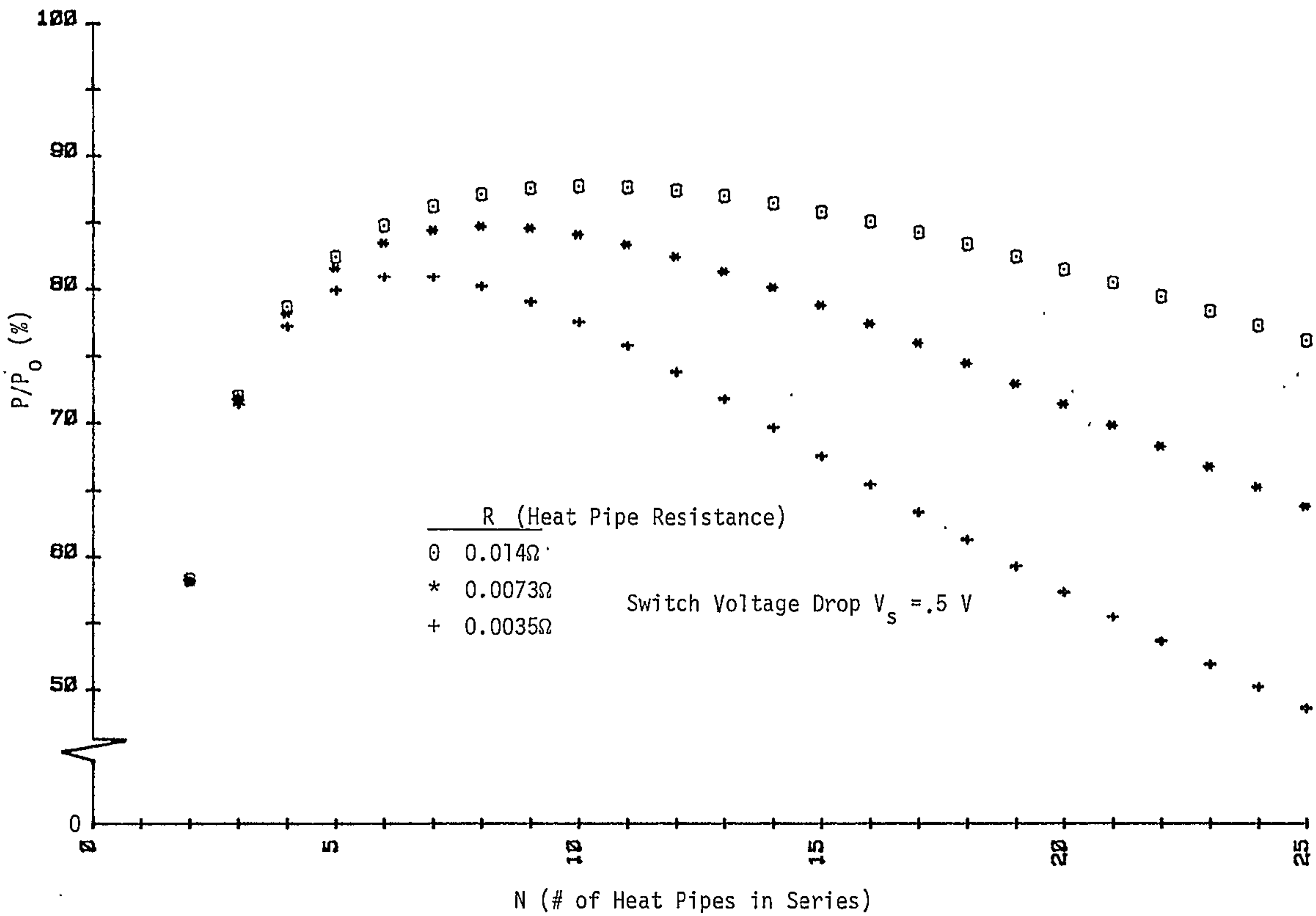


Fig. 14 Percentage of Output Power for a Series Connected Heat Pipe System. Ninety Heat Pipe Baseline Case. Heat Pipe Resistance is Parametric.

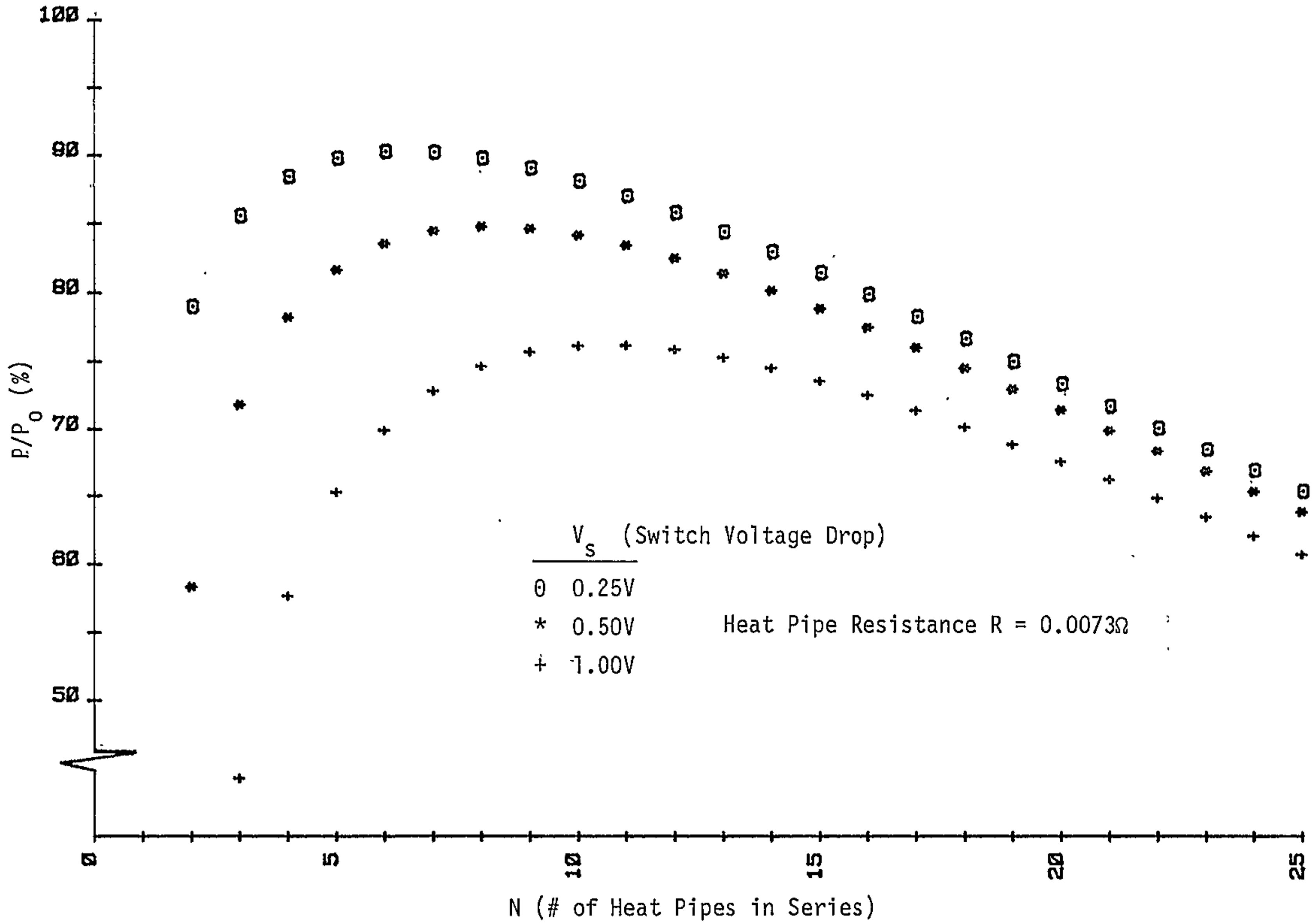


Fig. 15 Percentage of Output Power for a Series Connected Heat Pipe System. Ninety Heat Pipe Baseline Case. Transistor Switch Voltage Drop is Parametric.

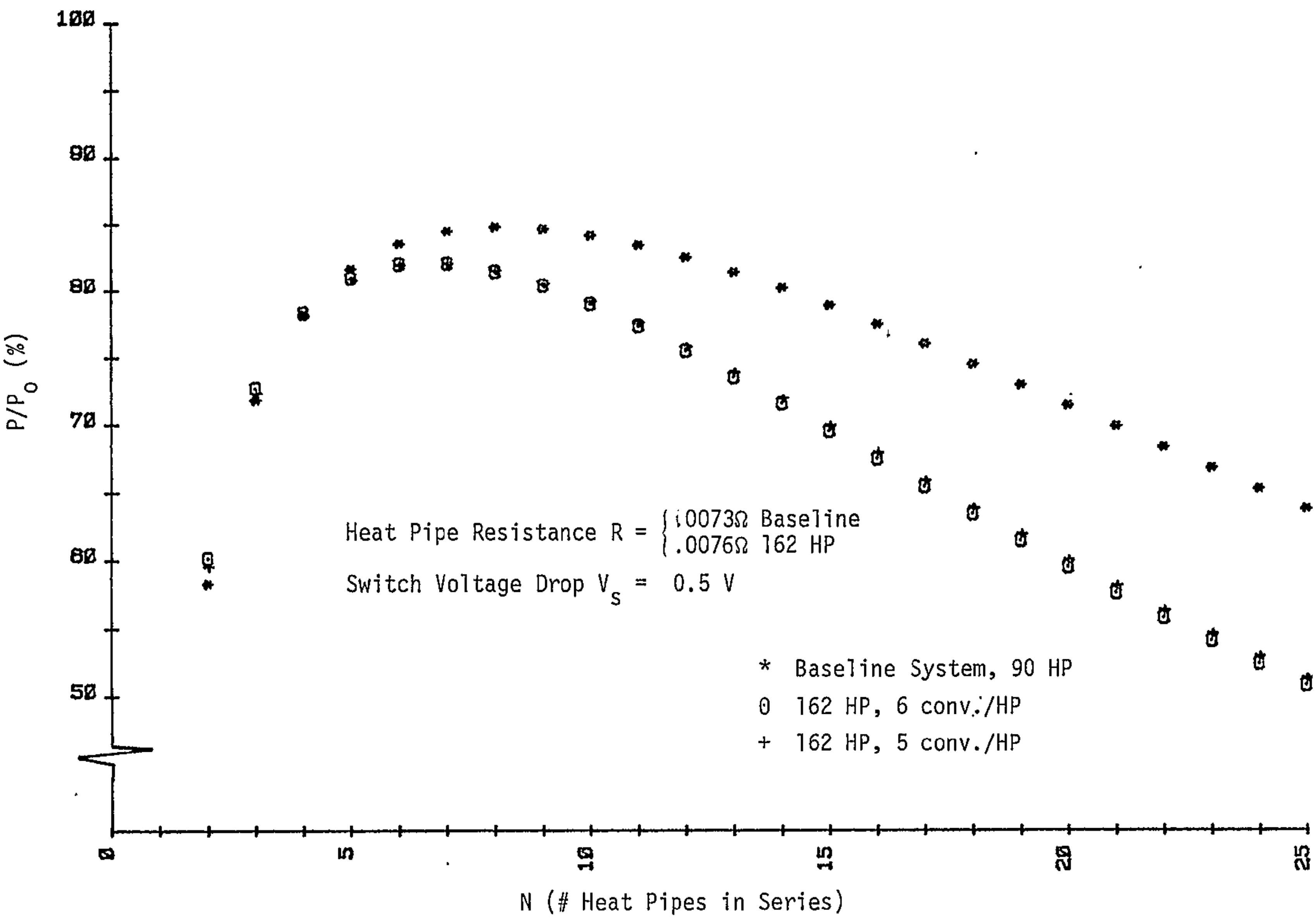


Fig. 16 Percentage of Output Power from 162 Heat Pipe System with T_E = 1650°K. Baseline system is shown for comparison.

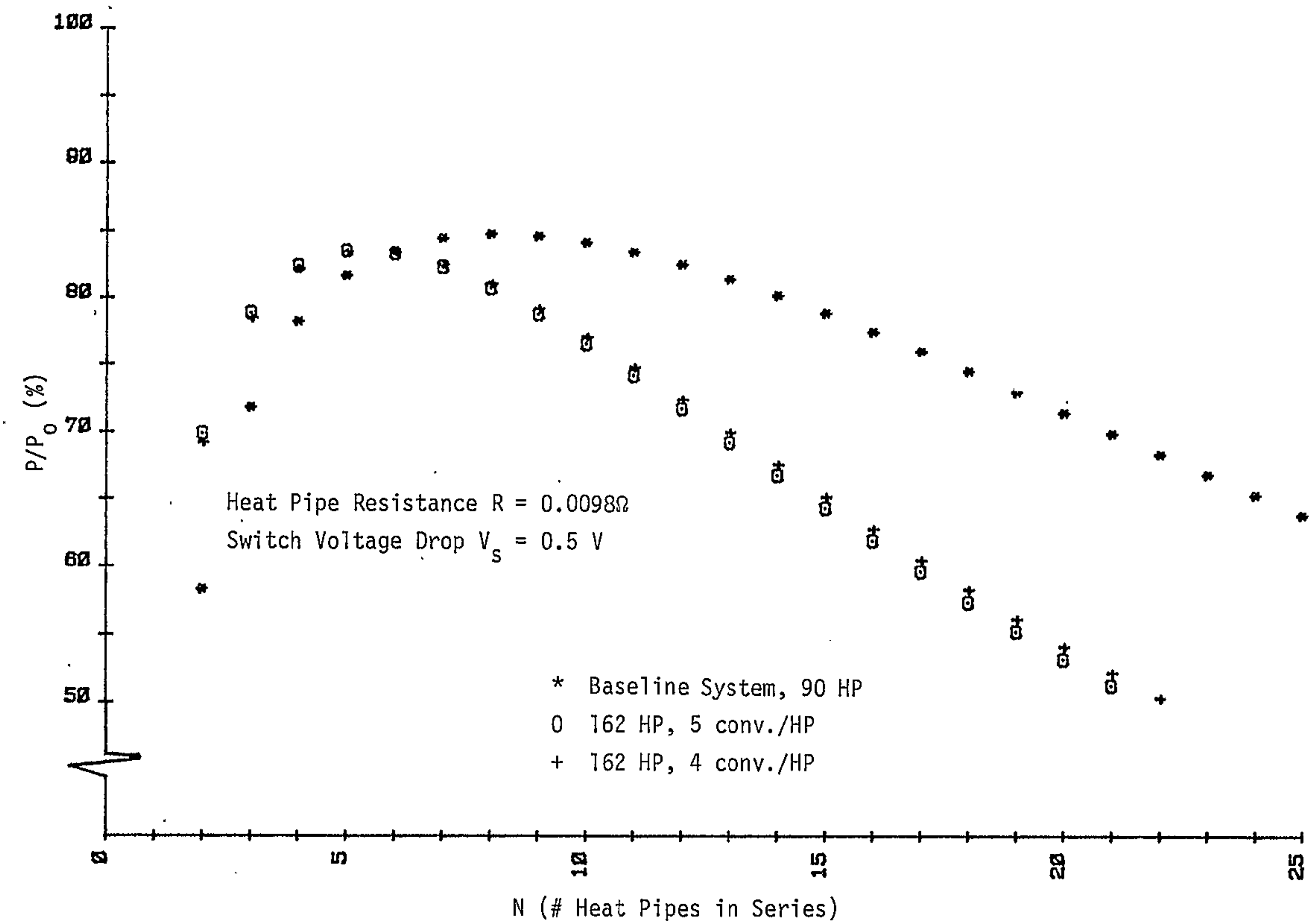


Fig. 17 Percentage of Output Power from 162 Heat Pipe System with T_E = 1800°K. Baseline system is shown for comparison.

Fig. 15 shows the effects on the baseline configuration of varying the voltage drop, V_S, of the inverter transistor switches. Curves are shown for V_S values of 0.25, 0.5, and 1.0 volt. The heat pipe resistance for all these cases is assumed to be 0.0073Ω. By decreasing the switch voltage from 1.0 to 0.25 volt the net output power at optimum N is increased significantly from about 75% of the available power to about 90%. Also, the optimum N decreases from 11 to 6 heat pipes connected in series. Transistors with voltage drops of 0.5 volts at 75A are commercially available and thus this value was assumed in subsequent calculations.

Plots of P/P_O versus N for the baseline configuration and for the two 162 heat pipe configurations with T_E = 1650°K are shown in Fig. 16. There is not much variation in the results between the 6 converters/1 heat pipe case and the 5 converters/heat pipe case due to the similar output voltages and currents. The main difference in the results between the 90 heat pipe baseline configuration and the 162 heat pipe designs is that the net output power at optimum N for the 162 heat pipe design is lower. This is due to the lower nominal output current of the converters on the 162 heat pipes. Under these conditions, leakage currents are a greater fraction of the nominal output current. The maximum output power for the 162 heat pipe configuration is 82% of the available output power with 7 heat pipes in series. The output voltage is 4.3 volts under these conditions.

Fig. 17 shows the plots of P/P_O versus N for two 162 heat pipe configurations with T_E = 1800°K and for the baseline case. The net output power at optimum N from the 1800°K heat pipes is higher than that for the 1650°K heat pipes despite the lower nominal output current of the 1800°K heat pipes. The optimum output power from the 1800°K heat pipes is 83.5% of the available output power, and the output voltage is 4.2 volts. This is due to the higher output voltage/converter (.84 volts versus .63 volts) and higher heat pipe resistance (0.0098Ω versus 0.0076Ω) of the 1800°K heat pipes. The optimum, however, occurs at lower N, 5, than the 1650°K heat pipes.

5.0 MASS AND COOLING IMPLICATIONS OF INDUCTIVE OUTPUT COUPLING AND SERIES CONNECTED HEAT PIPES

Estimates of the effects of the above power coupling alternatives on the NEP system mass and cooling requirements were made by perturbing the figures reported for the baseline system. The power balances shown in Figs. 18-22 were used in the perturbation analyses. All of the systems are called 400 kWe systems since they were designed to provide the same amount of electric power to the thrusters and the instrumentation as the nominal 400 kWe baseline system. The delivered power is 362 kWe, consisting of 352 kWe to the thrusters and 10 kWe to the instrumentation.

Fig. 18 shows the power balance for a push-pull system. The 50% duty cycle yields a duty cycle efficiency of .83 as calculated earlier in this report. A power conditioning efficiency of 0.96 was assumed to reflect transformer losses and auxiliary pulse power requirements. The power balance for a flux reset system is shown in Fig. 19. It has a duty cycle efficiency of .96 and a power conditioning efficiency of .86 (η = .98 for transformers, η = .88 for auxiliary pulse power).

The power balances for the series connected heat pipe output coupling method are shown in Figs. 20-22. Fig. 20 shows the 90 heat pipe design with T_E = 1650°K, Fig. 21 shows the 162 heat pipe design with T_E = 1650°K, and Fig. 22 shows the 162 heat pipe design with T_E = 1800°K.

5.1 Estimates of System Mass

The results of the perturbation analyses are summarized in Tables 3 and 4. The reactor mass was scaled in accordance with JPL estimates of the behavior of the reactor mass with output power.[3] The mass of the LiH shield was held fixed. Heat pipe and converter masses were scaled directly with converter length and wall cross-sectional area to yield the proper heat pipe length and the correct number of converters as dictated by the power balances and duty cycles. The bus bar interconnects were assumed to be similar to the baseline system. This assumption is justified by the requirement that the power conditioning transformers for all the output coupling alternatives be near the converter array. Primary radiator weights were scaled directly

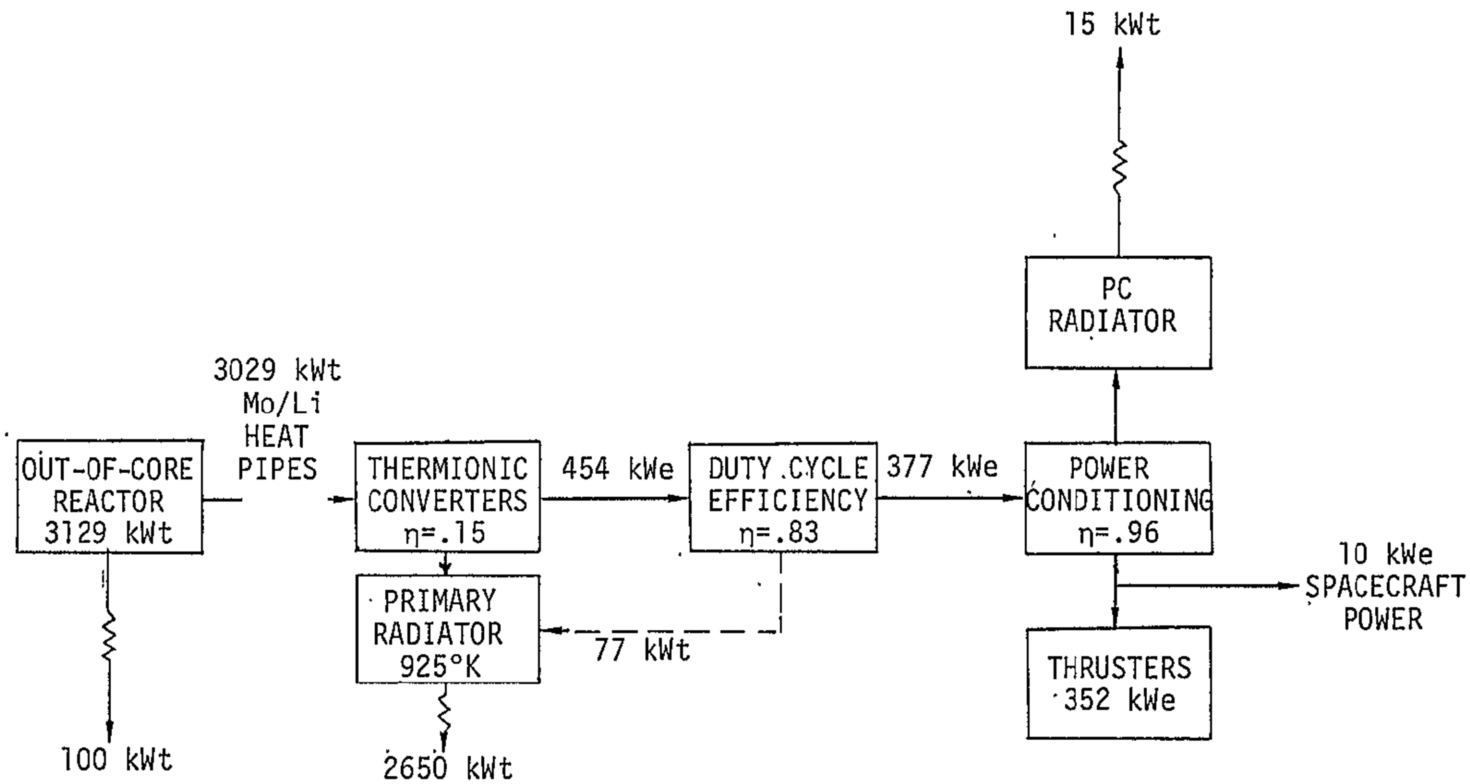


Fig. 18 Power Balance for NEP Power System with Push-Pull Inductive Output Coupling

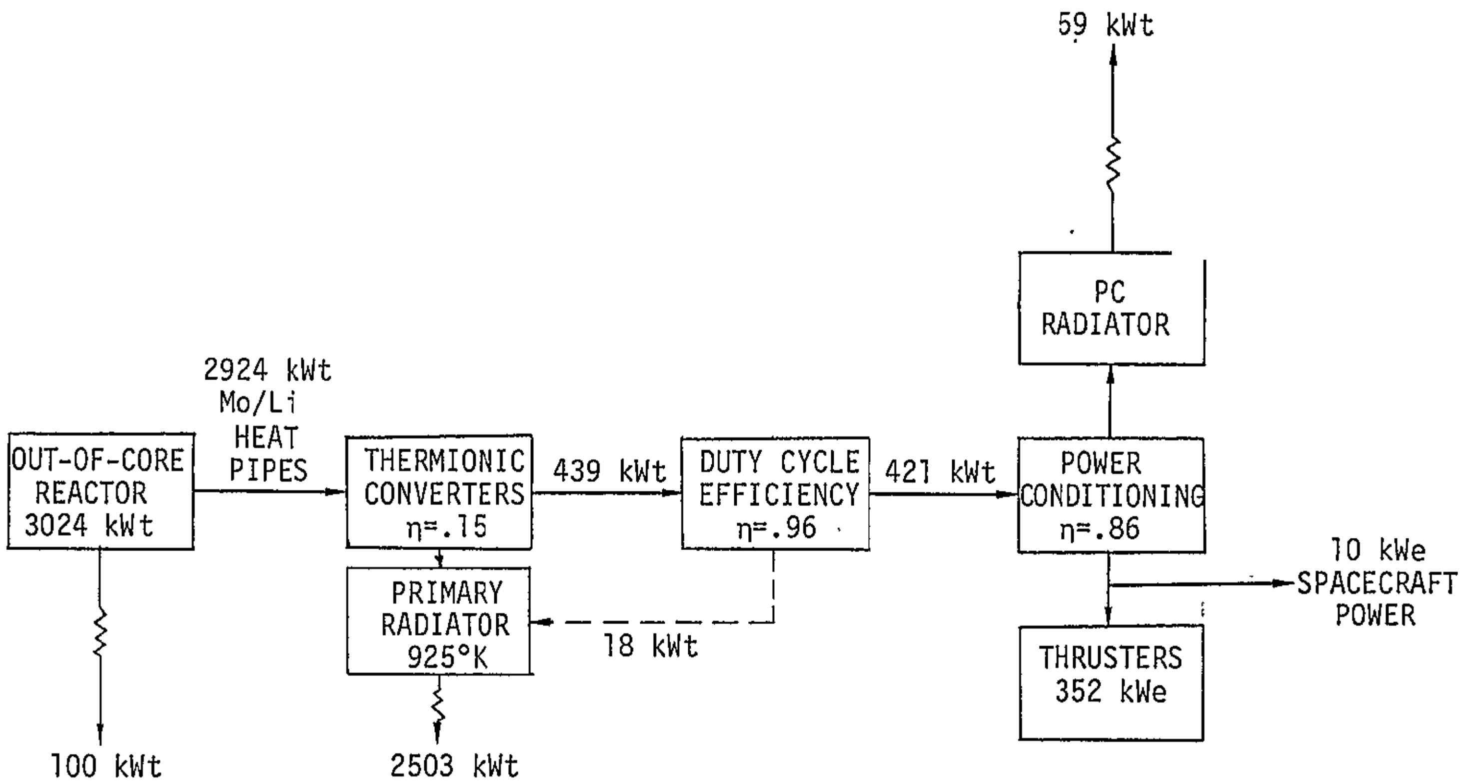


Fig. 19 Power Balance for NEP Power System with Flux Reset Inductive Output Coupling

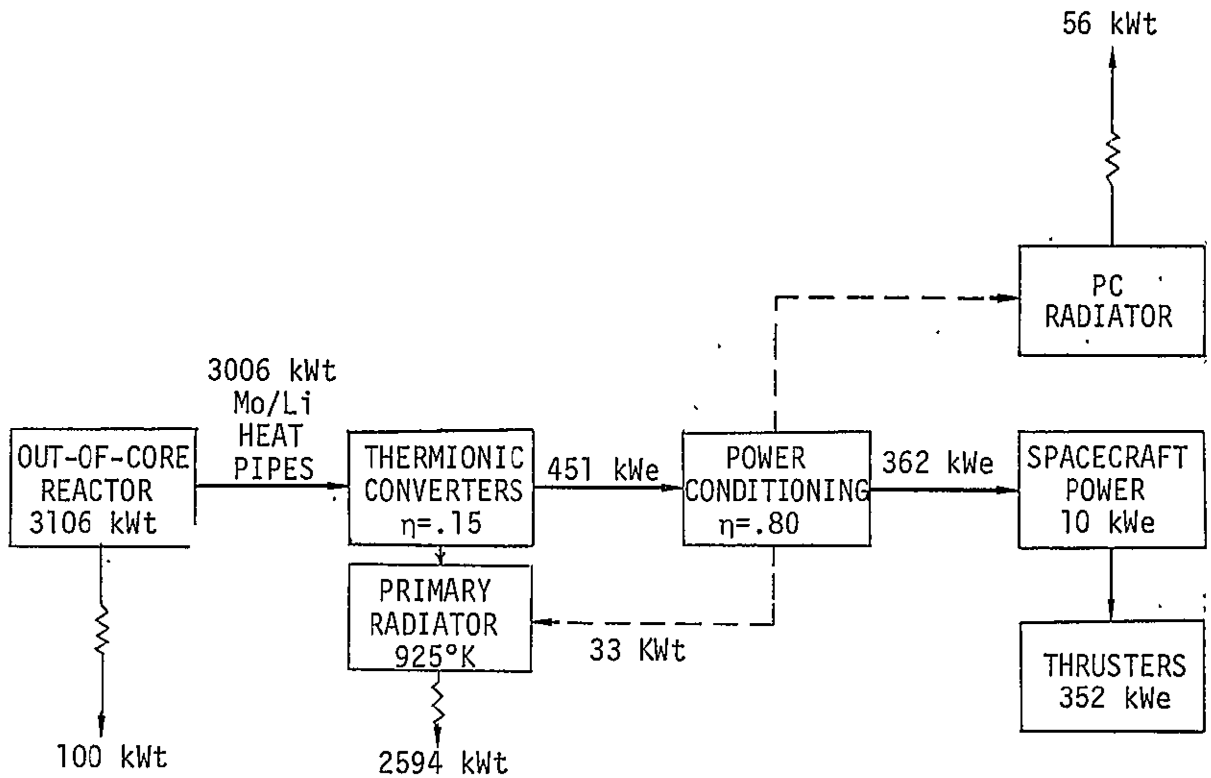


Fig. 20 Power Balance for NEP Power System with Series Connected Heat Pipes. 90 Heat Pipe Design.

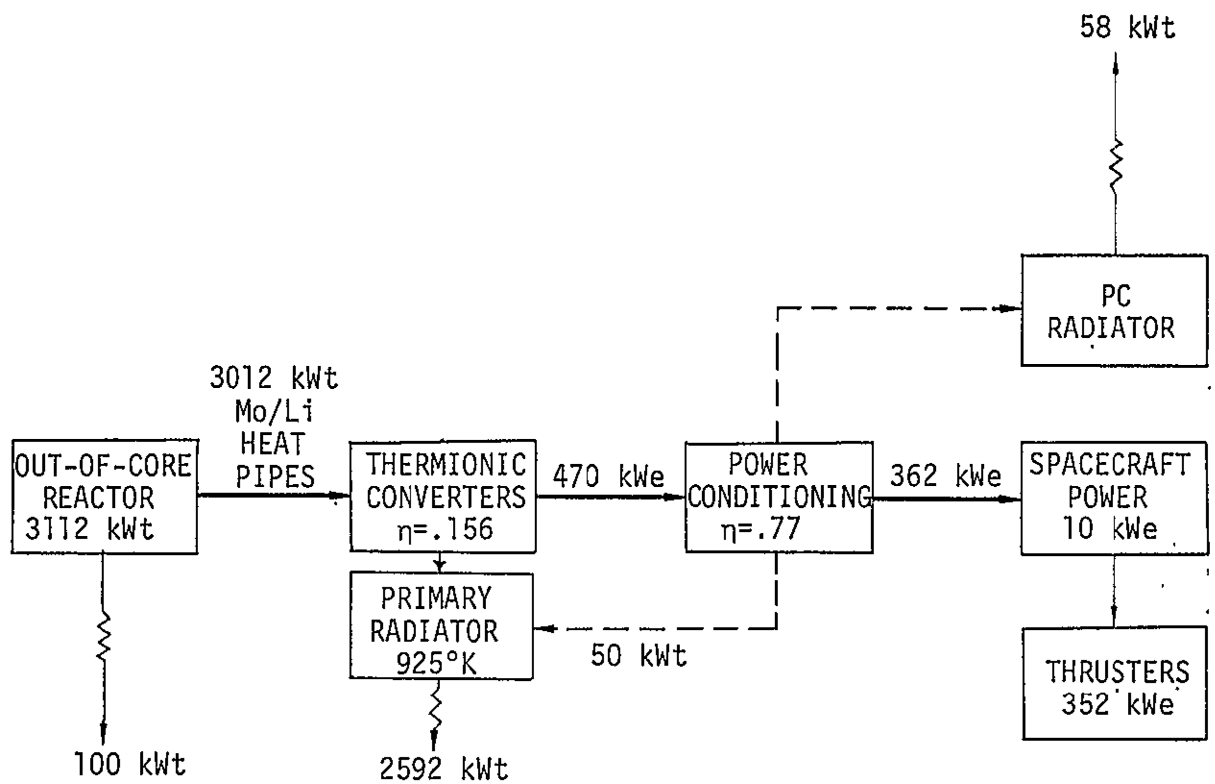


Fig. 21 Power Balance for NEP Power System with Series Connected Heat Pipes. 162 Heat Pipe Design. T_E=1650°K

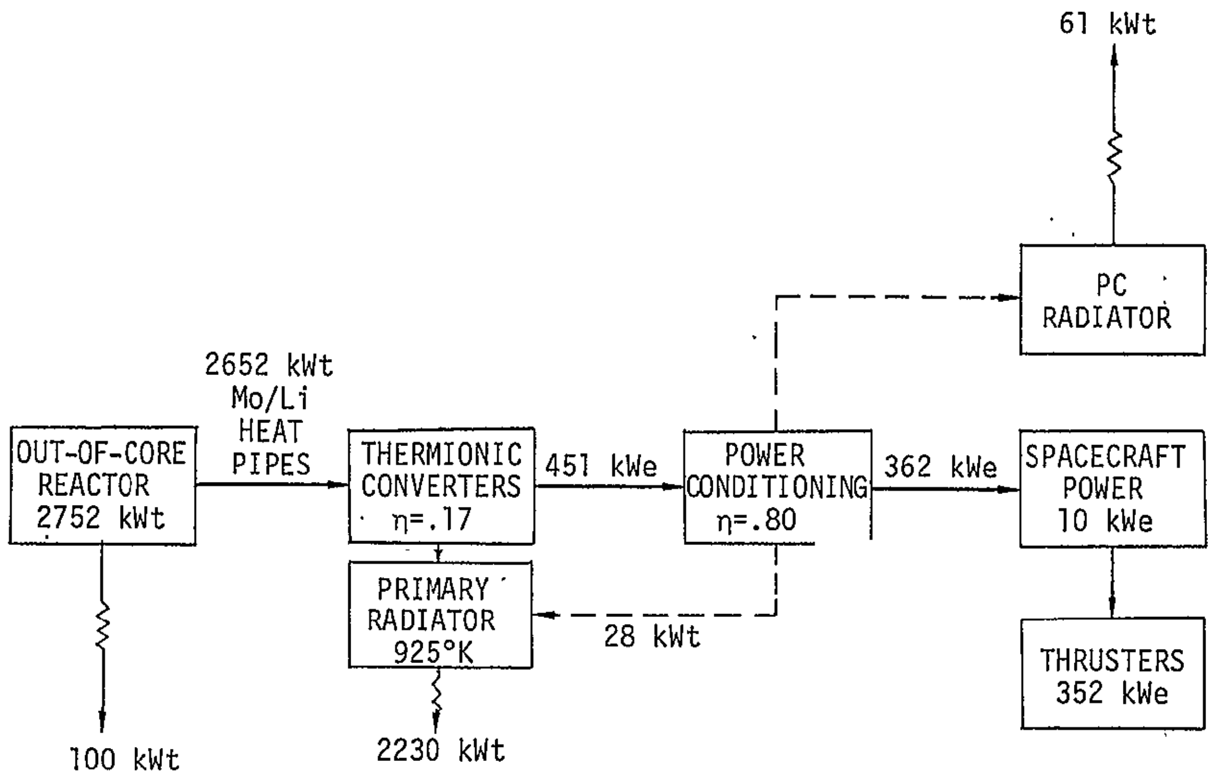


Fig. 22 Power Balance for NEP Power System with Series Connected Heat Pipes. 162 Heat Pipe Design. T_E=1800°K

Table 3

NEP SYSTEM MASS ESTIMATE (kg)

	Baseline	Push-Pull	Flux-Reset	Series+
Reactor Core	372	970	890	947
Reactor Reflectors and Control	518			
LiH Shield	1189	1189	1189	1189
Heat Pipes	735	977	1015	764
Thermionic Converters	805	1610	947	805
Molybdenum Busbars	200	400	200	200
Copper Busbars	400	---	---	---
Coolant Plumbing	116	232	116	116
Coolant	147	294	147	147
Primary Radiator	2045	2168	2045	2122
Support Structure (5%)	380	422	358	345
Sputter Barrier (1 cm Kapton)	464	464	464	464
Sputter Barrier Support (0.1 cm Ti)	147	147	147	147
Subsystem Mass (kg)	7518	8873	7518	7246
α kg/kWe (400 kWe System)	18.8	22.2	18.8	18.1
Transistor Mass (1890 ea 75 A/transistor)	NA	---	---	662
Auxiliary Radiator	NA	60	234	234
Transformer (Series 20 kHz Ferrite)	NA	---	---	48
Transformer (Flux Reset and Push-Pull)	NA	1200	1200	---
Total Mass	---	10133	8952	8198
α* Total (400 kWe System)	---	25.3	22.4	20.4

+90 Heat Pipe System

Table 4

Comparison of Series Heat Pipe Mass Estimates

	90 HP T_E=1650°K	162 HP T_E=1650°K	162 HP T_E=1800°K	162 HP* T_E=1800°K
Reactor Core Reactor Reflectors and Control	947	947	906	1200
LiH Shield	1189	1189	1189	1189
Heat Pipes	764	970	950	1030
Thermionic Converters	805	750	673	902
Molybdenum Busbars	200	360	360	306
Copper Busbars	---	---	---	---
Coolant Plumbing	116	209	209	209
Coolant	147	265	265	265
Primary Radiator	2122	2120	1824	2500
Support Structure (5%)	345	371	349	413
Sputter Barrier (1 cm Kapton)	464	464	464	464
Sputter Barrier Support (0.1 cm Ti)	147	147	147	147
Subsystem Mass (kg)	7246	7792	7336	8680
α kg/kWe (400 kWe System)	18.1	19.5	18.3	17.4
Transistors	662	693	775	968
Transformer (Series 20 kHz Ferrite)	48	48	48	60
Auxiliary Radiator	222	230	242	302
Total Mass	8178	8763	8401	10010
α* Total (400 kWe System)	20.4	21.9	21.0	20.0

*500 kWe System

with the power dissipation requirements. Transistor, transformer, and auxiliary radiator masses were estimated from empirically derived relations.[10]

Push-pull is the heaviest output coupling alternative. Due to the 50% duty cycle, twice as many converters as the baseline system are required to produce the same output power. The heat pipe must be lengthened to accommodate the increased number of thermionic converters. The heat pipes were also assumed to be larger in diameter in the region of the thermionic converters to compensate for the removal of the Sialon insulator. Mass increases in the coolant plumbing and coolant also reflect the larger number of converters. Copper bus bar masses were eliminated since the transformers must be located immediately adjacent to the converter array. The system mass excluding the transformers and auxiliary radiator is 8873 kg which yields a value of 22.2 kg/kWe for the specific mass of a 400 kWe push-pull system. If transformer and auxiliary radiator masses are included, the total mass is 10,133 kg and the total specific mass becomes 25.3 kg/kWe. A comparable estimate for the baseline system is not available since the mass of the power conditioning system has not been stated.

The specific mass of the flux reset output coupling alternative falls near the NEP baseline design value. The system mass without transformer and auxiliary radiator masses is 7518 kg (18.8 kg/kWe), and with these masses is 8952 kg (22.4 kg/kWe).

The series connected heat pipe output power coupling system is the simplest and least massive output coupling alternative. The specific mass is lower than the baseline design despite increases in the reactor, heat pipe, and primary radiator masses. For a 90 heat pipe system with T_E = 1650°K, the specific mass without the transistors, transformers, and auxiliary radiator is 18.1 kg/kWe. If these masses are included, the system specific mass becomes 20.4 kg/kWe.

The baseline system mass does not include power conditioning consequently, the specific mass of the series connected alternative without transistors, transformers, auxiliary radiator is the value which should properly be compared with the baseline specific mass i.e. 18.8 kg/kWe (baseline) vs 18.1 kg/kWe (series connected). This alternative is quite attractive because of its simplicity and the elimination of the Sialon insulators with no increase in mass.

Table 4 compares the results of four series connected heat pipe alternatives: 90 heat pipes, T_E = 1650°K; 162 heat pipes, T_E = 1650°K; 162 heat pipes, T_E = 1800°K, 400 kWe; 162 heat pipes, T_E = 1800°K, 500 kWe. The specific mass of the 162 heat pipe, 1650°K system is slightly larger than the 90 heat pipe system because of the larger heat pipe mass and the larger molybdenum busbar mass. Coolant plumbing and coolant masses are also higher due to the larger number of heat pipes.

The results for the 1800°K, 162 heat pipe alternatives are of particular interest. The net output power from a 162 heat pipe system with T_E = 1800°K was made equal to the net output power from the baseline system (by using fewer and shorter converters per heat pipe). Under these conditions, the system specific mass is only slightly less than the 162 heat pipe 1650°K system. Although the higher efficiency of 1800°K converters results in lower masses for the reactor, converter array, and primary radiator, these differences are not large compared to the masses of components which are insensiti to converter performance. Thus the specific mass is only slightly improved, since the electric output is unchanged.

However, it would be possible to generate considerably more electric power with 1800°K converters than with the baseline system. Significant reductions in specific mass result when the 1800°K, 162 heat pipe system is sized to produce 500 kWe of output power instead of 400 kWe as in the baseline system. Under these conditions, the estimates shown in Table 4 indicate that the total specific mass should be near 20 kg/kWe and the total mass should be about 10,000 kg. However, the specific mass of a 500 kWe system not including transformers, transistors, and auxiliary radiator is only 17.4 kg/kWe; which should be compared with 18.8 kg/kWe for the baseline system.

5.2. Cooling and Location Requirements

The power dissipation requirements for both systems using inductive output coupling and for the system using series connected heat pipes are indicated on Figs. 18-22. These requirements were used to specify the area of the primary and power conditioning radiators for each of the systems. The area of the primary radiator for each system was estimated by scaling the area reported for the baseline system in proportion to the power dissipation requirements. The results are shown in Table 5.

Also shown in Table 5 are the area estimates for the power conditioning radiator for each system. These were calculated by assuming that the radiators were radiating to a 0°K heat sink so that

$$A = \frac{P_R}{\sigma \, \varepsilon \, T_R^4}, \tag{21}$$

where A = Radiator area (m^2)

P_R = Radiator power dissipation (W)

$\sigma = 5.669 \times 10^{-8}$ W/m^2-°K^4

ε = Radiator emissivity = .9

T_R = Radiator temperature (°K).

The temperature of the power conditioning radiator was assumed to be 408°K. This reflects a 423°K transistor case temperature and a 15°K temperature drop from the transistors to the radiator.

The inductive output coupling transformer cores must be maintained at ≲500°K for suitable operation. The copper bus rings which surround these transformers are at a temperature of ~925°K. It is possible to insert multifoil insulation between the core regions of the transformers and the bus rings to reduce the thermal conductivity in this area to ~5 x 10^{-6} W/cm-°K. Under these conditions it is estimated that ~2 kW of additional waste heat at

Table 5

NEP SYSTEM COOLING REQUIREMENTS

	Primary Radiator Area (m^2)	Power Conditioning Radiator Area (m^2)
Baseline	73	100
Push-Pull	77.4	10.6
Flux Reset	73.1	41.7
90 HP, 1650°K	75.7	39.6
162 HP, 1650°K	75.7	41.0
162 HP, 1800°K	65.1	43.1

500°K would have to be dissipated. The additional radiator area required for this purpose is small compared to either the primary or auxiliary radiator areas. Approximately 100 kg of additional weight would be required for cooling the transformer cores. This weight has not been included in mass estimates for the inductive coupling systems.

The location of the power conditioning components in relation to the converter array and the radiators is especially important. In all of the systems it is necessary to locate the transformers close to the converter array to minimize lead losses. Consequently, the power conditioning radiator must also be located near the converter array.

Under these conditions, a power conditioning radiator which is deployed from the primary radiator (as in the current NEP system design) would probably be unsuitable. A potential solution would be to locate the power conditioning radiator in place of the kapton sputter barrier. With a cone angle of 30°, the radiating area available in this location is about 75 m^2. This is an adequate amount of radiating area for all the power coupling systems discussed in this study.

Location requirements for the power conditioning components are slightly less critical for series connected heat pipe coupling systems since the output voltage is higher than that for push-pull and flux reset systems. For the series connected systems, transformers, transistor switches, and thus, the power conditioning radiator must also be located near the converter array. Again, a radiator in place of the kapton sputter shield would be suitable. If the radiator is placed in this location, special precautions would have to be taken to prevent radiative heat transfer between it and the heat pipe converter array.

6.0 SUMMARY AND CONCLUSIONS

It has been shown that the elimination of the high temperature Sialon insulator from the NEP system design is possible by using push-pull or flux reset inductive output coupling. The high temperature insulators could also be eliminated by using a system of series connected heat pipes in which the resistance of heat pipes provides the necessary electrical isolation between converters.

The specific mass of a 400 kWe system using push-pull output coupling was estimated to be 22.2 kg/kWe. This is comparable to the baseline system specific mass of 18.8 kg/kWe. A push-pull system would be the heaviest output coupling alternative due to its low duty cycle and consequent high converter and heat pipe masses.

A 400 kWe flux reset system was shown to have a specific mass of 18.8 kg/kWe, a value equal to that of the baseline system. This is the more attractive of the inductive output coupling methods, since the insulators could be eliminated with no increase in system mass.

The most attractive coupling scheme, both in simplicity and specific mass, is the series connected heat pipe method. The specific mass of a 400 kWe series heat pipe system using baseline converter parameters and 90 heat pipes connected directly to the reactor was estimated to be 18.1 kg/kWe. This is lower than the specific mass of the proposed baseline system. Mass estimates were also obtained for several other series connected systems with 162 heat pipes directly connected to the reactor. The specific mass of a 1800°K system with 162 heat pipes and the same net output power as the baseline system was estimated to be 18.3 kg/kWe. A similar system with 500 kWe of output power was estimated to have a specific mass of about 17.4 kg/kWe.

The series connected heat pipe output coupling method appears to be most attractive for the NEP spacecraft in terms of mass, performance, and reliability. If the need for the high temperature insulators is removed through the use of this output coupling method, then converter operation with higher emitter temperatures is possible. At $T_E \gtrsim 1800°K$, the thermionic performance requirements can nearly be achieved with existing devices. The series connected 162 heat pipe design can simultaneously avoid two difficult technical problem areas: the Sialon insulators and the heat pipe-to-heat pipe heat exchanger. It is recommended, therefore that additional systems studies be undertaken to more completely define the potential utility of this coupling method in the NEP spacecraft power system.

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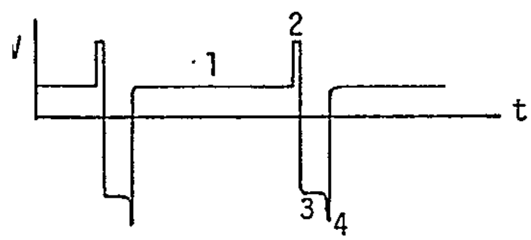
APPENDIX A

CALCULATION OF FLUX RESET DUTY CYCLE

The waveforms shown below is typical of flux reset inductive output coupling. Power delivery to a load occurs at points 1 and 2, and transformer core flux resetting occurs at points 3 and 4. Let



t_1, t_2, t_3, t_4 be the amount of time required for power delivery, turn-off, reset, and ignition respectively. The duty cycle is defined to be the ratio of the time power is delivered t_p, to the total cycle time, T. From the waveform it can be seen that

$$t_p = t_1 + t_2$$

$$\text{and } T = t_1 + t_2 + t_3 + t_4$$

So, the duty cycle is t_p/T or

$$\text{Duty Cycle} = \frac{t_1 + t_2}{t_1 + t_2 + t_3 + t_4} \tag{22}$$

In most operating systems, $t_2 << t$, and $t_4 << t_3$.

By using these relations, the duty cycle may be rewritten:

$$\text{Duty Cycle} \approx \frac{t_1}{t_1 + t_3} \tag{23}$$

This ratio can be expressed as a function of the reset and operating voltages if it is noted that the volt-seconds during the power delivery and turn-off portions of the cycle must equal the volt-seconds during reset, or,

$$V_1t_1 + V_2t_2 = V_3t_3 + V_4t_4 \tag{24}$$

where V_1 = operating voltage

V_2 = turn-off voltage

V_3 = reset voltage

V_4 = ignition voltage

Typically,

$$V_2t_2 << V_1t_1$$

and $V_4t_4 << V_3t_3$,

hence Eq. (24) becomes

$$V_1t_1 = V_3t_3. \tag{25}$$

or, $$t_1 = \frac{V_3t_3}{V_1} \tag{26}$$

Substitution of t_1 in Eq. (23) with Eq. (26) yields

$$\text{Duty Cycle} = \frac{V_3/V_1}{(V_3/V_1) + 1} . \tag{27}$$

Eq. (27) shows that if $V_3 >> V_1$ the duty cylce approaches 100%. Also, as $V_3 \approx V_1$, the duty cycle becomes 50%. To obtain an 85% duty cycle with the NEP baseline system (V_1 = operating voltage = .6V), the reset voltage, V_3, must be 3.4 V out of the power quadrant. The ignition voltage must be slightly larger than this.

APPENDIX B

COMPUTER PROGRAM FOR SERIES HEAT PIPE CALCULATIONS HP9825A DESK TOP COMPUTER WITH HP9872A PLOTTER

```
fit 3
1: ent "Io -ilw,
 ,"Vo",V[0],'R ,
 R,"Vs",S
2: prt "HPipe
 Current=",I[0];
 spc 2;prt "Cell
  Voltage=",V[0],
 ;spc 2
3: prt "Pipe
 Resistance",R;
 spc 2;prt "Swit
 c  drop",S;spc
 2;fxd 6;10+I
4: scl 0,25,40,
 100
5: xax 40,1,0,
 25,5
6: yax 0,5,50,
 100,1;csiz
7: 1-r;fxd 5
8: "RESET":for
 H=1 to N+1;0-V[
 H];0+I[H];next
 H
9: 10-T;0-V
10: 1+K
11: "V[K]":0-V[K
 ];0+I[K]
12: for J=0 to
 K-1
13: (V[0]/I[0])I
 [J]+V[K]-V[K]
14: next J
15: I[K]":for
 J=1 to K
16: V[J]+I[K]+I[
 K]
17: next J
18: (I[K]-IR)(1/
 P)+I[K]
19: if K=N;gto
 "TEST"
23: I[N]+T/L.
 next H
24: if abs((I-
 L)/L)<.01;(I+
 L)/2+I;gto "GOO
 D"
25: "BAD":I-
 L)>I;I+T+I;gto
 "CLEAR"
26: I-T+I;T/10-T
 ;gto "CLEAR"
27: "CLEAR":for
 H=1 to N+1;0-V[
 H];0+I[H];next
 H
28: 1-K;gto "V[K
 ]"
29: "GOOD":for
 H=0 to N
30: (V[0] I[0])I
 [H]+V[H-1]-V[H+
 1]
31: next H
32: for H=1 to
 N+1;V[H]+V+V;
 next H
33: prt "Heat
 Pipes",N+1
34: prt "Output
 Voltage",V
35: prt "Output
 Current",I[0]-I
36: (V-S)(I[0]-
 I)+F;V[0]I[0](N
 +1)+U
37: P/U+F;prt
 "P/Fo(%)",100F;
 spc 1
38: plt N+1,100F
 ;pen
39: cplt -.32,-
 .25
40: lbl "0"
41: cplt -.67,
 .25
42: N+1+N;gto
```

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APPENDIX C

RESULTS OF SERIES HEAT PIPE CALCULATIONS
FOR 5 HEAT PIPES IN SERIES

C.
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Equation (20) was solved for an example case of 5 heat pipes in series. The baseline values of V_o, I_o, and R were used:

$$V_o = 0.6 \text{ V}$$
$$I_o = 8205 \text{ A}$$
$$R = 0.0073\Omega.$$

Also, the inverter transistor voltage drop was assumed to be $V_s = 0.5$ V. The results generated by the computer program listed in Appendix B are shown in Fig. 23.

The output voltage, V, from 5 series heat pipes is

$$V = \sum_{k=1}^{5} V_k = 2.99 \text{ V}.$$

The individual V_k are shown in Fig. 23: $V_1 = 0.6$ V, $V_2 = 0.59$ V, $V_3 = 0.59$ V, $V_4 = 0.6$ V, $V_5 = 0.61$ V. Some of these differ from V_o because the leakage currents cause the converters on adjacent heat pipes to operate at different points on their I-V curves. The net output voltage, V_{net}, is $V-V_s$.

The output current from 5 heat pipes in series is I_{net}, which is the difference between I_o and the sum of the leakage currents I. So,

$$I_{net} = I_o - \sum_{j=1}^{4} I_j = 8205 - 163.6 = 8041.4 \text{ A}.$$

I_o is assumed to be flowing in the first heat pipe. The net output power, P, is calculated from the net output current and the net output voltage

$$P = V_{net} I_{net} = (2.49 \text{ V})(8041.4 \text{ A}) = 20.02 \text{ kW}.$$

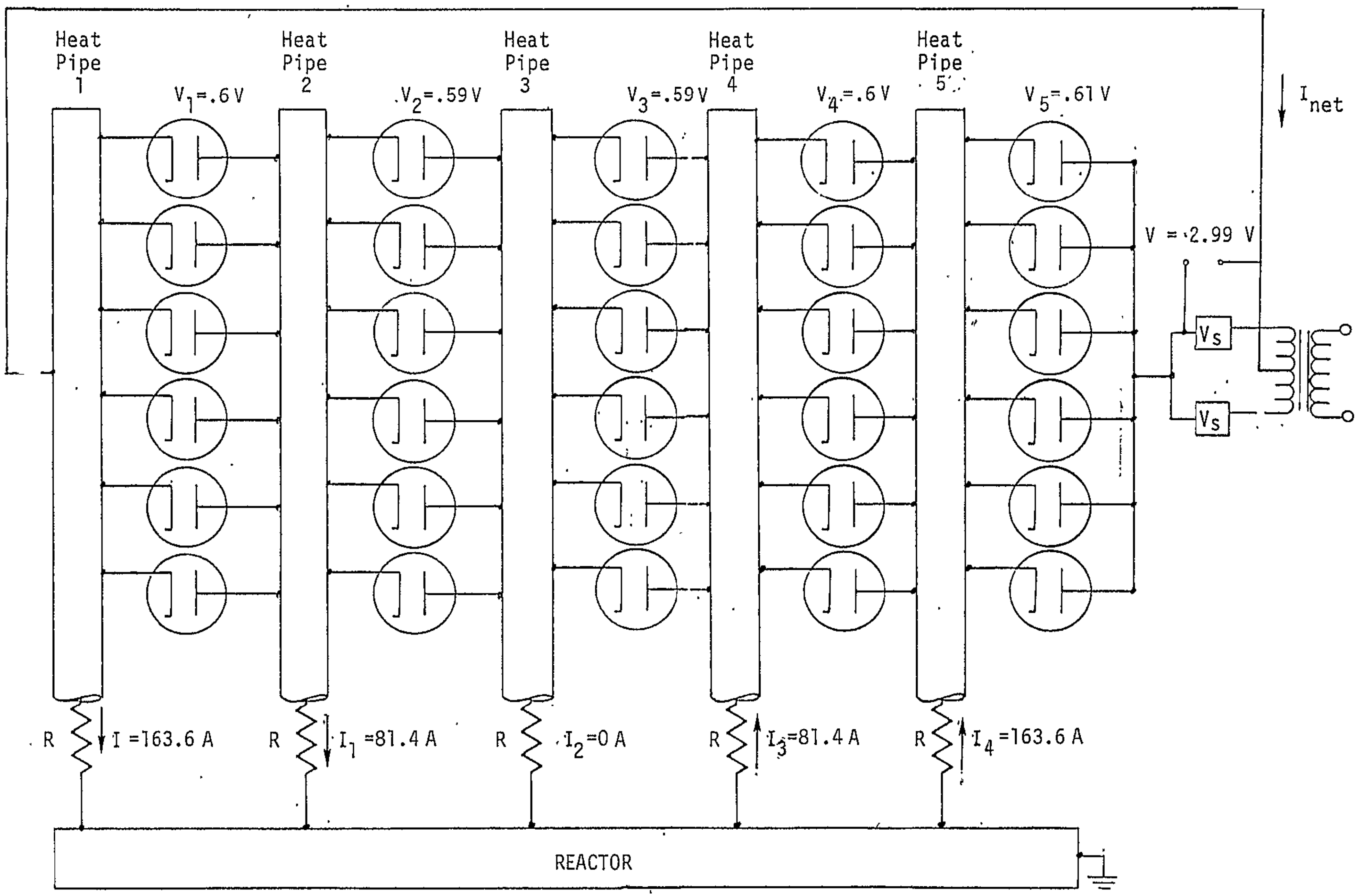

Fig. 23 Example of Series Heat Pipe Calculation Results for 5 Heat Pipes in Series Baseline System.

The available output power, P_o, from 5 heat pipes with no leakage paths (i.e. perfectly isolated from each other) is

$$P_o = V_{out} I_o,$$

where $V_{out} = 5\ V_o = 3.0\ V,$

$I_o = 8205\ A.$

Thus; $P_o = (3.0\ V)(8205\ V) = 24.62\ kW$

The percentage of available output power is P/P_o. For 5 series connected heat pipes this is

$$\frac{P}{P_o} = \frac{24.04}{24.62} \times 100 = 81.3\%$$

This point can be found in Figs. 14 and 15 as a part of the results for the baseline configuration.