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# EEFECT OF ELECTROTHERMAL INSTABILITIES ON BRAYTON- AND RANKINE-CYCLE MAGNETOHYDRODYNAMIC SPACE-POWER GENERATION SYSTEMS

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16. Abstract
Plane wave electrothermal instabilities are included in the analysis of idealized Brayton- and Rankine-cycle magnetohydrodynamic generators. It is shown that the instabilities cause an increase in Joule heating and a reduction in output power. An increase in the magnetic field can compensate for the reduction in output power.

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# EFFECT OF ELECTROTHERMAL INSTABILITIES ON BRAYTON- AND RANKINE-CYCLE MAGNETOHYDRODYNAMIC SPACE-POWER GENERATION SYSTEMS

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## SUMMARY

The effect of fluctuations in the electron density on Brayton- and Rankine-cycle magnetohydrodynamic generators is analyzed. The generators are designed for minimum magnet volume, the Brayton cycle using neon seeded with cesium and the Rankine cycle using lithium seeded with cesium.

An important consequence of the electron density fluctuations is an increase in Joule heating within the generator and a reduction in output power. The power loss increases as the maximum cycle temperature decreases. An increase in the entrance magnetic field can compensate for the reduction in output power. For a given entrance magnetic field, generator length, generator efficiency, and maximum cycle temperature, the power output of the Brayton-cycle generator is maximum at an entrance Mach number of 1.0.

## INTRODUCTION

The need for increasingly larger, lighter sources of power in spacecraft has stimulated interest in alternatives to the conventional turbogenerator set. A closed-cycle magnetohydrodynamic (MHD) generator using high-temperature gases is one possibility, and has been investigated by several authors (see refs. 1 and 2). Nichols (ref. 3) compared two different MHD cycles with a turbogenerator set and studied the range of parameters which give comparable system weights.

All of these references use the conventional formulation for electrical conductivity and Hall parameter in the ionized gas. This formulation neglects any nonuniformities in the plasma. However, some investigators (refs. 4 and 5) have noted that in the presence of strong magnetic fields nonuniformities develop in the plasma which lead to a reduction in the electrical conductivity and changes in other properties. Analytical studies of this phenomenon have developed the concept of a critical Hall parameter. When the microscopic Hall parameter is larger than this critical value, any variation is amplified and appreciable fluctuations in the local properties occur. The value of this critical Hall parameter depends on the electron temperature and, to a lesser extent, on the amount of radiation and thermal diffusion present. Solbes (ref. 4) has derived analytical expressions for the critical Hall parameter, the changes in bulk properties, and the magnitude of the fluctuations.

In this report, the expressions developed by Solbes (ref. 4) are used to modify the calculations given by Nichols (ref. 3). The same thermodynamic cycles discussed by Nichols are considered, and similar assumptions are made. The only change is in the formulation of electrical conductivity. The effective value predicted by Solbes is substituted whenever the Hall parameter is above its critical value. This change should make the estimates of generator performance more accurate and the comparison between generators more valid.

## SYMBOLS

| | |
|---|---|
| $B$ | magnetic field strength |
| $eV_i$ | ionization potential of the seed |
| $j$ | current density |
| $K$ | parameter accounting for variations in electron temperature and loss factor |
| $k$ | Boltzmann constant |
| $M$ | entrance Mach number |
| $m_c$ | atomic mass of the carrier |
| $m_e$ | electron mass |
| $m_s$ | atomic mass of the seed |
| $\overline{m}$ | average particle mass |
| $N_e$ | electron number density |
| $N_g$ | total gas (seed plus carrier) number density |
| $N_s$ | total seed (ion plus neutrals) number density |
| $Q_c$ | electron-neutral collision cross section of carrier |
| $Q_s$ | electron-neutral collision cross section of seed |
| $r$ | parameter specifying importance of Coulomb collisions |

| | |
|---|---|
| $S$ | seed fraction |
| $T$ | bulk gas temperature |
| $T_e$ | electron temperature |
| $Z$ | parameter related to effective conductivity |
| $\alpha$ | degree of ionization, $N_e/N_s$ |
| $\beta$ | local Hall parameter |
| $\beta_{crit}$ | critical Hall parameter |
| $\beta_{eff}$ | effective Hall parameter |
| $\Delta$ | composite loss factor |
| $\nu_e$ | electron collision frequency, $\nu_{ei} + \nu_{en}$ |
| $\nu_{ei}$ | electron-ion collision frequency |
| $\nu_{en}$ | electron-neutral collision frequency |
| $\sigma$ | local conductivity |
| $\sigma_{eff}$ | effective conductivity |
| $\langle\ \rangle$ | average of quantity over space |

## GENERATOR CYCLE SPECIFICATION

The following discussion is based on the report by Nichols (ref. 3), and a more detailed analysis can be found there. Two magnetohydrodynamic generators were considered; a Rankine cycle using lithium seeded with cesium and a Brayton cycle using neon seeded with cesium. A turbogenerator using potassium was the reference cycle. Since waste heat must be radiated away in space, and the radiator is one of the more massive components as well as one that is sensitive to assumed operating conditions, the two MHD generators were restricted so that all three cycles require equal radiator area. The reference cycle is a Rankine cycle using potassium and a turboalternator. A detailed description of the reference cycle is given in reference 3.

The two MHD generators were assumed to be ideal except for Joule-heating losses. No heat diffusion or radiation losses were considered. Both generators had a fixed length and a fixed aspect ratio. The values of $j^2/\sigma$ and $jB$ were required to be constant over the length of the generator. This last restriction provides for uniform dissipation and uniform power generation along the duct. The generator area variation which minimizes generator volume at constant pressure ratio was assumed. The Brayton cycle had a pressure ratio of 0.5, the Rankine cycle 0.1. The efficiency of this minimum-volume generator is very close to that of the maximum-efficiency case computed by Pleshanov (ref. 6). Following the procedure of reference 3, the maximum pressure, entrance Mach number, entrance current-density ratio, entrance magnetic field, and entrance Hall parameter for each cycle were found as a function of the maximum temperature. The requirement of equal radiator areas in both the MHD generators and the reference cycle specifies the generator efficiency as a function of maximum cycle temperature (fig. 10 in ref. 3). From this generator efficiency the values of entrance Mach number and entrance current-density ratio were calculated (fig. 12 in ref. 3), based on the minimum-volume solution. The entrance magnetic field necessary to give the proper pressure drop within a generator length of 0.5 meter was then determined. The generator efficiency is the actual change in enthalpy divided by the isentropic change between the same pressure limits.

## CALCULATION OF PLASMA PROPERTIES

The temperature of the electrons in the plasma may be higher than the bulk temperature of the gas because of Joule heating. In steady state, the energy gained by the electrons through Joule heating must be lost to the heavy species by collisions. The balance can be written as

$$\frac{j^2}{\sigma} = 3\frac{m_e}{\overline{m}}\nu_e N_e k(T_e - T)\Delta \tag{1}$$

This equation holds locally in the plasma and the value of each variable, particularly $N_e$, may fluctuate.

In order to find an effective value for $\sigma$, equation (1) is averaged over space

$$\left\langle \frac{j^2}{\sigma} \right\rangle = \left\langle 3\frac{m_e}{\overline{m}}\nu_e N_e k(T_e - T)\Delta \right\rangle$$

$$= 3\frac{m_e}{\overline{m}} k \left\langle \nu_e N_e (T_e - T)\Delta \right\rangle$$

and an effective $\sigma$ is defined as

$$\sigma_{eff} \equiv \frac{\langle j \rangle^2}{\left\langle \frac{j^2}{\sigma} \right\rangle}$$

Then substituting for $\langle j^2/\sigma \rangle$ results in

$$\frac{\langle j \rangle^2}{\sigma_{eff}} = 3 \frac{m_e}{\overline{m}} k \langle \nu_e N_e (T_e - T) \Delta \rangle \tag{2}$$

The requirement that $jB$ and $j^2/\sigma$ be constant is replaced by the requirement that $\langle j \rangle B$ and $\langle j \rangle^2/\sigma_{eff}$ be constant along the generator.

## ASSUMPTIONS ABOUT FLUCTUATIONS AND PLASMA CONDITIONS

The analysis of Solbes (ref. 4) is used to evaluate $\sigma_{eff}$ and to perform the averages in equation (2). An analysis similar to that of Solbes (ref. 4) has been made by Louis (ref. 5). However, Louis's results are restricted to plasmas where Coulomb-type collisions are dominant. Solbes's expression is more general in this respect, the relative influence of Coulomb collisions being arbitrary. For this reason, Solbes's development is followed rather than Louis's.

The fluctuations are assumed to be plane waves whose wavelength is much smaller than the dimensions of the channel. This means that the minimum dimension of the generator must be about 10 centimeters (ref. 7). The bulk properties of the plasma, such as velocity, pressure, and temperature, are assumed to be uniform on a length scale which is large when compared with the wavelength of the disturbance. In the averaging process these properties are assumed to be constant, and only fluctuations with small wavelengths satisfying this requirement are considered. The fluctuations are also assumed to be periodic in space and to have small amplitudes. Only first-order terms in density fluctuations are retained, with one exception. Second-order effects must be considered in the Joule-heating term of the energy equation since it is the source of the instability. The plasma consists of a weakly ionized seeded gas.

### Determination of Critical Hall Parameter

An equation for the energy in the fluctuations is found by averaging the local energy equation and subtracting this averaged equation from the local energy equation. The point at which the energy in the fluctuations changes from a decreasing function of time to an increasing one is the point where instability occurs and the fluctuations may be amplified. This point is reached when the Hall parameter is equal to, or greater than, the critical Hall parameter $\beta_{crit}$. The value of $\beta_{crit}$ as derived by Solbes is given by

$$\beta_{crit} = 2\sqrt{(1 + K)(r + K)} \tag{3}$$

The parameter r is a measure of the importance of Coulomb-type collisions and varies between 0 and 1. Its value is given by

$$r = \frac{\nu_{ei}}{\nu_{en} + \nu_{ei}} = \frac{\nu_{ei}}{\nu_e}$$

The parameter K relates the variation in electron temperature $T_e$ and in loss factor $\Delta$ to the fluctuation in electron density. Its value is given in reference 4 by

$$K = \frac{1}{2}\,\frac{2 - \alpha}{1 - \alpha}\left(\frac{kT_e}{eV_i}\,\frac{T_e}{T_e - T}\right) + \frac{1}{2}\,\frac{r(r - 1)\left(\dfrac{m_s}{m_c} - 1\right)}{r(1 + y) + (1 - r)\left(\dfrac{m_s}{m_c} + y\right)}$$

where

$$y \equiv \frac{N_s(1 - \alpha)}{N_g - N_s}\,\frac{Q_s}{Q_c}$$

As shown by Solbes, the fluctuations in $T_e$ are much smaller than those in $N_e$ unless the degree of ionization $\alpha$ approaches 1. In this report, $\alpha$ is typically less than $10^{-3}$. Any fluctuations in $T_e$ are therefore neglected.

## Calculation of Effective Conductivity and Hall Parameter

Once the magnitude of $\beta_{crit}$ is found, the effective conductivity is determined (ref. 4, eq. (3)):

$$\sigma_{eff} = \langle\sigma\rangle \left[\frac{(1 - r)^2 + \beta_{crit}^2}{(1 - r)^2 + \langle\beta\rangle^2}\right]^{1/2} \equiv \frac{\langle\sigma\rangle}{1 + Z} \tag{4}$$

where $\langle\sigma\rangle$ and $\langle\beta\rangle$ are average values of the conductivity and the Hall parameter. Equation (4) defines a new parameter $Z$ which relates $\sigma_{eff}$ and $\langle\sigma\rangle$.

The value of $\beta$ used in equation (4) is the usual value based on the strength of the magnetic field and electron temperature. However, in experiments where density fluctuations occur, a different "effective" value of $\beta$ is measured. A change in $\beta$ is also indicated by the analysis. The effective Hall parameter $\beta_{eff}$ is the open-circuit voltage perpendicular to the average current divided by the voltage parallel to the average current. Its value is given by

$$\beta_{eff} = \frac{\langle\beta\rangle}{1 + Z} - \left(\frac{Z}{1 + Z}\right)\left[\frac{1 - r}{\langle\beta\rangle} + \sqrt{\left(\frac{1 - r}{\langle\beta\rangle}\right)^2 + 1}\right] \tag{5}$$

## Calculation of Electron Temperature

Now the value of $T_e$ can be found by substituting equation (4) into equation (2).

$$T_e = T + \left(\frac{\langle j\rangle^2}{\langle\sigma\rangle}\right)\left[\frac{(1 + Z)\overline{m}}{3m_e k\langle\nu_e N_e \Delta\rangle}\right] \tag{6}$$

where

$$\langle\sigma\rangle = \frac{e^2}{m_e}\left\langle\frac{N_e}{\nu_e}\right\rangle$$

$$T_e = T + \frac{\langle j\rangle^2(1 + Z)\overline{m}}{3ke^2\langle\nu_e N_e \Delta\rangle}\left\langle\frac{\nu_e}{N_e}\right\rangle \tag{7}$$

Note that variations in $T_e$ have been neglected, so that the term $T_e - T$ is a constant during the averaging process.

Equation (7) is analogous to equation (39) in reference 3. Once the electron temperature $T_e$ is determined, the calculation of the entrance magnetic field strength may be completed.

## Seed Fraction Specification

The seed fraction (ratio of seed density to carrier density) remains to be specified. Consistent with the previous effort to minimize the weight of the magnet, the seed fraction which minimizes the entrance magnetic field is selected. In reference 3, a different criterion is used to specify the seed fraction, but the values used in both that work and this one are similar.

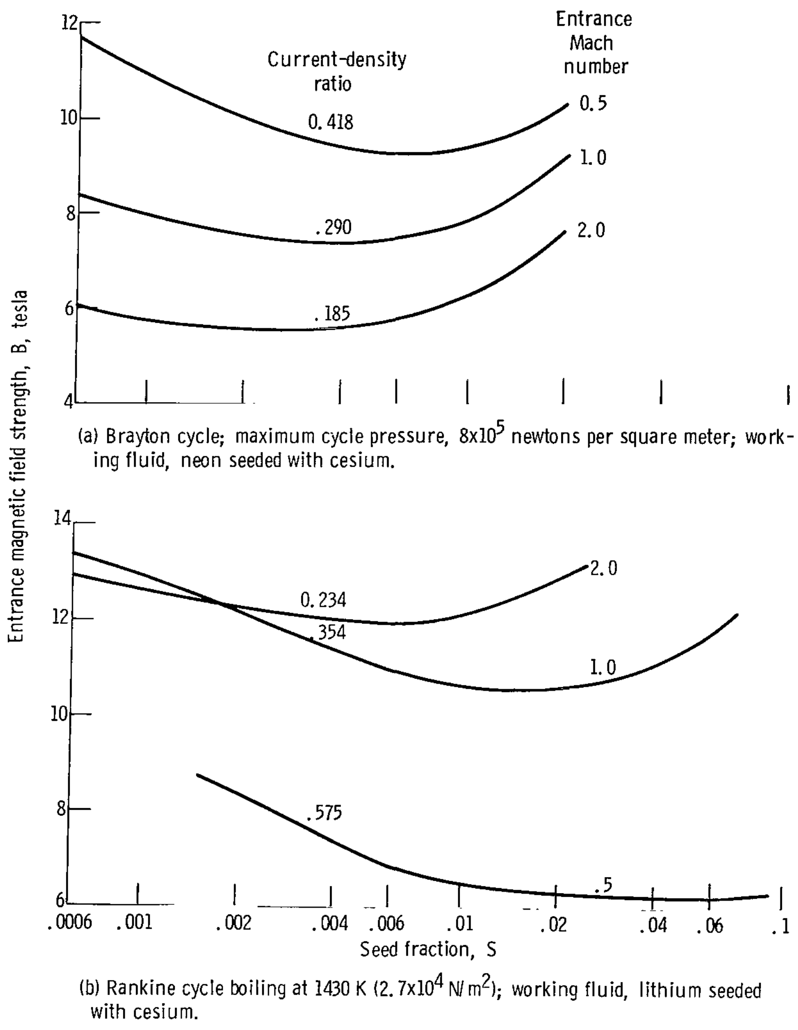



Figure 1. - Magnetic field strength required to provide a generator length of 0.5 meter as a function of seed fraction with entrance Mach number as a parameter. Maximum cycle temperature, 2100 K.

In figure 1(a) the entrance magnetic field of the Brayton cycle is shown as a function of seed fraction with entrance Mach number as a parameter. The maximum temperature, maximum pressure, and current-density ratio are fixed. Note that the value of seed fraction which minimizes magnetic field is dependent on Mach number. At $M = 0.5$, it is about 0.006; at $M = 1.0$, about 0.004; and at $M = 2.0$, about 0.003. In reference 3 a similar seed fraction of 0.001 is recommended.

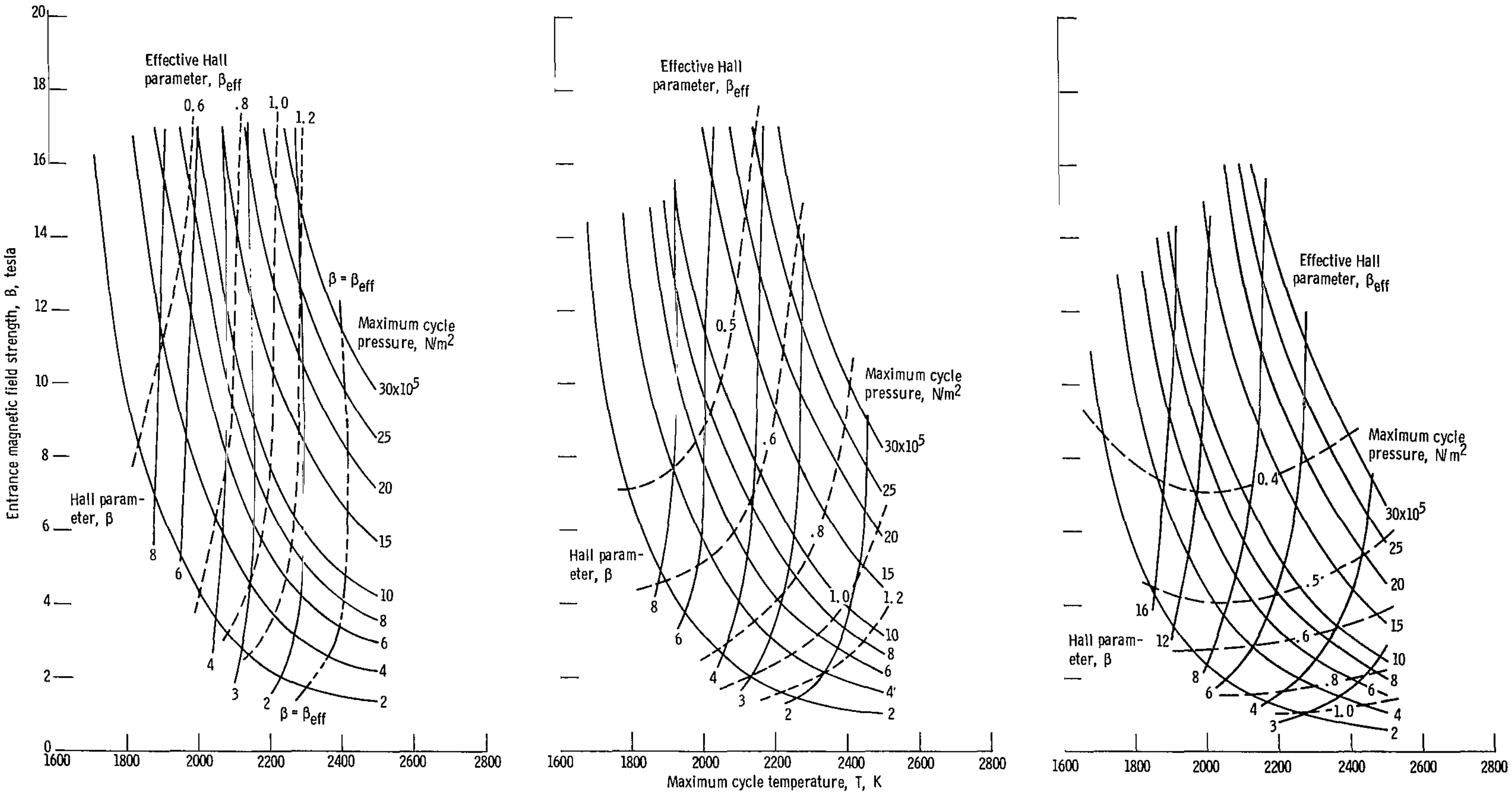
For the Rankine cycle, figure 1(b) shows the entrance magnetic field as a function of seed fraction with entrance Mach number as a parameter. The maximum temperature, maximum pressure, and entrance current-density ratio are fixed. For $M = 2.0$, the minimum magnetic field occurs at a seed fraction of 0.006; for $M = 1.0$, at 0.015. The curve for $M = 0.5$ is very flat, giving a minimum value of magnetic field at a seed fraction of about 0.050. However, increasing the seed fraction from 0.01 to 0.05 decreases the magnetic field by only 10 percent. A separate calculation shows that a decrease in output power of about 10 percent also accompanies this increase in seed fraction. The increase in seed fraction lowers the speed of sound in the plasma and reduces the input energy at constant entrance Mach number. A seed fraction of 0.01 is used in the Rankine cycle operating at an entrance Mach number of 0.5.

## RESULTS AND DISCUSSION

### Brayton Cycle

The results of the Brayton-cycle calculations are shown in figure 2. The generator length is 0.5 meter, a specific radiator area equal to that of the reference cycle is maintained, and the optimum seed fraction is used. The entrance magnetic field strength is plotted as a function of maximum temperature, with Hall parameter, effective Hall parameter, and maximum pressure as parameters. In figure 2(a) the entrance Mach number is 0.5, and the seed fraction is 0.006; in figure 2(b) the entrance Mach number is 1.0, and the seed fraction is 0.004; and in figure 2(c) the entrance Mach number is 2.0, and the seed fraction is 0.003. Figure 2 is similar to figure 20 in reference 3, except that curves of $\beta_{eff}$ have been added.

The variation of the parameters in figure 2 is qualitatively similar to those in reference 3. The entrance magnetic field increases with increasing pressure, increasing Hall parameter, decreasing temperature, and decreasing Mach number. Note the changes in $\beta_{eff}$ with entrance Mach number. At high Mach number, $\beta_{eff}$ is only a slight function of maximum temperature, while at low Mach number $\beta_{eff}$ is a very strong function of temperature. As the maximum cycle temperature increases, $\beta_{eff}$ approaches $\beta$. At the point where $\beta = \beta_{crit}$, the fluctuations are absent. For




(a) Entrance Mach number, 0.5; seed fraction, 0.006.

(b) Entrance Mach number, 1.0; seed fraction, 0.004.

(c) Entrance Mach number, 2.0; seed fraction, 0.003.

Figure 2. - Entrance magnetic field strength required to provide a generator length of 0.5 meter as a function of maximum cycle temperature with maximum cycle pressure as a parameter. Brayton cycle; working fluid, neon seeded with cesium.

$\beta > \beta_{crit}$, $\beta_{eff} = \beta$ and $\sigma_{eff} = \sigma$. This occurs at about 2400 K for M = 0.5, as shown in figure 2(a); and at temperatures above 2500 K for the higher entrance Mach numbers.

The effect of instabilities is to increase the necessary entrance magnetic field, particularly at the lower temperatures. This is shown in figure 3, where a comparison is made with the calculations given in reference 3. The maximum pressure is fixed at $8\times10^5$ newtons per square meter. The solid curves are taken from figure 2, with optimum seed fraction, while the dashed curves are from a calculation similar to that given in reference 3 with a seed fraction of 0.001.

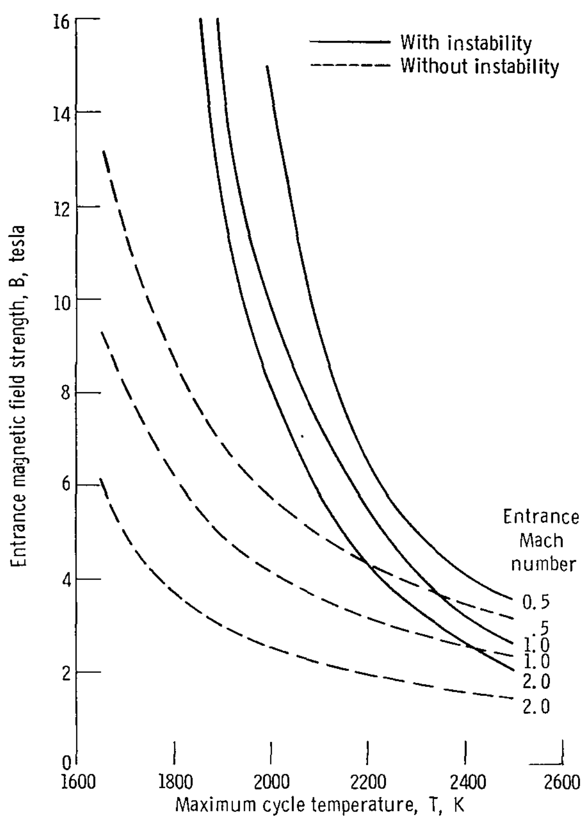



Figure 3. - Effect of instability on the required magnetic field as a function of maximum cycle temperature with entrance Mach number as a parameter. Brayton cycle; maximum cycle temperature, 2100 K; maximum cycle pressure, $8\times10^5$ newtons per square meter; working fluid, neon seeded with cesium.

## Rankine Cycle

In figure 4 the results of the Rankine-cycle calculations are given. A generator length of 0.5 meter, equal specific radiator areas, and optimum seed fraction are maintained. Two boiling temperatures for the lithium are presented (1430 and 1645 K), and entrance Mach number is plotted as a parameter. The entrance magnetic field is a strong function of temperature, increasing rapidly as the temperature falls. The variation with entrance Mach number is not as definite, depending on both boiling temperature and maximum temperature.

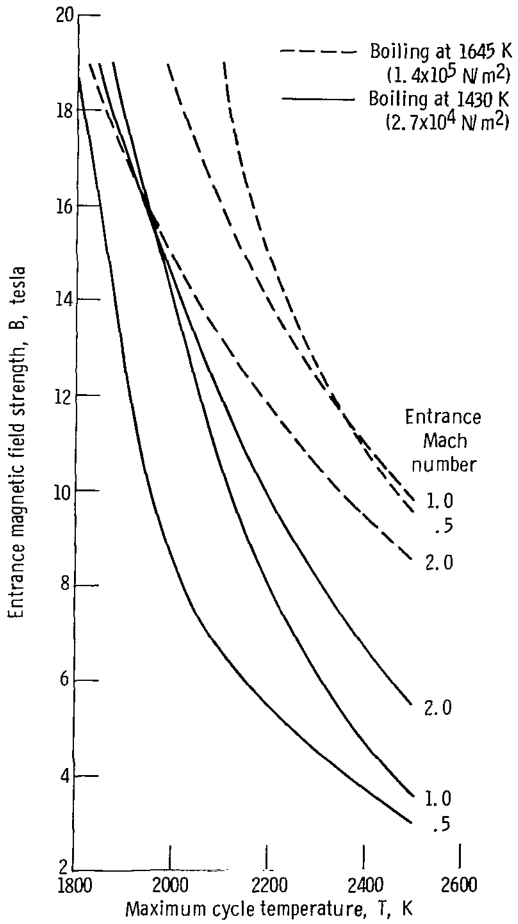



Figure 4. - Entrance magnetic field strength required to provide a generator length of 0.5 meter as a function of maximum cycle temperature with entrance Mach number as a parameter. Rankine cycle; working fluid, lithium seeded with cesium.

The comparison with reference 3 is shown in figure 5 for boiling at 1430 K. Again, the instabilities increase the necessary entrance magnetic field at a given maximum temperature. The solid curves are from figure 4, while the dashed curves are from reference 3 with a seed fraction of 0.01.

It is clear that for a fixed maximum cycle temperature, the effect of the electron density fluctuations is to increase the necessary entrance magnetic field. Alternatively, for a fixed entrance magnetic field, the maximum temperature in the cycle must be higher in order to produce the equivalent power. Both the Brayton cycle and the Rankine cycle show this increase.

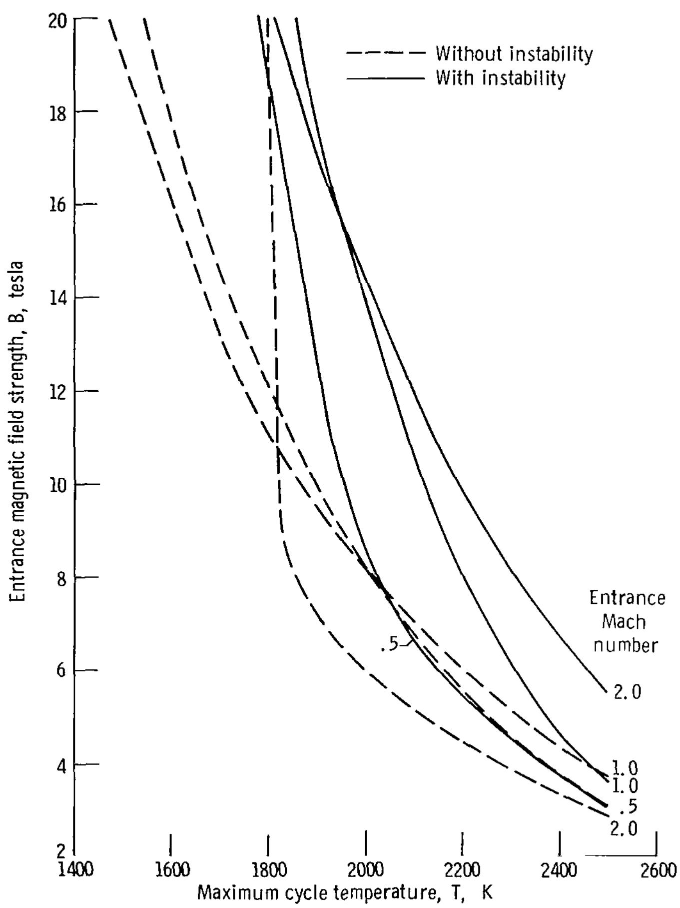



Figure 5. - Effect of instability on the required magnetic field as a function of maximum cycle temperature with entrance Mach number as a parameter. Rankine cycle boiling at 1430 K ($2.7\times10^4$ N/m$^2$); working fluid, lithium seeded with cesium.

## Comparison of Cycles

In figure 6 the output power at a fixed entrance magnetic field of 10 tesla is plotted against maximum cycle temperature with entrance Mach number as a parameter. Similar data from reference 3 are also given. The higher cycle temperature necessary to maintain the same power output is evident in this graph. The maximum power is produced by the Brayton cycle operating at $M = 1.0$. Slightly less power is produced at $M = 0.5$ and at $M = 2.0$. The output power of the Rankine cycle is considerably lower than that of the Brayton cycle. The two boiling pressures selected for the Rankine cycle appear as discrete points, while the continuous range of maximum pressure in the Brayton cycle forms a smooth curve.

All of these results are qualitatively similar to those in reference 3. The fluctua-

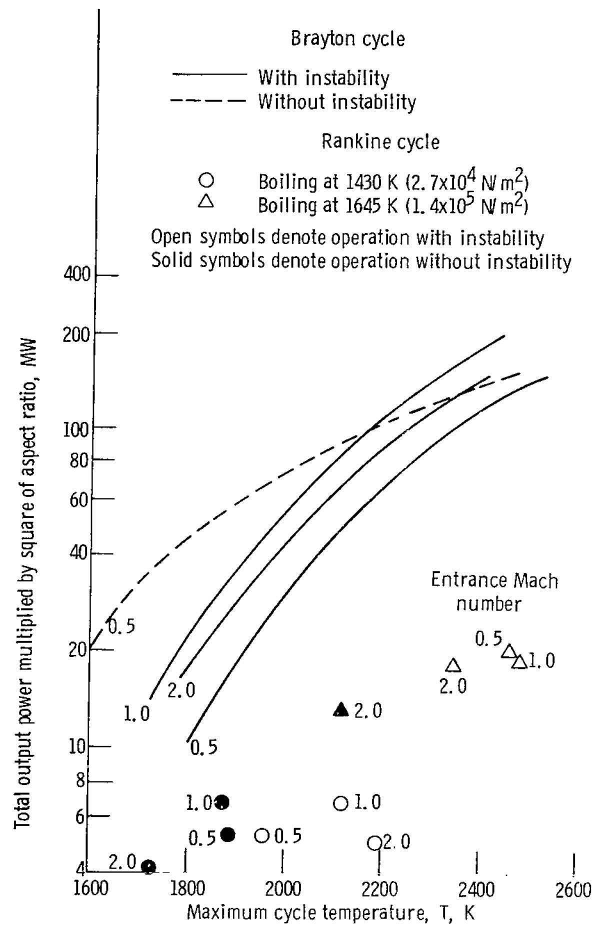



Figure 6. - Generator output as a function of maximum cycle temperature with entrance Mach number as a parameter. Entrance magnetic field strength, 10 tesla; Brayton cycle working fluid, neon seeded with cesium; Ranking cycle working fluid, lithium seeded with cesium.

tions in electron density change the numerical value of the results, primarily by decreasing the conductivity and increasing the power dissipated in Joule heating. This implies either a lower power output or an increase in magnetic field strength to compensate for the loss.

## CONCLUSIONS

The effects of electron density fluctuations on the performance of Brayton and Rankine magnetohydrodynamic (MHD) generators has been studied. The analysis indicates that

1. The electron density fluctuations decrease the power output for a given generator and magnetic field strength. The power loss increases as the maximum cycle temperature decreases. For the Brayton cycle, maximum power output is achieved at a Mach number of 1.
2. Increasing the magnetic field strength will compensate for the output power loss due to fluctuations. Although a somewhat larger magnet is necessary, this does not limit MHD generators for space-power applications because the magnet weight is expected to be a small fraction of the total system weight.
3. There is a seed fraction which minimizes the entrance magnetic field strength for each generator. However, in some cases the advantage of a decrease in magnetic field is offset by a decrease in power output.
4. The effective Hall parameter is considerably lower than the Hall parameter based on magnetic field and electron temperature. This means that the Hall voltage between segments of the electrode is smaller.
5. The power output of the Brayton cycle is larger than the Rankine cycle for the same maximum temperature, radiator area, length, entrance Mach number, and magnetic field strength.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, August 7, 1969,
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