Annular-Beam Ion Engines

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The strip-beam cesium contact ion engine forms a major class of electrostatic propulsion engines that develop thrust by means of the acceleration of charged particles. This strip configuration offers a number of fundamental advantages compared to other forms of ion engines, including higher current density, ease of fabrication, high overall thrust density, etc. Such ion engines, built in the forms of multiple linear strips and circular strip or annular configurations, have been built and operated. This paper presents some of the considerations entering into the design of efficient engines of this type, quotes performance achieved to date on a small circular form of this strip engine, and describes preliminary results of some more advanced forms of engines. The emphasis is on the circular strip or ring type of ion engine and particularly on such an engine that was developed for an early flight test demonstration. Future improved performance from this type of ion engine also is indicated, based on the experience to date.

I. Introduction

Among the various types of electrical propulsion systems proposed to date,[1] the cesium contact ion engine inherently possesses great potential for those practical space applications requiring high specific impulse. During the past two years considerable progress has been made toward the realization of this potential.

It is obvious that all other performance characteristics are irrelevant unless the basic engine design permits the attainment of continuous and reliable operation for thousands of hours. One of the central problems in reaching this goal consists of refining the ion beam trajectory control to the point where ion interception and hence electrode erosion become virtually negligible. Because of the precisely defined manner in which the ions are generated in the contact-type engine, the ion optical system is amenable to high-accuracy design techniques such as those employed in the design of high current density electron guns.[2] Other technical areas of the ion engine system which affect the life and reliability of the engine system include the source of the ions, the propellant storage and phase separation system, and the electronic components that form the power conditioning system.

High engine efficiency, in addition to its obvious importance in obtaining maximum thrust for a given power availability, also is related directly to reliability, since it implies that the electrodes and support structure operate at low temperature. High efficiency is attained by minimizing the power required to maintain the ionizer at its operating temperature and by maximizing the current density drawn from the ionizer surface.

After the basic characteristics of total current, voltage, and total engine perveance are determined for a given mission, it is necessary to decide on the geometrical form of the engine. An efficient and compact form of cesium ion engine can be made in the shape to produce a thin strip beam of ions. This strip geometry offers several fundamental advantages:

1) The basic strip configuration can be made in either a linear or a circular shape, with essentially no change in the accelerator geometry or ion optical characteristics.

2) The ionizer is compact; that is, only the actual emitting surface radiates toward other electrodes, resulting in cooler electrodes and a more efficient engine, together with relatively high values of thrust density.

3) This design can form the basis of higher thrust unit engines composed of concentric rings or closely packed linear strips, yielding an efficient and compact engine.

4) The ejected beam can be neutralized in detail by the injection of electrons into each strip.

5) The strip geometry lends itself to design with existing proved technology and therefore provides engines with well-defined properties. The simple mechanical shape can be machined and assembled conveniently and with great accuracy.

6) Because of the electric field configuration inherent in the strip accelerator, higher current densities can be drawn for a given electric field strength than with other geometrical arrangements.

This paper will describe some of the results to date in the development of strip ion engines, with emphasis on the annular or circular strip geometry.

An artist's drawing of a simple, single-circular-strip ion engine is shown in Fig. 1 to illustrate the principal elements involved. The ionizer is heated by means of a filament behind the cesium distribution duct. The several electrodes shown in the decelerator system form an electron injector to effect neutralization of the ion beam before it leaves the engine. The shape of the accelerator and decelerator electrodes is critical for control of the ion trajectories and to effect uniform current density across the ionizer. The source of ions is a porous tungsten ring, fed with cesium from the cesium duct that is connected to the propellant feed system.

II. Some Ion Engine Design Considerations

The major problem facing the engine developer is that of improving the overall performance of the thrust unit to the point where it is a practical propulsion device from the point of view of the engine user. From the latter viewpoint the following criteria, arranged in approximate order of importance, are believed to be appropriate: 1) efficiency of conversion of power to thrust; 2) reliability and life; 3) thrust per unit total frontal area; 4) magnitude of high voltages required; 5) engine weight per unit thrust; and 6) control problems and restart capability.

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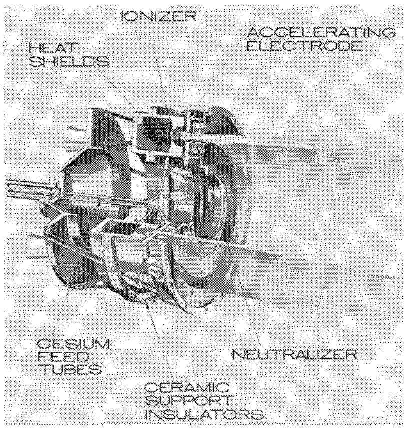

Fig. 1 Artists' cutaway sketch of an annular cesium contaction engine showing the essential features of the thrust unit

A. Thermal Efficiency

To consider the first criterion, assume for the moment that power losses due to accelerator and neutralizer electrode current drains are negligible. In this situation, thermal radiation from the ionizer constitutes most of the power loss and is the major factor associated with ion engine efficiency. Since the ionizer temperature is determined by the required ion current density, the ionizer heating power can be decreased by 1) decreasing the heated area of the ionizer assembly, 2) providing good heat transfer from the heater to ionizer, 3) lowering the emittance of heated surfaces, and 4) providing effective heat shielding.

Two methods used to heat annular ionizers are shown in Fig. 2. The area of the ionizer support structure for the newer strip heater design has been reduced to 60% of that for the coil heater design. Ionizer and accelerator electrode temperatures as a function of heater power are shown in Fig. 3. Approximately 200 w into the strip heater maintains the ionizer at 1100°C and the accelerator electrode below 350°C, whereas the coil heater requires approximately 300 w for an ionizer and accelerator electrode temperature of 1100° and 430°C, respectively. The effect of such improvements on engine performance will be shown later. The effectiveness of heat shielding to conserve the ionizer heating power has been investigated experimentally and has resulted in significant reductions in ionizer heating power and, therefore, increased efficiency.

Comparison of the ratio of ionizer emittance ϵ_T to heating efficiency η_H for different engine configurations is made in Fig. 4. Since the heater power is $P_H = \epsilon_T/\eta_H \sigma A_i T_i^4$, where σ is the Stefan-Boltzmann constant, A_i is the cesium emitting area, and T_i is the ionizer temperature, the parameter ϵ_T/η_H is a direct measure of the ratio of power radiated from the ionizer surface (for a given temperature) to the required input power. The ratios ϵ_T/η_H for the single ring coil heater and single ring strip heater engines (Fig. 2) were calculated using measured heater powers. Values of the parameter ϵ_T/η_H for the two ring, five ring, and eight parallel-linear-strip engines were calculated using the compact ionizer design of the strip heater and the power saved by mutual radiation between adjacent rings or strips.

The emittance of the ionizer surface obviously affects the heater power required for a given ionizer temperature; this parameter therefore has been studied extensively. Normal

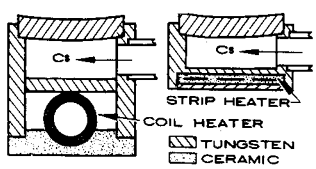

Fig. 2. Two methods of ionizer heating

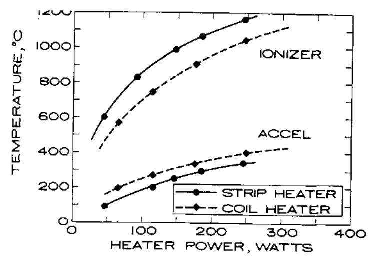

Fig. 3 Comparison of ionizer heater powers for the two methods of ionizer heating of Fig. 2. These data were measured for a 3-in. mean diameter annulus whose porous tungsten emitting area was 15.5 cm²

total emittance‡ measured for various porous tungsten samples ranged from 0.2 to 0.6 at 1100°C. The emittance appears to be a function more of the surface finish and thermal history than of the particle size. The emittance exhibits a trend with time toward higher values when the sample is heated in a vacuum on the order of 10^{-6} Torr. Thus, significant increases in ionizer heating efficiency have resulted from development of compact ionizer assemblies (small radiating area and large conduction paths from heater to ionizer). Further increases in efficiency will result from the development of suitable methods of treatment of ionizer surfaces to obtain low emittances without impairing the ion current emission capabilities and from improvements in heat shield fabrication and heater design.

B. Scaling and Design Limitations

In addition to improvements of thermal efficiency, a program of developing engines exhibiting improved performance over early model ion engines is aimed toward the use of higher current densities and thus higher thrust density and to engine units providing higher thrust. The higher current densities and thrust levels can be acquired in five ways: 1) reducing the engine scale, 2) increasing the accelerator voltage, 3) increasing the perveance per inch, 4) increasing the ionizer area, and 5) fabricating multiple strip units (multiple concentric rings or close-packed linear strips). Each of these methods involves certain restrictions or difficulties. Scaling down the engine size is limited by mechanical strength and breakdown voltage unless the voltage also is scaled. The maximum acceleration voltage also is limited by breakdown. The obtainable values of perveance per square are limited by the ion optical characteristics of the accelerator. There is also an upper limit to the allowable perveance per inch due to the limiting perveance phenomena in the exhaust beam. Multi-ring structures will be susceptible to both electrical and thermal insulator problems and to the design problem of

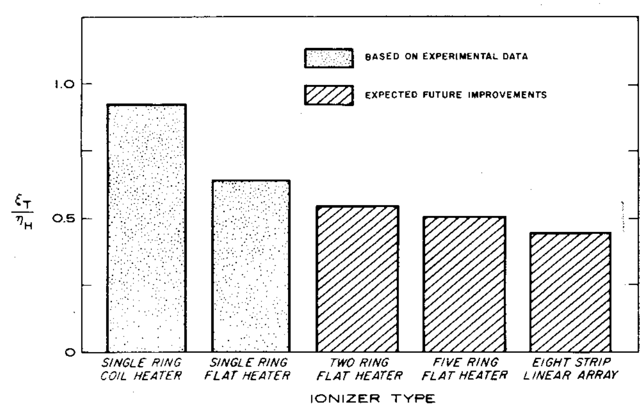

Fig. 4 Comparison of the ratio of ionizer emittance ϵ_T to heating efficiency η_H for different engine geometries. The multiple ring geometry is composed of concentric annuli

‡ For a discussion of the terms normal total emittance, hemispherical total emittance, total emittance, spectral emittance, emittance, and emissivity, see Ref. 3.

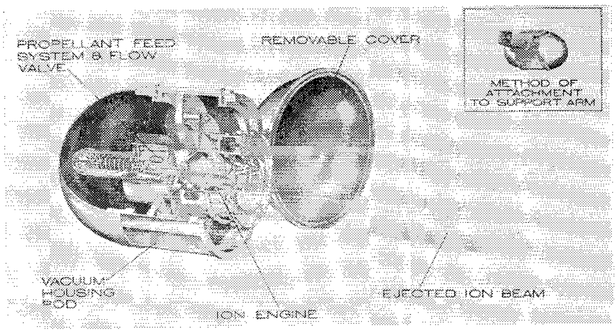

Fig. 5 SERT I ion engine shown mounted in a vacuum housing pod

electrode mountings and leadthroughs. The first two methods described for achieving improved performance can be shown to be of limited value, whereas the last three seem to offer the best promise. Some advances in engine performance resulting from these steps will be described below.

III. Ion Engine Characteristics and Performance

The desirability of conducting an early space test of an electrostatic propulsion device has dictated the emphasis of efforts during the initial development stages of cesium contact ion engines at Hughes. An annular beam ion engine was designed conservatively early in 1961 to meet the objectives of the initial Space Electric Rocket Test series being conducted by NASA. As reported in greater detail elsewhere,[4] the SERT I ion engine (see Fig. 5) has the following design characteristics:

Thrust = 1.6 mlb
Specific impulse = 8900 sec
Accel. perveance = 54 $\times$ 10^{-9} $A/V^{3/2}$
Beam perveance = 153 $\times$ 10^{-9} $A/V^{3/2}$
Accel. voltage = 10.6 kv
Decel. voltage = 5.3 kv
Ion current = 58.4 ma
Beam power = 310 w

The performance of this engine to date has been satisfactory in that all the electrical and environmental objectives for the planned SERT I test have been realized. Individual SERT I engines for this 30-min test have been operated for up to 50 hr total running time under varying current-voltage conditions. A photograph of this engine while undergoing test in a vacuum chamber is shown in Fig. 6. Pulse techniques have demonstrated that ion space charge of the exhaust beam can be neutralized fully by controlled radial injection of electrons.[5] To determine whether a true space environment will modify the neutralization state is one of the objectives of the flight tests.

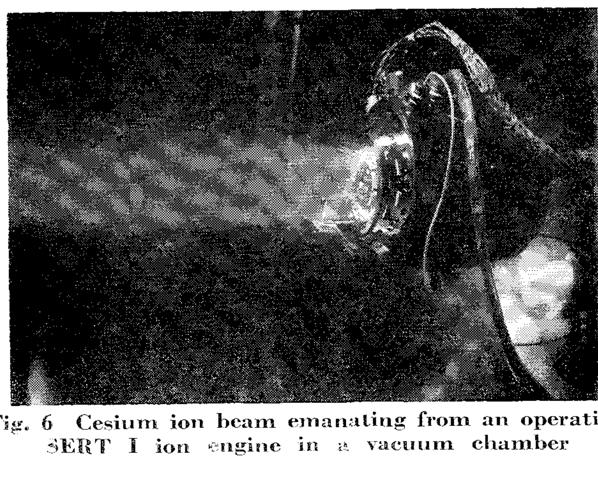

Fig. 6 Cesium ion beam emanating from an operating SERT I ion engine in a vacuum chamber

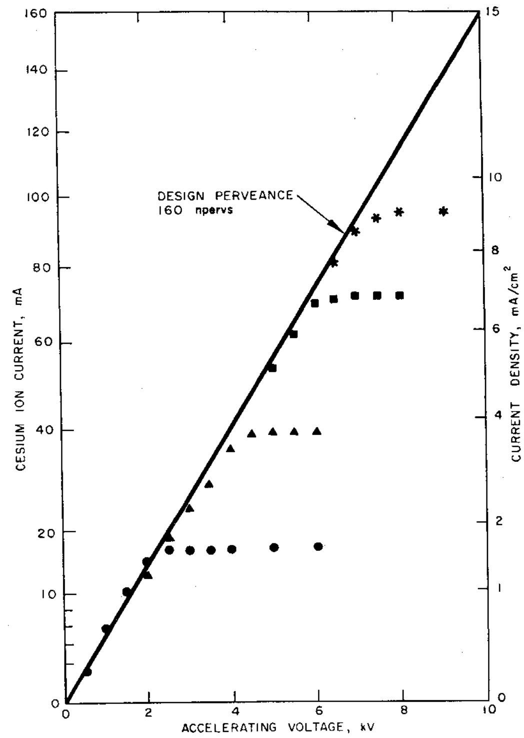

Fig. 7 Perveance characteristics of an advanced-design single-ring ion engine. The ionizer has a mean diameter of 3 in.

The design of this engine has been supported by detailed studies of the ion optical characteristics by means of trajectory traces and electron-gun analogs. It was found possible to achieve a design producing a suitably laminar flow of the ion beams with interception values on the acceleration electrode calculated from these trajectories to be about 10^{-8} (based on transverse thermal spreading only), with measured values of acceleration current to ion beam current ratio of 10^{-3}. However, this latter value includes leakage currents that are higher than the actual ion interception. From these interception values and observations of actual erosion (primarily due to bombardment by charge-exchange ions), one can make rough calculations of the electrode erosion rate to arrive at an estimated lifetime of several thousand hours without significant effect on the optics of the accelerator.

Laboratory tests on many engines of this type have demonstrated performance quite close to the design characteristics, thus inspiring confidence that future engines based on this strip geometry concept will perform as predicted. This flight test engine therefore can be regarded as a laboratory-proven prototype on which to base the design of future larger engines.

Application of the perveance scaling principle has resulted in two new engine designs with acceleration perveances of 17.6 and 22 nanoperv/in. of ionizer length. This corresponds to an increase in the perveance per unit length by a factor of 3 to 4 over the SERT I engine. At an acceleration voltage of 10 kv and a specific impulse of 9000 sec, the higher perveance engine in the shape of a 3-in.-diam annulus is designed to produce a thrust of 5.6 mlb and a cesium ion current of 200 ma, corresponding to an ionizer current density of 15 ma/cm.^{2} Cesium ion current densities as high as 22 ma/cm^2 have been extracted from a porous tungsten ionizer in experiments at Hughes by Husmann.[6]

Tests of these higher thrust density ion engines have proved promising, as shown by the results in Fig. 7. The measured current-voltage characteristics agree quite closely with the design acceleration perveance of 160 nanoperv for space-charge-limited emission.

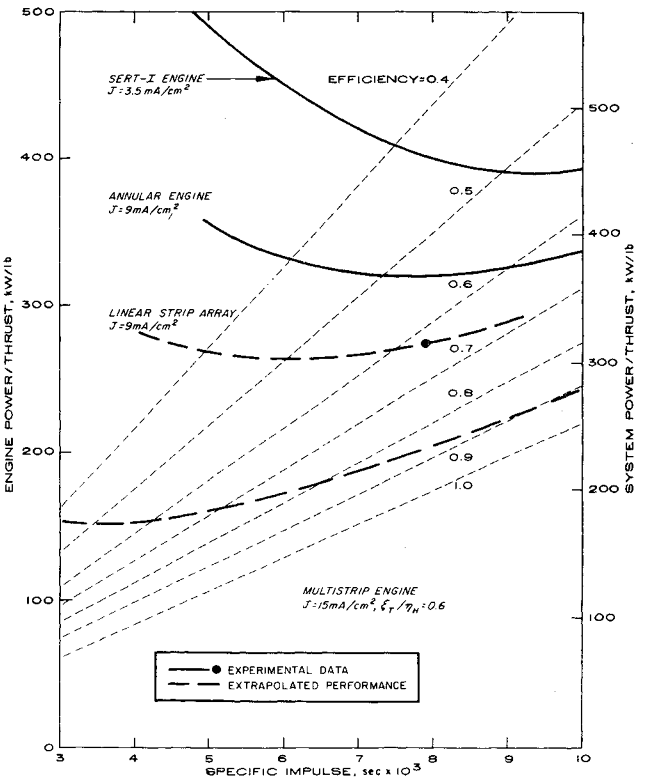

Fig. 8 Power-thrust characteristics for several cesium ion engine designs. Engine power is defined as beam power plus ionizer heater power plus any losses caused by electrode drain currents. System power is defined as the engine power plus the losses encountered in the power conditioning equipment and the cesium boiler and neutralizer heater powers. The value of ϵ_T/η_H for the experimental data was approximately unity

A 3-in. mean diameter annular engine (22 nanoperv/in.) has been operated for 120 continuous hours at ionizer current densities up to 11.2 ma/cm².§ Thrust calculated from these parameters was 3.9 mlb at 8000 sec. The ion emission density was maintained at 10 ma/cm² for 100 hr. Metallographic examination of the engine after this test indicated that erosion of the acceleration electrode was negligible.

Electron beam welding techniques have been perfected for the bonding of porous tungsten emitter rings to dense tungsten support manifolds. Such an ionizer assembly was employed in the forementioned ion engine. In addition to the fabrication of vapor-tight joints with electron beams, this technique has been employed to surface melt selectively and to resinter tungsten in order to suppress cesium vapor effusion from areas other than the desired ion emitting surface. These techniques have been applied successfully to the assembly of ionizers composed of an array of linear strips.

One such ionizer consisting of four 4-in.-long parallel emitting strips was operated in an ion engine that produced a thrust of 4.9 mlb at 7960 sec.‖ The ionizer current density was 9 ma/cm². This engine also had a measured power to thrust ratio of 273 kw/lb at 7960 sec which extrapolated to 263 kw/lb at 6000 sec. The engine efficiency at 7960 sec was 64%. In addition, an electron-beam welded eight-channel ionizer was operated in a multistrip engine, which resulted in the attainment of a thrust level of 9 lbm at 9000 sec at a current density of 8.5 ma/cm².

Of the several graphical ways of presenting ion engine performance data for evaluation and comparison of engines, a plot of the ratio of the input power to the thrust produced (P/T) vs the exhaust specific impulse is one of the most useful. In general, the input power from any power-conditioning equipment to the ion engine is composed primarily of beam power that appears as thrust and power required to heat the ionizer. The latter factor, which is essentially a power loss when divided by the ion emission current, represents the energy required to create one ion. This energy loss can be decreased by increasing the ion emission density and by more efficient heating techniques.

§ These results in the linear version of the strip engine have been obtained by M. D. Stribling, Hughes Research Laboratories, Malibu, Calif., since the ARS Electric Propulsion Conference in March 1962.

‖ See the forementioned results of Stribling.

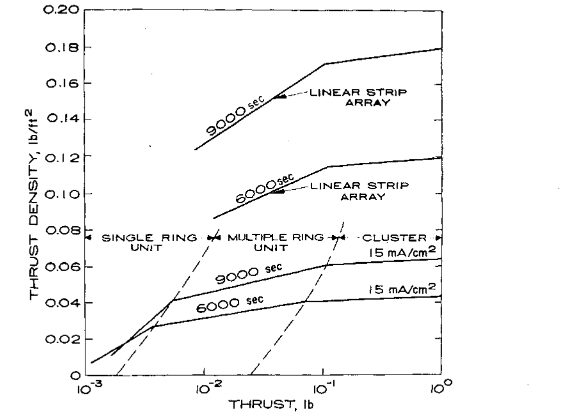

Fig. 9 Thrust per unit frontal area as a function of total thrust for several cesium ion engine designs

Based upon the demonstrated improvements in ionizer heater efficiency and current density, the present and predicted future performance of strip ion engines is shown in Fig. 8, where P/T and efficiency are plotted vs specific impulse. The large reduction in P/T from the SERT I engine to the higher perveance annular and linear strip engines is a consequence of higher current density operation and improved heater efficiency. Extrapolation to the case of a multistrip engine assumes that the operating current density can be maintained at 15 ma/cm² and that the ionizer heating losses can be decreased from the present value of $\epsilon_T/\eta_H = 0.75$ to $\epsilon_T/\eta_H = 0.60$. Attainment of these values would result in an engine P/T value of 170 kw/lb at 6000 sec with an efficiency of 78%. The corresponding efficiency at 9500 sec is 90%. The overall system power-to-thrust would be slightly higher because of power losses in the cesium boiler and neutralizer heaters and in the power-conditioning equipment.

Another characteristic that concerns the engine user is that of thrust density calculated on a unit frontal area basis. This quantity has been determined for a number of present and future strip engine designs, and the results are shown in Fig. 9 as a function of thrust level for two values of specific impulse. The sequence of the evolution of higher thrust annular ion engines is outlined: single-ring unit → multiple-strip unit → cluster of multiple-strip unit engines, and their areas of preeminence in terms of thrust. For the linear strip array operating at a specific impulse of 9000 sec and a thrust level of 0.1 lb, the thrust density will be approximately 0.17 psf.

IV. Conclusions

This paper has presented a brief description and performance results on a class of cesium contact ion engines for which the emergent beam is in the shape of a thin strip, either in a linear or annular shape. Several of the technical areas that influence ion engine performance and that are receiving attention also have been discussed so as to result in further improved performance values. Most of the data reported herein resulted from tests on a relatively low performance engine designed almost two years ago for use in a flight test demonstration of cesium ion engine operation in space. Although this engine does not represent by any means the current state of the art, its development has served to delineate those technical factors that affect engine performance and has resulted in a proven and reliable engine for the intended space test. These studies have served as an effective tool for the demonstration of the feasibility of cesium ion engines for space propulsion (at least as far as ground tests can so demonstrate) and have resulted in design parameters producing considerably improved engine performance. The authors believe, for example, that efficient, compact, cesium contact ion engines operating at an ionizer current density of 15 ma/cm^2 and incorporating improved ionizer heating techniques, propellant feed system, laboratory-proven neutralization systems, etc., can be made with confidence to exhibit performance values of less than 200 kw/lb in the 5000-sec specific impulse region and less than 250 kw/lb in the 10,000-sec specific impulse range.

Future work, which is essential to further improvement in engine performance in order to make such units available for space propulsion, includes studies of reliability over extended periods of time, space flight tests of certain critical engine characteristics, ionizer research, etc.

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Interaction Between Sound and Flow: Stability of T-Burners[1]

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The question of the effect of gas flow on the damping of an acoustic cavity with an orifice is of considerable importance in connection with the experimental determination of the acoustic admittance of burning solid propellants. The present investigation considers a center-vented rigid-walled cylindrical cavity that contains burning propellant at either or both ends. The only acoustic loss mechanism considered is that of the orifice. It is found that the presence of flow will, in general, have a significant effect on the conditions necessary for the acoustic stability of such a cavity and on the interpretation of the growth and decay rates in terms of the acoustic admittances characterizing the ends of the cavity.

ROCKET motors sometimes break into acoustic oscillation of such amplitude that the consequences are devastating to the performance and even to the integrity of the motor. This phenomenon has led a number of investigators to the study of the mechanics by which the energy of burning propellants is converted to high amplitude sound. In the considerable literature that has resulted from these studies, attention has been focused on the gains and losses presented by the various boundaries of the rocket cavity to the sound field. In general, the approach has been to attempt to represent these boundaries acoustically as admittances and then to discuss the problem of stability in the same manner as one would any ordinary acoustic system of this particular geometry.

More careful consideration, however, reminds one that the cavity is fundamentally somewhat different from those usually treated. It contains a mean flow field. This has consequences not usually encountered in describing resonances in acoustic cavities. One way of looking at the problem is to say that acoustic energy in such a cavity is propagated not only by the usual mechanical transfer but also by convective transport.

In assessing stability, one must account for the energy transferred by both of these mechanisms. For example, some regions of the cavity might have the ability to transform convectively transported energy. They would then, in a sense, appear to be "virtual amplifiers" of sound and would have to have admittances (which are intimately connected with mechanical transport) assigned to their surfaces accordingly. These assignments obviously would not be the same as would be made in the absence of the flow field. For example, insofar as the sound field is concerned, an orifice region could be an active, rather than a passive, acoustic element. Such behavior is implied by calculations of nozzle admittances that show negative real parts (1, 2).[5]

As an example of the modification that a flow field makes in stability criteria, consider the case of a propellant surface discharging gas into a cylinder cavity that is centrally vented to the outside (T-burner), as in Fig. 1. Attention will now be focused on the axial modes of this system.

If one neglects flow field effects, then, in the absence of any losses elsewhere in the system, stability would be determined

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[5] Numbers in parentheses indicate References at end of paper.