NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON, D.C. 20546

REPLY TO
ATTN OF:

March 29, 1971

TO: USI/Scientific & Technical Information Division
Attention: Miss Winnie M. Morgan

FROM: GP/Office of Assistant General
Counsel for Patent Matters

SUBJECT: Announcement of NASA-Owned
U.S. Patents in STAR

In accordance with the procedures contained in the Code GP to Code USI memorandum on this subject, dated June 8, 1970, the attached NASA-owned U.S. patent is being forwarded for abstracting and announcement in NASA STAR.

The following information is provided:

U.S. Patent No. : 3,367,114

Corporate Source : Hughes Aircraft Company

Supplementary
Corporate Source :

NASA Patent Case No.: XNP-02923

Please note that this patent covers an invention made by an employee of a NASA contractor. Pursuant to Section 305(a) of the National Aeronautics and Space Act, the name of the Administrator of NASA appears on the first page of the patent; however, the name of the actual inventor (author) appears at the heading of Column No. 1 of the Specification, following the words ". . . with respect to an invention of. . . ."

Gayle Parker

Enclosure:
Copy of Patent

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Feb. 6, 1968 JAMES E. WEBB 3,367,114

ADMINISTRATOR OF THE NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

CONSTRUCTION AND METHOD OF ARRANGING A PLURALITY OF ION ENGINES TO FORM A CLUSTER

Filed Oct. 8, 1965

Fig. 1

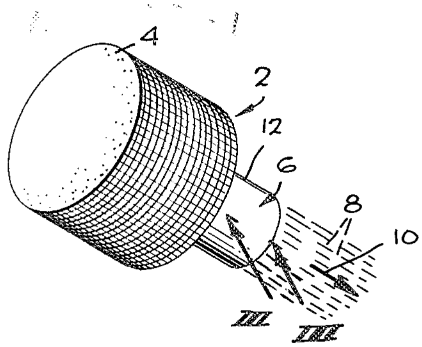
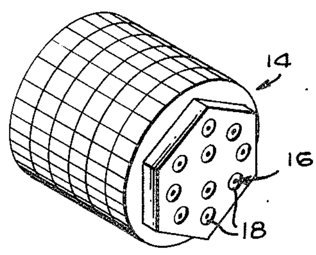
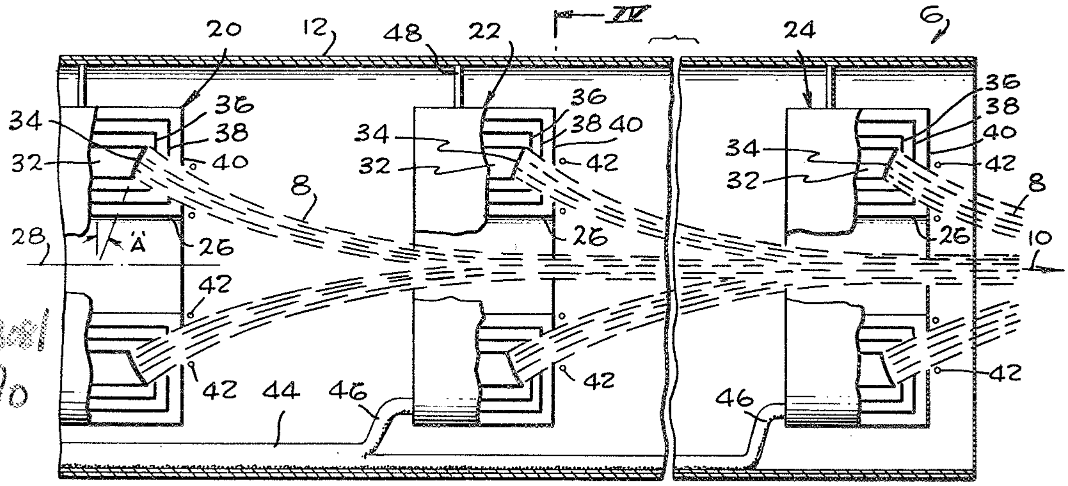


Fig. 2



PRIOR ART

Fig. 3



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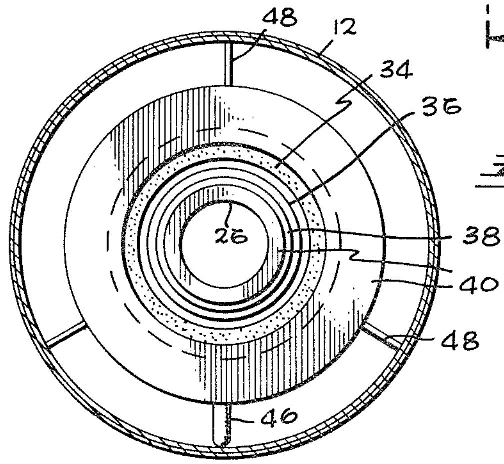

Fig. 4

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3,367,114

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3,367,114
CONSTRUCTION AND METHOD OF ARRANGING A PLURALITY OF ION ENGINES TO FORM A CLUSTER

James E. Webb, Administrator of the National Aeronautics and Space Administration, with respect to an invention of Hayden E. Gallagher, Malibu, Calif.

Filed Oct. 8, 1965, Ser. No. 494,280
13 Claims. (Cl. 60—202)

ABSTRACT OF THE DISCLOSURE

A plurality of ion engines are positioned, one upstream of the other, rather than in side by side relationship. In the disclosed form, a downstream engine is positioned to shield the engine upstream of it. The engines are also constructed so the ion beam from an upstream engine will not impinge on a downstream engine. Such a construction decreases the amount of heat loss by an ion engine to space. This creates a much more efficient cluster. Additionally, when the engines are positioned in a line, with a common longitudinal axis, it is easier to accurately control the total thrust if one engine should become inoperative. This is because, even if an engine should become inoperative, the direction of thrust of the remaining engines would still continue to be along their common longitudinal axis.

The invention described herein was made in the performance of work under a NASA contract and is subject to the provisions of Section 305 of the National Aeronautics and Space Act of 1958, Public Law 85–568 (72 Stat. 435; 42 USC 2457).

This invention relates to ion engines. More particularly, it teaches how to arrange a group of ion engines into a cluster for use on a spacecraft, so as to increase the efficiency and control of the group of ion engines.

In the more demanding space missions for spacecraft, that is, for missions beyond the moon, it is planned to use ion engines to propel the spacecraft. However, one ion engine cannot, by itself, develop sufficient thrust for the mission. It is therefore necessary to use a group of ion engines to provide the required thrust. This group of ion engines is normally called a cluster.

In forming the cluster, it has been customary to position the ion engines in side-by-side relation, generally in the same plane. This is much like a bank of flood lights that are positioned to illuminate an area.

With a cluster of the above type, there is a problem of efficiency. Generally, as will be more fully explained later on, an ion engine includes an ionizer heater to heat the ionizer. The expellant is fed to the ionizer where it is ionized and issues from the engine as an ion beam. The efficiency of an ion engine depends directly on the power used to heat the ionizer heater and is given approximately by the formula:

$$N=\frac{P_1}{P_1+P_H}$$

where

N=efficiency
P_1=ion beam power
P_H=ionizer heater power

That is, the efficiency of the ion engine is equal to the ion beam power divided by the ion beam power plus ionizer heater power. In an ion engine, the power to heat the heater is the major source of power loss. This is because about half of the heater power of an ion engine is radiated from its ionizer surface to space, and half is radiated and conducted to other parts of the engine.

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Where ion engines are in side-by-side relationship, the ionizer surface radiating to space is increased for each engine added to the cluster. Consequently, the efficiency of the cluster is approximately the same as for a separate engine. If the heat radiated to space by the ionizer surfaces could be decreased, it follows that the efficiency of the cluster would be greatly improved.

Another problem is in control, when ion engines are positioned in side-by-side relation, and one or more engines fail to operate. If an engine of the group fails to operate, there is a change in magnitude and direction of the force of propulsion of the cluster. When an ion engine becomes inoperative it is analogous, for example, to what happens to a four engine airplane when one of its four engines ceases to operate. The remaining three engines cause the plane to veer from its previous course unless they are carefully adjusted to compensate for the inoperative engine.

Where a spacecraft is far from earth, and an ion engine becomes inoperative, it is a much more difficult problem to compensate for both a change in magnitude and direction of the force of propulsion. It follows that any cluster arrangement that can decrease this problem will make control of the spacecraft more accurate.

With the above in mind, it is therefore an object of this invention to teach how to arrange a group of ion engines into a cluster to provide higher efficiencies than were previously attainable with previous constructions.

It is also an object of this invention to teach how to arrange a group of ion engines into a cluster to provide more accurate control of the spacecraft in the event one or more ion engines of the cluster should become inoperative.

Essentially, this invention teaches how to increase efficiency of the cluster of ion engines by decreasing the heat radiated to space by individual ion engines. This is accomplished by positioning them in a line, one upstream of the other, rather than in side-by-side relationship. The ion engines are coaxially aligned, and constructed so that each ionizer's surface is shielded by a downstream engine. To permit the engines to be coaxially aligned, each ion engine is provided with a passage to permit the ion beam of the engines upstream of it to pass right through it.

To make the ion beam from an upstream engine pass through the passage of a downstream engine, the ion beam is slightly bent. The ionizer of each engine is made slightly inclined, and this, in cooperation with the ion engine's focus electrode, bends the ion beam through a small angle so it will pass through the passage of a downstream engine.

With the above construction, the amount of heat radiated to space by each ionizer's surface is greatly decreased since it is shielded by a downstream engine. Further, the ion engines are additionally insulated from space by radiation shields encircling the engines. This additionally decreases the heat radiated to space to further increase the efficiency of the group.

Also, with the ion engines coaxially aligned, such a construction permits more accurate control of the group. This is because the force of propulsion of all of the ion engines is now directed in the same direction along their common longitudinal axis. With such a construction, if one or more ion engines should become inoperative, the force exerted by the remaining engines would still be in the same direction along the longitudinal axis of the group. There would be no change in the direction of the force of propulsion. There would only be a change in the magnitude of the force of propulsion. If an ion engine now fails to operate, it is a simple matter to adjust the output of one or all of the remaining ion engines to compensate for the inoperative engine.

Other objects and advantages will become apparent upon consideration of the following description taken in conjuction with the accompanying drawings, wherein:

FIGURE 1 shows a satellite using ion engines for propulsion;

FIGURE 2 is a view of a prior art cluster of ion engines in side-by-side relationship;

FIGURE 3 is a sectional view of FIGURE 1 in the direction of arrows III—III showing a portion of the ion engine cluster, and

FIGURE 4 is a sectional view of FIGURE 3 taken in the direction of arrows IV—IV showing a cross section of an ion engine.

Referring to FIGURE 1, there is shown, generally, how the invention may be used on a spacecraft **2** using ion engines for propulsion. As is conventional, the spacecraft shown comprises generally a main portion **4** that may carry the various experiments and controls, and a propulsion portion **6** that propels the spacecraft. Ion beam **8** is shown issuing from the spacecraft. The force of propulsion exerted on the ion beam is shown by vector **10**. A cylindrical member **12** is also shown in FIGURE 1 and is a radiation shield used to reduce radiation from the ion engines to space, as will be explained below.

Before describing the invention, attention is directed to FIGURE 2 showing a spacecraft **14** using a prior art cluster **16**. A plurality of ion engines **18** are carried by spacecraft **14** in side-by-side relation. It will be seen that each ion engine **18** is individually exposed to space. It will also be noted that due to the side-by-side relationship, if one or more ion engines should fail to operate, this would change the direction in which the spacecraft would be propelled because the engines are located at different distances from the center of the satellite.

With the previous illustration in mind, the present invention will now be described. Referring to FIGURES 3 and 4, there is shown a sectional view of spacecraft propulsion section **6** showing the relationship and construction of the ion engines of the cluster of the invention.

Propulsion section **6** includes, essentially, a plurality of ion engines **20**, **22**, and **24**, that are arranged in a line. They are coaxial, face in the same direction, and are made annular to provide a passage **26** through them. The ion engines have a common longitudinal axis **28**. Although only three engines are shown, it will be apparent that the number used will depend on the thrust desired. For terms of reference, ion engine **20** will be referred to as an upstream ion engine, while ion engine **24** will be referred to as a downstream ion engine. In the above frame of reference, ion engine **22** will be upstream of ion engine **24**, and downstream of ion engine **20**.

While the general operation of an ion engine, per se, is well known and is not part of this invention, it will be briefly explained as an aid in describing the operation and advantages of the cluster.

Each ion engine generally contains a reservoir (not shown) that contains an ion expellant, such as cesium, for example. Generally carried within the reservoir is an ionizer heater (not shown), to heat the expellant to vaporize it. The expellant is then fed to porous ionizer **32** that ionizes the expellant and from which it issues as ion beam **8**. Most heat loss from the ion engine is from the ionizer surface **34**, which is heated by the ionizer heater (not shown). In the present invention (referring to left side of FIGURE 3), surface **34** of ionizer **32** is slightly inclined at an angle A to the normal of longitudinal axis **28** so as to tilt the ion stream issuing from it. A series of electrodes are used to focus and accelerate the ion beam issuing from ionizer **32**.

To focus the ions there is positioned in front of and on each side of ionizer **32** a focus electrode **36**. Focus electrode **36** is annular in shape. It is provided with a highly positive voltage relative to the ions. The positive voltage repels the ions to focus them into an extremely narrow concentrated beam. Focus electrode **36** is positioned relative to ionizer surface **34** and cooperates with it to bend ion beam **8** at a slight angle toward longitudinal axis **28** of the ion engines, so the ion beam will pass through passages **26** in a downstream ion engine.

To accelerate the ion stream there is positioned directly in front of the focus electrode an accelerator electrode **38**. Accelerator electrode **38** is provided with a highly negative voltage relative to the ions, and operates to accelerate them and give them their thrust. The ions do not impinge on the accelerator electrode because the focus electrode causes the ion beam to narrow so the ions will miss the accelerator electrode as they pass by it.

To bring the ion beam to the proper velocity, there is provided a decelerator electrode **40**. This electrode forms essentially the outer casing of the engine. It functions to bring the ion beam down to the proper velocity. It is maintained essentially at ground potential. Finally, to give the ion beam an overall neutral charge, there is provided a neutralizer electrode **42** that adds electrons back to the ions in the beam, so that ion beam **8** is electrically neutral.

In line with the teaching of this invention, all of the electrodes are made annular and concentric to provide axial passage **26** through each ion engine. Connected to each engine, and shown only diagrammatically in FIGURE 3, is a main trunk **44** having a branch **46** to each engine. These are the various electrical leads that are connected to the various electrodes and heaters carried by each ion engine. The specific leads and connections would depend on the type of ion engine and do not form part of the invention.

As mentioned previously, decelerator electrode **40** is maintained at substantially ground potential relative to the spacecraft, and this electrode forms the outer casing of the ion engine. It is important that the outer casing of the ion engine be neutral, so it will not affect the ion beam passing through it. The ion beam itself is also neutral when it passes through the engine downstream of it. The ion beam has passed neutralizer electrode **42** and electrons have been already added to the ion beam. It can be seen that if the ion beam of one engine were to impinge on the engine upstream of it, this would erode the engine and greatly shorten its life.

Finally, there is provided a plurality of radiation shields **12** surrounding ion engines **20**, **22**, **24**, to further decrease radiation to space to increase their efficiency. The ion engines are connected by supports **48** to radiation shields **12**, and these shields are connected by means (not shown) to main portion **4** of the spacecraft.

With the construction shown in FIGURE 3, wherein each ion engine is aligned one upstream of the other, the ionizer areas **34** radiating to space are not increased as the engines are clustered. The ionizer area is shielded by the engine downstream of it. That is, ion engine **20** is shielded by ion engine **22**, and this in turn is shielded by ion engine **24**. The result is that the normal engine efficiency, which is about 50% when ion engines are clustered side-by-side, is much increased. It has been calculated that with the construction taught by this invention, that for a cluster consisting of ten ion engines aligned one upstream of the other, the efficiency can be increased from 50% to 90%, a substantial increase.

As shown in FIGURE 3, the ion beam is bent through a small angle A so it will pass through passages **26** of a downstream engine. This angle is typically about 30°, although it is not critical. Since the angle to which the beam is bent is rather small, this can be easily accomplished by the focusing electrode structure **36** of the ion engine. There is no need for additional magnetic fields or electrostatic lenses or other complicated control constructions to bend the beam. With respect to angle A, this would depend on the spacing desired between the engines. That is, the steeper the angle the beam is bent the closer the engines can be positioned to each other.

However, if the angle is made too steep it would become more difficult to bend the beam.

It will be noted that with the ion engines in a line the force of propulsion of each engine, represented by vector **10**, is along longitudinal axis **28** of the group. If one or more ion engines should become inoperative, this would not change the direction of vector **10**. The force exerted by the remaining engines would still be along the longitudinal axis of the group. All that would change is the magnitude of vector **10**.

If, for example, one engine should become inoperative, it would only be necessary to increase the accelerating electrode voltages of the other remaining ion engines to compensate for the force lost by the inoperative engine. It is not necessary to compensate for a change in direction as would be required if the ion engines were in side-by-side relation. Thus this construction permits more accurate and easier control than prior art constructions.

In summary, there is provided a cluster of ion engines **20**, **22**, **24**, one upstream of the other. Each engine is positioned so the engine downstream of it shields it. This cuts down on heat radiated to space from the individual ionizer surface **34** of each engine. Each engine has an axial passage **26** that permits ion beam **8** from upstream engines to pass through downstream engines. In addition, there is provided a plurality of cylindrical radiation shields **12** encircling the ion engines to further cut down on heat radiated to space from the ion engines.

To bend the ion beams, each ionizer surface **34** is tilted at a small angle and cooperates with focus electrode **36** to direct the ion beam through passages **26** in a downstream engine. There are no complicated magnetic fields, or electrostatic lenses needed to bend the ion beam. With this construction, efficiency can be increased from 50%–90% for a 10 engine cluster.

In addition, with the ion engines coaxially positioned, the force of propulsion (vector **10**) of each ion engine is along the common longitudinal axis **28**. It is therefore easier to control the force of propulsion of the cluster to provide more accurate control of the spacecraft.

While the ion engines are shown as annular, they could just as easily be other shapes such as square, with an opening through their axis. Also, while the radiation shields and engines are shown extending out of the spacecraft, it is apparent that the engines can be carried within the spacecraft, with an opening provided for the exit of the ion beam. In that case, radiation shielding would not be needed. It will also be apparent that while only a single row of ion engines is shown, that under some circumstances it might be desirable to provide a plurality of rows of ion engines where even larger forces of propulsion are desired.

It will be understood that other various changes in the details, which have been described herein, and illustrated in order to explain the nature of the invention, may be made by those skilled in the art without departing from the true spirit and scope of the invention, and thus it is not intended to limit the invention except by the terms of the appended claims.

What is claimed is:

1. In a high efficiency cluster of ion engines for spacecraft, the combination comprising:
   - a plurality of ion engines, each of said ion engines, including an ionizer, and a focus electrode to focus the ions into a concentrated beam, and,
   - structure to position said ion engines, one upstream of the other, a downstream engine positioned to decrease radiation to space from an upstream ion engine, while being constructed to avoid the ion beam of an upstream engine;

2. In a high efficiency cluster of ion engines for a spacecraft, the combination comprising:
   - a plurality of ion engines, each of said ion engines including an ionizer and a focus electrode to focus the ions into a concentrated beam;
   - structure to position said ion engines, one upstream of the other, to decrease radiation to space from said ion engines; and,
   - each ion engine being constructed to direct its ion beam so it does not impinge on ion engines downstream of it.

3. In a high efficiency cluster of ion engines for a spacecraft, the combination comprising:
   - a plurality of ion engines, each of said ion engines including an ionizer, and a focus electrode to focus the ions into a concentrated beam, and each of said engines containing a passage;
   - structure to position said ion engines, one upstream of the other, to decrease radiation to space from said ion engines; and,
   - each ion engine being constructed to bend its ion beam so it will pass through the passages of the ion engines downstream of it.

4. In a high efficiency cluster of ion engines for a spacecraft, the combination comprising:
   - a plurality of ion engines, each of said ion engines including an ionizer, and a focus electrode to focus the ions into a concentrated beam, and each of said engines containing a passage in its center;
   - structure to position said ion engines coaxially, one upstream of the other; and,
   - each ion engine being constructed to direct its ion beam along the longitudinal axis common to all of the ion engines to facilitate control of the group of ion engines.

5. In a high efficiency cluster of ion engines for a spacecraft, the combination comprising:
   - a plurality of annual ion engines, each of said ion engines including an ionizer, and a focus electrode to focus the ions into a concentrated beam, each of said annular engines providing a passage in its center;
   - structure to position said ion engines, one upstream of the other, to retard radiation to space from said ion engines; and,
   - each ion engine being constructed to bend its ion beam so it will pass through the passages of the annular ion engines downstream of it.

6. In a high efficiency cluster of ion engines for a spacecraft, the combination comprising:
   - a plurality of annular ion engines, each of said ion engines including an ionizer, and a focus electrode to focus the ions into a concentrated beam, and each of said annular engines providing a passage in its center;
   - structure to position said ion engines coaxially, one upstream of the other, to retard radiation to space from said ion engine; and,
   - each ion engine being constructed with its ionizer tilted toward its longitudinal axis to aid in bending said ion beam so it will pass through the passages of the annular ion engines downstream of it.

7. In a high efficiency cluster of ion engines for a spacecraft, the combination comprising:
   - a plurality of annular ion engines, each of said ion engines including an ionizer, a focus electrode to focus the ions into a concentrated beam, and each of said annular engines providing a passage in its center;
   - structure to position said ion engines coaxially, one upstream of the other;
   - each of said ion engines constructed and positioned to shield the ionizer of the ion engine upstream of it to decrease said ionizer radiation to space; and,
   - each ion engine's focus electrode constructed to cooperate with said ionizer to bend said ion beam so it will pass through the passage of the annular ion engines downstream of it.

8. In a high efficiency cluster of ion engines for a spacecraft, the combination comprising:
   - a plurality of annular ion engines, each of said ion engines including an ionizer, and a focus electrode to focus the ions into a concentrated beam, and each of said annular engines providing a passage in its center;
   - structure to position said ion engines coaxially, one upstream of the other;
   - each of said ion engines constructed and positioned to shield the ionizer of the ion engine upstream of it to decrease said ionizer radiation to space;
   - each ion engine constructed with its ionizer tilted towards its longitudinal axis, and its focus electrode constructed to cooperate with said ionizer to bend said ion beam so it will pass through the passage of the ion engines downstream of it.

9. In a high efficiency cluster of ion engines, the combination comprising:
   - a plurality of annular ion engines, each of said ion engines including an ionizer, and a focus electrode to focus the ions into a concentrated beam, and each of said annular engines providing a passage in its center;
   - structure to position said ion engines coaxially, one upstream of the other;
   - each of said ion engines constructed and positioned to shield the ionizer of the ion engine upstream of it to decrease said ionizer radiation to space;
   - each ion engine constructed with its ionizer tilted toward its longitudinal axis, and its focus electrode constructed to cooperate with said ionizer to bend said ion beam so it will pass through the passage of the ion engines downstream of it; and
   - a plurality of radiation shields surrounding said ion engines to further decrease radiation to space from said engines.

10. An ion engine for a high efficiency cluster of ion engines comprising:
   - a plurality of annular ion engines, each of said ion engines including an ionizer, and a focus electrode to focus the ions into a concentrated beam, and each of said annular engines providing an axial passage in its center;
   - structure to position said ion engines coaxially, one upstream of the other;
   - each of said ion engines constructed and positioned to shield the ionizer of the engine upstream of it to decrease its radiation to space;
   - each ion engine constructed with its ionizer tilted at an angle of approximately 30° toward the engine's longitudinal axis, and said focus electrode constructed to cooperate with said tilted ionizer to bend said ion beam so it will pass through the coaxial passages of the ion engines downsteram of it; and
   - a plurality of radiation shields surrounding said ion engines to further decrease radiation space from said engines.

11. A method of clustering ion engines to form a high efficiency group, comprising the steps of:
   - providing a plurality of ion engines, each of said ion engines containing an ionizer, and a focus electrode to focus the ions into a concentrated beam;
   - positioning said ion engines, one upstream of the other, to decrease radiation to space from said ion engines and, directing said ion beam so that it does not impinge on a downstream ion engine.

12. A method of clustering ion engines to form a high efficiency group, comprising the steps of:
   - providing a plurality of ion engines, each of said ion engines including an ionizer, and a focus electrode to focus the ions into a concentrated beam, and each of said engines containing a passage;
   - positioning said ion engines, one upstream of the other, so the engine downstream of it shields the ionizer of the engine upstream of it to decrease its radiation to space; and
   - directing the ion beam of each engine through the passages of the ion engines downstream of it.

13. A method of clustering ion engines to form a high efficiency group, comprising the steps of:
   - providing a plurality of annular ion engines, each of said ion engines containing an ionizer, and a focus electrode to focus the ions into a concentrated beam, and each of said annular engines providing a passage in its center;
   - positioning said ion engines coaxially, one upstream of the other, so the engine downstream shields the ionizer of the engine upstream of it to decrease its radiation to space; and,
   - directing the ion beam of each engine so it will pass through the passages in the center of the ion engines downstream of it.

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