Nov. 25, 1969 F. E. JAMERSON ET AL 3,480,803

NUCLEAR THERMIONIC CONVERTER

Filed Oct. 20, 1965 2 Sheets-Sheet 1

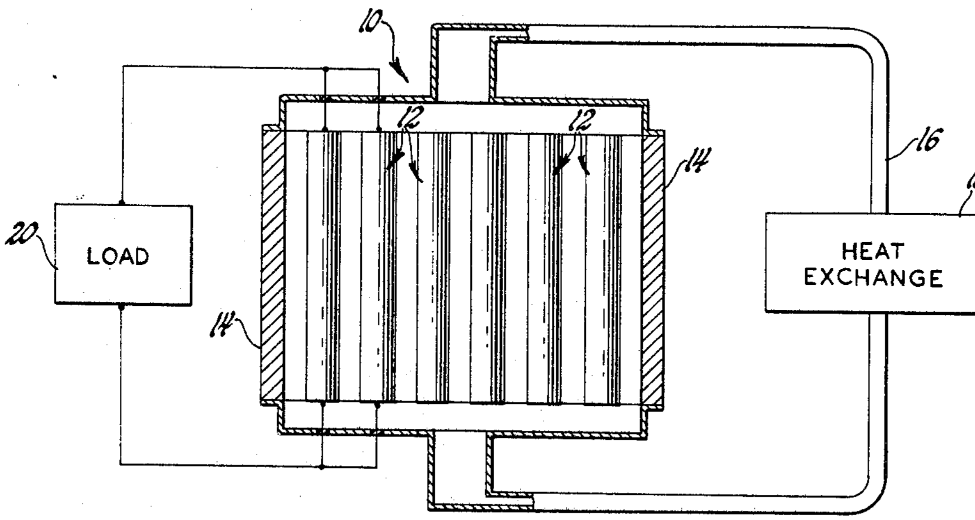

Fig.1

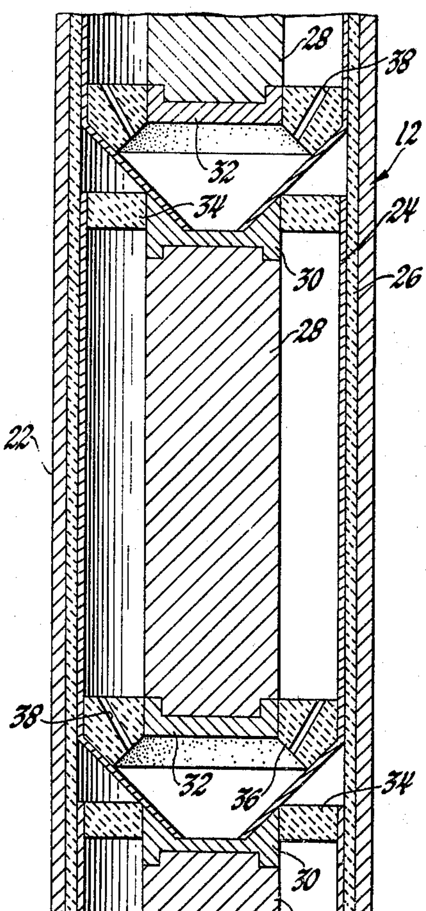

Fig.2

MAJOR GAS SPECIES / MINOR GAS SPECIES	He	Ne	Ar	Kr	Xe	Hg	Em (ev) META-STABLE LEVELS	Ei (ev) IONIZATION POTENTIAL
He							19.88 20.65	24.580
Ne							16.62 16.72	21.559
Ar	•	•					11.53 11.72	15.755
Kr	•	•					9.82 10.51	13.996
Xe	•	•					8.28 9.4	12.127
Rn	•	•	•					10.698
Hg	•	•	•	•			5.47 4.67	10.434
Ba	•	•	•	•	•		1.138 1.185	5.210
Li	•	•	•	•	•	•		5.390
Na	•	•	•	•	•	•		5.138
K	•	•	•	•	•	•		4.339
Rb	•	•	•	•	•	•		4.176
Cs	•	•	•	•	•	•		3.893

Fig.3

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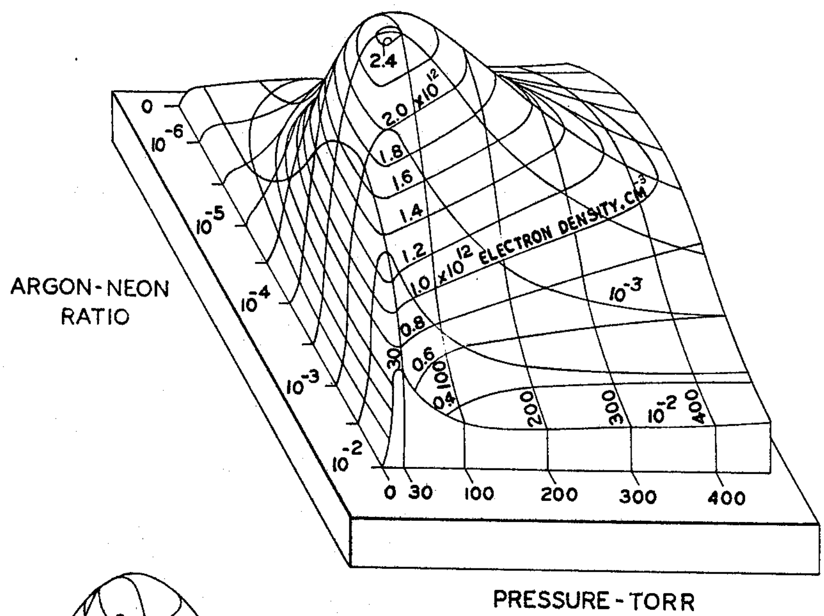

Fig. 4

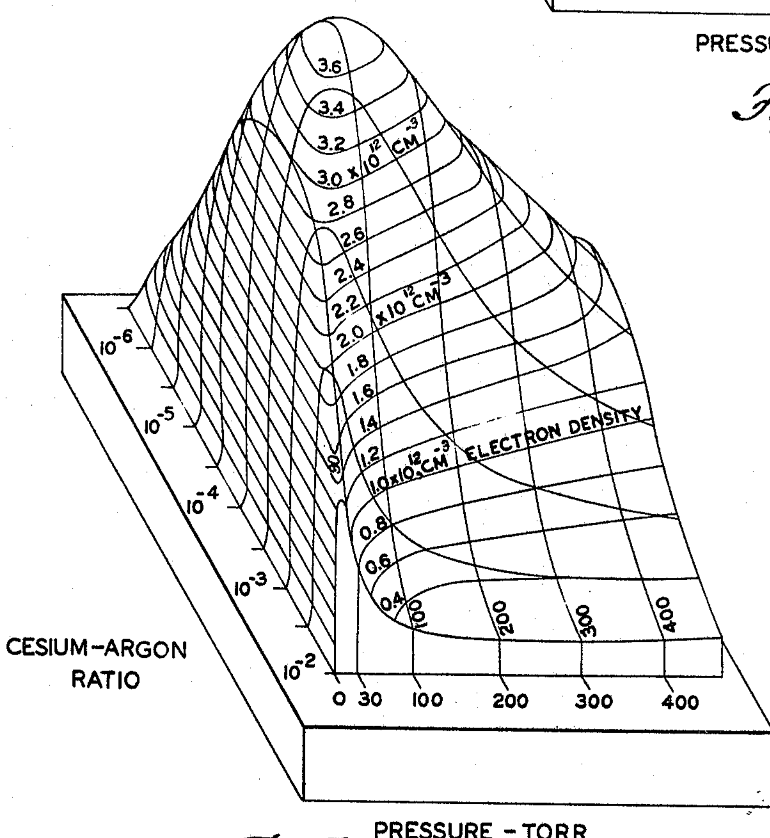

Fig. 5

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NUCLEAR THERMIONIC CONVERTER

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Int. Cl. H02n 3/00, 7/00
U.S. Cl. 310—4 8 Claims

ABSTRACT OF THE DISCLOSURE

A nuclear thermionic diode having a binary gas mixture in the interelectrode spacing. The mixture comprises a major species having a metastable state of higher energy than the ionization potential of the minor species and the pressure and ratio of gas quantities are chosen to produce a maximum electron density in the plasma produced by fission fragment bombardment.

This invention relates to nuclear thermionic energy converters and particularly to such a converter including an interelectrode gas mixture of selected composition and pressure for improving the efficiency of the conversion process through the generation of an interelectrode plasma.

It has been shown that nuclear heat can be converted directly to electricity by the use of a thermionic energy converter. One such converter is described in United States Patent No. 3,093,567 and employs a noble gas in the space between a hot cathode and a cooled anode. The noble gas is ionized by fission fragment bombardment, the fragments emanating from a fissile material. This fission fragment bombardment generates a plasma which compensates for the space charge between the cathode and anode.

According to the present invention, the efficiency of a nuclear thermionic energy converter employing an interelectrode plasma may be improved by selection of the parameters, particularly the composition and the pressure, of the gas from which the interelectrode plasma is generated by fission fragment bombardment. In general, this is accomplished through the selection of a binary gas composition consisting of a major gas species X and a minor gas species Y which are present in such a ratio and at such a pressure as to maximize the electron number density in the plasma upon bombardment thereof by fission fragments from a fissile material. In the binary gas composition the major gas species is chosen to exhibit at least one metastable state of higher energy level than the ionization potential of the minor gas species.

The invention is best described by reference to specific examples such as those described in the following specification. The specification is to be taken with the accompanying figures of which:

FIGURE 1 is a simplified schematic diagram in cross section of a nuclear reactor to which the present invention may be applied;

FIGURE 2 is a cross-sectional view of a converter cell as used in the reactor of FIGURE 1;

FIGURE 3 is a table of binary gas mixture constituents which may be employed in the converter cell of FIGURE 2;

FIGURE 4 is a three-axis plot of electron number density as a function of $X{:}Y$ and pressure for a mixture of argon and neon; and

FIGURE 5 is a three-axis plot of electron number density as a function of $X{:}Y$ and pressure for a mixture of cesium and argon.

In FIGURE 1 the nuclear reactor **10** is schematically shown to include a plurality of cylindrical converter elements **12** positioned inside a vessel having reflective side walls **14**. The converter elements **12** are spaced apart to permit circulation of a fluid coolant past the cylindrical surfaces thereof through a circulation path **16**. The path **16** includes a heat exchange station **18** which serves to dump the heat picked up by the fluid in passage through the reactor vessel. The converter elements are electrically connected in parallel across a load **20** which utilizes the electrical energy produced by the cells **12**. It is to be underseood that each of the fuel elements, as shown in detail in FIGURE 2, contains sufficient fissile material such that in the aggregate the total fissile material in the core zone exceeds criticality and hence can sustain a nuclear chain reaction. Suitable control rods may be inserted into the core zone of the reactor **10** to control the rate of nuclear reaction. A more detailed description of a reactor similar to that shown in FIGURE 1 is given in the aforementioned United States Patent No. 3,093,567.

Referring now to FIGURE 2, one of the converter cells **12** from the array of FIGURE 1 will be described in further detail. Cell **12** is a DC current generating nuclear thermionic fuel element comprising a plurality of series-arranged thermionic diodes. The diodes are arranged end-to-end inside of a cylindrical steel casing **22**. Each of the diodes includes a cylindrical collector **24** constructed of a conductive material and spaced from the steel casing **22** by a layer of ceramic insulation **26**. Concentric with the collector **24** and inwardly spaced therefrom is a cylindrical uranium bearing emitter **28** which rests in upper and lower metallic supports **30** and **32**, respectively. A suitable emitter is the uranium carbide-rhenium type described in copending application United States Serial No. 194,448 filed on May 14, 1962. Upper support **30** has a tapering upper recess adapted to receive the tapered lower end of the collector **24** of the diode immediately above. Upper suport **30** is maintained in concentric relation with but electrically insulated from the collector **24** by an annular ceramic insulator **34**. Lower support **32** is maintained in position by a ceramic insulator ring **36**. The spacing between the emitter **28** and the collector **24** is filled with a gas mixture which, as later described, is bombarded with fission fragments to produce an interelectrode plasma. The conical cavity between the tapered portion of the anode **24** and the lower support **32** may be used as a reservoir for one of the gases in the mixture and hence the ceramic insulator **36** may be formed to include one or more transport holes **38** communicating the reservoir with the interelectrode gas chamber. Coolant circulates past the outside of the entire assembly as indicated by the path **16** in FIGURE 1.

In operation, the nuclear fission which occurs within the core zone of the reactor **10** generates heat within the uranium bearing emitters **28**. Fission fragments emanating from the cylindrical emitters **28** travel through the interelectrode spacing which is filled with a gas mixture to be described. The fission fragments ionize the gas composition to generate a plasma between the hot emitter **28** and the relatively cool collector **24** to support a DC current.

Without ion generation in a thermionic diode such as that shown in FIGURE 2, the current flow between the emitter **28** and the surrounding collector **24** would be quickly limited by a resulting space charge about the emitter **28**. To neutralize this space charge effect, the present invention contemplates the production of a low impedance plasma between the electrodes **28** and **24** by the interaction of the fission fragments emanating from the uranium bearing emitter **28** with the gas mixture in the interelectrode space. Increasing the current carrying capacity of the plasma decreases the power losses in the converter and thus increases the efficiency thereof. The effectiveness of the plasma in supporting current flow is a function of the electron number density (n_e). Therefore, optimum conversion efficiency for constant values of electrode spacing and neutron flux is accomplished by maximizing the electron number density. This quantity, n_e, is a function of the ion generation rate from fission fragment ionization as well as the ion and electron loss rate from complex reactions which define the loss mechanism. It has further been found that the electron number density n_e may be made exceptionally high by the selection of certain binary gas mixtures of which the constituents are present in predetermined ratios and within predetermined pressure ranges thereby to produce a plasma which is most suitable for thermionic energy conversion, that is, the plasma has a maximum electrical conductivity.

The interelectrode gas mixture employed in the cell **12** of FIGURE 2 is, according to the present invention, a binary composition comprising a major species X and a minor species Y. As previously described, the major species X must have at least one metastable state of higher energy level than the ionization level of the minor species Y. The table of FIGURE 3 may be referred to in determining possible constituents for an $X+Y$ mixture which satisfies the above requirements. The left-hand column lists minor gas or Y constituents, the top row lists major gas or X constituents and the intersections marked with a dot indicate the combinations permitted by the above defined criteria relating to energy level (metastable) and ionization potential. The actual electron-volt figures for these parameters are also given in FIGURE 3.

It can readily be determined from the table of FIGURE 3 that examples of permissible $X+Y$ binary gas mixtures include mixtures of noble gases, noble gas with an alkali metal vapor, mercury with an alkali metal vapor and a noble gas with mercury.

Referring specifically to FIGURE 3, it can be seen that neon has a metastable energy level of 16.62 electron volts (ev.) and the ionization potential for argon is 15.755 ev. Therefore a binary gas mixture $X+Y$ which is permissible in accordance with the present invention is neon+argon. On the other hand, the ionization potential of krypton is approximately 14.0 ev. and higher than the highest metastable state of argon 11.72 ev., and thus the argon-krypton mixture does not meet the criteria for $X+Y$ established above.

As previously mentioned, high thermionic conversion efficiency promoted by optimum electron number density in the interelectrode plasma requires not only an $X+Y$ mixture comprising the proper constituents as defined above, but also that such constituents be present in predetermined ratios and at predetermined pressures. It has been found that the proper selection of parameters including (a) the ratio of $X:Y$ and (b) the pressures of X and Y produce a marked peak in the electron number density n_e of the fission-fragment-produced plasma. This peaking effect is strikingly demonstrated in FIGURES 4 and 5 which are three-dimensional graphs of electron number density n_e as a function of $X:Y$ and pressure for two exemplary binary gas mixtures. Specifically, FIGURE 4 shows the singular electron number density peak in a fission-fragment-generated plasma of X=neon and Y=argon. FIGURE 5 shows the same n_e peak for the mixture of X=argon and Y=cesium. Similar curves exist for the other permissible $X+Y$ mixtures defined in FIGURE 3 and thus it is to be understood that the invention, except as defined in the claims, is not limited to the mixtures specifically illustrated in FIGURES 4 and 5.

In each of FIGURES 4 and 5, total gas pressure in torr is plotted along the x-axis, the ratio $X:Y$ is plotted along the y-axis and electron number density is plotted along the z-axis. Operating temperature in each of FIGURES 4 and 5 is 1300° K. In the case of X=neon and Y=argon, the maximum enhanced plasma electron concentration is achieved at an operating gas temperature of 1300° K. with the neon (X) constituent present in the quantity of 3.0×10^{18} atoms per cubic centimeter, which is a total gas pressure of 94 torr at a gas filling temperature of 300° K. and the $X:Y$ ratio of 3.4×10^{-4}. In the case of X=argon, Y=cesium, the same parameters define the maximum n_e except the $X:Y$ ratio which is 1.7×10^{-4}.

For a thermionic converter the current carrying capability of the plasma is proportional to the random electron current (J_R) which is related to the electron number density by

$$J_R=n_e(\text{cm.}^{-3})/10^{12}, \text{ amps/cm.}^2$$

Current densities of value to thermionic energy conversion must be greater than 1 amp/cm.^{2} to yield an efficient device. Therefore from the foregoing equation we must have n_e greater than 10^{12} cm.$^{-3}$. The critical range of enhanced electron density is thus defined as that wherein

$$n_e\geq\tfrac{1}{2}n_e^\circ$$

where n_e° is the peak or maximum value from a curve such as that of FIGURE 4 or 5. This may be visualized by passing an imaginary plane through the curve parallel to the x–y plane at a height of $\tfrac{1}{2}n_e^\circ$. The curves of FIGURES 4 and 5 are tabulated as follows:

	Neon-Argon	Argon-Cesium
$n_e^\circ=n_e$(max), cm.$^{-3}$	2.4×10^{12}	3.8×10^{12}
Y at n_e°, cm.$^{-3}$	3.0×10^{18}	3.0×10^{18}
X/Y at n_e°	3.4×10^{-4}	1.7×10^{-4}
Definition of region of enhancement:		
$n_e\geq\tfrac{1}{2}n_e^\circ$, cm.$^{-3}$	1.2×10^{12}	1.9×10^{12}

X/Y	Range of $T\times10^{-18}$(cm.$^{-3}$) where $n_e\geq\tfrac{1}{2}n_e^\circ$	
1.00×10^{-5}	4.4–8.4	0.8–11.1
3.16×10^{-5}	1.6–11.8	0.4–13.0
1.00×10^{-4}	0.9–12.1	0.4–12.0
3.16×10^{-4}	0.7–9.4	0.4–8.4
1.00×10^{-3}	0.7–5.1	0.4–3.7
3.16×10^{-3}	0.7–1.6	0.4–1.0

A physical explanation of the enhanced electron number density and resulting thermionic conversion efficiency which is produced by the present invention is offered in the following. It is to be understood, however, that the utility of the invention is in no way predicated upon the accuracy or completeness of this explanation.

Considering the neon-argon system (FIGURE 4) as an example, the dominant ion in the neon-argo plasma over the area of interest is the atomic argon ion Ar^+. The value of the electron density n_e which is largely governed by the concentration of Ar^+ in the interelectrode spacing can thus be increased not only by increased ion production but also by reducing the loss rate of Ar^+. This loss rate is dependent upon the total gas pressure of the system and on the argon-neon ratio as has previously been indicated. Discussing the dependence of the loss rate on total pressure, one should consider the variation of electron number density with pressure for a constant value of the ratio Ar:Ne. At low pressure, i.e., less than 10 torr, the atomic argon ion rapidly diffuses out of the plasma and the value of the electron density n_e decreases with decreasing pressure. On the other hand, at high pressure, i.e., greater than 300 torr, the three-body conversion of Ar^+ to Ar^+_2 (which promptly loses its charge via recombination) becomes rapid so that the value of n_e decreases with increasing pressure. This decrease occurs despite the increased ion generation rate which accompanies increasing pressure. Between these two extremes of low and high pressure there exists a maximum in the value of n_e for a given value of Ar:Ne.

Considering now the dependence of n_e on the gas constituent ratio at a fixed value of total pressure, it can be seen that if the ratio is too small, i.e., much less than 10^{-4}, there is insufficient production of Ar^+ from neon metastable states because argon is present in too minor a concentration. If the ratio of Ar:Ne is greatly increased, i.e., much greater than 10^{-4}, Ar^+ is copiously produced, but this benefit is more than outweighed by the excessive loss rate of Ar^+ to Ar^+_2 in the three-body conversion process. This loss rate increases directly with the increasing concentration of argon, the minor gas constituent. Between these limits of insufficient production of Ar^+ at low values of Ar:Ne and excessive loss of Ar^+ at high values of Ar:Ne there exists an optimum ratio where the value of n_e is a maximum for a given value of total pressure.

While the present invention has been described largely with reference to the specific examples of

$$X+Y=\text{neon}+\text{argon}$$

or argon+cesium, it is to be understood that the invention contemplates a thermionic converter including any binary gas mixture which satisfies the criterion previously defined the constituents of which are present in such a ratio and at such a total gas pressure as to produce an electron number density of at least one half the maximum electron density available for such a mixture. For a definition of the invention reference should be had to the appended claims.

We claim:

1. A nuclear thermionic converter comprising an emitter having a portion of fissile material for emitting fission fragments, a collector physically separated from the emitter to define an interelectrode spacing, and a binary gas mixture in the interelectrode spacing, the mixture comprising a major gas species X and a minor gas species Y, X having a mestable energy state of higher energy level than the ionization potential of Y, the ratio of X to Y being in the range between 10^{-5} and 5×10^{-3} and the total gas pressure of X and Y being in the range between 50

and 200 torr so as to minimize the loss rate of the minor gas ions and produce in said spacing a plasma having an electron number density of substantially the maximum electron number density for said mixture when bombarded with fission fragments.

2. The combination defined in claim **1** wherein X and Y are noble gases.

3. The combination defined in claim **1** wherein X is a noble gas and Y is an alkali metal vapor.

4. The combination defined in claim **1** wherein X is mercury vapor and Y is an alkali metal vapor.

5. The combination defined in claim **1** wherein X is a noble gas and Y is mercury.

6. The combination defined in claim **1** wherein X is neon and Y is argon.

7. The combination defined in claim **1** wherein X is a noble gas and Y is cesium vapor.

8. The combination defined in claim **1** wherein X is argon and Y is cesium vapor.

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U.S. Cl. X.R.

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UNITED STATES PATENT OFFICE
CERTIFICATE OF CORRECTION

Patent No. 3,480,803 Dated November 25, 1969

Inventor(s) Frank E. Jamerson, Charles B. Leffert
David B. Rees

It is certified that error appears in the above-identified patent and that said Letters Patent are hereby corrected as shown below:

In the tabulation, Column 4, line 32, the title "Range of T X 10^{-18}" should read --Range of Y X 10^{-18}--.

SIGNED AND
SEALED
FEB 24 1970

(SEAL)
Attest:

Edward M. Fletcher, Jr.
Attesting Officer

WILLIAM E. SCHUYLER, JR.
Commissioner of Patents