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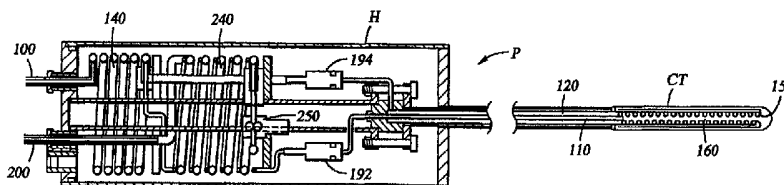
(57) Abstract

     A miniature mixed gas refrigeration system and method of operation are disclosed. An optimum gas mixture is formulated from a group of component fluids, according to calculated thermodynamic properties of a group of candidate fluid mixtures. The gas mixture is pressurized by a compressor to a pressure less than 420 psia, for safety reasons. The compressed gas mixture is passed through a primary heat exchanger, and then through a primary-to-secondary heat exchanger, to precool the gas mixture. The secondary side of the primary/secondary heat exchanger is cooled by a secondary Joule–Thomson refrigeration system. Properly sized flow restrictions in the primary side of the primary/secondary heat exchanger can solidify and trap liquid contaminants that may be in the gas mixture. The gas mixture exiting the primary outlet of the primary/secondary heat exchanger passes to a primary expansion element where the high pressure gas is expanded isenthalpically to a lower temperature at least as low as 183K. This low temperature gas cools a heat transfer element mounted in the outer wall of the cathether, to cool an external object. Return gas flows back through the primary heat exchanger to further precool the incoming high pressure gas mixture. A distal primary heat exchanger can be added between the primary/secondary heat exchanger and the primary expansion element.

TITLE OF THE INVENTION

Precooling System for Joule-Thomson Probe

BACKGROUND OF THE INVENTION

5   This invention is in the field of cooling miniature objects or very small portions of objects to very low temperatures. The objects to be cooled may include biological matter, electronic components, and others.

In many different fields of endeavor, it is desirable to be able to selectively cool a very small or even microscopic object to a very low temperature without
10   affecting the temperature of surrounding objects. This is true in the field of electronics, where it may be desirable to apply cooling to a miniature component on a circuit board without substantially cooling adjacent components. It is also true in the field of medicine, where it may be desirable to be able to cool miniature discrete portions of biological tissue to very low temperatures in the performance of
15   cryosurgery, without substantially cooling adjacent tissues of the organ. In the interest of simplicity, this specification will address the fulfillment of this need in the field of medicine, but it should be understood that application of the present invention in other fields, such as electronics, is also contemplated within the scope of the present invention.

20   Cryosurgery has become an important procedure in medical, dental, and veterinary fields. Particular success has been experienced in the specialties of gynecology and dermatology. Other specialties, such as neurosurgery and urology, could also benefit from the implementation of cryosurgical techniques, but this has only occurred in a limited way. Unfortunately, currently known cryosurgical
25   instruments have several limitations which make their use difficult or impossible in some such fields. Specifically, known systems are not optimally designed to have sufficient precision and flexibility to allow their widespread use endoscopically and percutaneously.

In the performance of cryosurgery, it is typical to use a cryosurgical
30   application system designed to suitably freeze the target tissue, thereby destroying diseased or degenerated cells in the tissue. The abnormal cells to be destroyed are often surrounded by healthy tissue which must be left uninjured. The particular probe

1

or other applicator used in a given application is therefore designed with the optimum
shape and size for the application, to achieve this selective freezing of tissue. Where a
probe is used, the remainder of the refrigeration system must be designed to provide
adequate cooling, which involves lowering the operative portion of the probe to a
5   desired temperature, and having sufficient power or capacity to maintain the desired
temperature for a given heat load. The entire system must be designed to place the
operative portion of the probe at the location of the tissue to be frozen, without having
any undesirable effect on other organs or systems.

Currently known cryosurgical systems typically use liquid nitrogen or nitrous
10   oxide as coolant fluids. Liquid nitrogen is usually either sprayed onto the tissue to be
destroyed, or it is circulated to cool a probe which is applied to the tissue. Liquid
nitrogen has an extremely low temperature of approximately 77K, and a high cooling
power, making it very desirable for this purpose. However, liquid nitrogen typically
evaporates and escapes to the atmosphere during use, requiring the continual
15   replacement of storage tanks. Further, since the liquid is so cold, the probes and other
equipment used for its application require vacuum jackets or other types of insulation.
This makes the probes relatively complex, bulky, and rigid, and therefore unsuitable
for endoscopic or intravascular use. The need for relatively bulky supply hoses and
the progressive cooling of all the related components make the liquid nitrogen
20   instruments less than comfortable for the physician, as well, and they can cause
undesired tissue damage.

A nitrous oxide system typically achieves cooling by pressurizing the gas and
then expanding it through a Joule-Thomson expansion element, such as a valve,
orifice, or other type of flow constriction, at the end of a probe tip. Any such device
25   will be referred to hereinafter simply as a Joule-Thomson "expansion element". The
typical nitrous oxide system pressurizes the gas to 700 to 800 psia., to reach practical
temperatures of no lower than about 190K to 210K. Nitrous oxide systems are not
able to approach the temperature and power achieved by the nitrogen systems. The
maximum temperature drop that can be achieved in a nitrous oxide system is to 184K,
30   which is the boiling point of nitrous oxide. The nitrous oxide system does have some
advantages, in that the inlet high pressure gas is essentially at room temperature until
it reaches the Joule-Thomson element at the probe tip. This eliminates the need for

2

insulation of the system, facilitating miniaturization and flexibility to some extent. However, because of the relatively warm temperatures and low power, tissue destruction and other applications are limited. For many such applications, temperatures below 184K are desirable. Further, the nitrous oxide must typically be

5   vented to atmosphere after passing through the system, since affordable compressors suitable for achieving the high pressures required are not reliable and readily commercially available.

In most Joule-Thomson systems, single non-ideal gasses are pressurized and then expanded through a throttling component or expansion element, to produce

10   isenthalpic cooling. The characteristics of the gas used, such as boiling point, inversion temperature, critical temperature, and critical pressure determine the starting pressure needed to reach a desired cooling temperature. Joule-Thomson systems typically use a heat exchanger to cool the incoming high pressure gas with the outgoing expanded gas, to achieve a higher drop in temperature upon expansion and

15   greater cooling power. For a given Joule-Thomson system, the desired cooling dictates the required heat exchanger capacity. Finned tube heat exchangers have been used, but these are necessarily bulky to achieve the required cooling, preventing their use in micro-miniature systems such as catheter delivered instruments. Smaller heat exchangers have also been known, constructed of photo-etched glass plates. These

20   heat exchange systems are still in the range of several centimeters square in size, making them still too bulky for true micro-miniature use, such as in endoscopes, catheters, and other systems. Further, these heat exchangers are planar and difficult to incorporate into tubular structures such as catheters or endoscopes. In many of these medical applications, the dimensions of the components must be less than

25   approximately 3 mm. in width to allow incorporation into a catheter or endoscope, and preferably less than 15 mm. in length to allow sufficient flexibility.

Heat exchanger requirements can be reduced somewhat by pre-cooling the gases prior to the probe tip heat exchanger. This can be done by incorporating a Peltier device in the flow path prior to the probe tip heat exchanger. Gas flowing

30   through a heat exchanger on the surface of the cold side of the Peltier device would be cooled prior to reaching the probe tip heat exchanger. Alternatively, the inlet high pressure stream could be split so that a portion of the stream could be diverted and

- 4 -

expanded to cool the remaining portion of the inlet stream prior to reaching the probe tip heat exchanger.

A dramatic improvement in cooling in Joule-Thomson systems can be realised by using a mixture of gasses rather than a single gas. For example, the addition of hydrocarbons
5 to nitrogen can increase the cooling power and temperature drop for a given inlet pressure. Further, it is possible to reduce the pressure and attain performance comparable to the single gas system at high pressure. Similar to single gas systems, these mixed gas systems have heat exchanger requirements and are limited in their miniaturisation potential by the size of the heat exchanger. The improvement in cooling performance realised by mixed gas systems is
10 very desirable for medical and other microminiature systems.

Some mixed gas systems have been designed where high pressure is not a major concern, and where bulky high efficiency heat exchangers can be used, but they are typically used in defence and aerospace applications. The glass plate heat exchangers mentioned above are used in some such systems, and these systems sometimes require pressures of 1200 psia.
15 In many applications, such as laser systems, superconductors, electronic and cryosurgery, pressures above approximately 420 psia are undesirable for safety reasons, and because the devices exhibit poor longevity, high cost, and poor reliability. Further, endoscopic or percutaneous use prevents implementation of any heat exchanger having a width greater than about 3mm or a length of more than about 15mm.
20 Specifically, it would be desirable to develop a long, slender, flexible cyroprobe, such as a transvascular cardiac catheter. Cardiac catheters must be very slender, in the range of less than 5mm, and they must exhibit considerable flexibility, in order to be inserted from an access point in a remote blood vessel into the heart. A cryosurgical catheter to be used in such an application must also have a relatively low operating pressure for safety reasons. It
25 must have the cooling power to overcome the ambient heat load imposed by the circulating blood, yet it must be able to achieve a sufficiently low temperature to destroy the target tissue. Finally, the cold heat transfer element must be limited to the tip or end region of the catheter, in order to prevent the damaging of tissue other than the target tissue.

The present invention seeks to provide a method and apparatus for precooling a
30 primary loop fluid mixture with a secondary loop Joule-Thomson

refrigeration cycle and then using the primary loop fluid mixture in a miniature mixed gas refrigeration system which is capable of achieving a cooling temperature of 183K or less, utilizing a high pressure of no greater than 420 psia., with components capable of fitting within a hand held cryoprobe. It is a further object of the present invention

5   to provide a method and apparatus for precooling a primary loop fluid mixture and then using the fluid mixture in a miniature refrigeration system to provide a sufficiently cool high pressure gas mixture for isenthalpic expansion through a Joule-Thomson expansion element, to achieve an expanded gas temperature of at least as low as 183K, to have sufficient cooling power to maintain this temperature when a

10 heat load is applied, and to perform with an inlet high pressure of no greater than 420 psia.

BRIEF SUMMARY OF THE INVENTION

The present invention comprises a method and apparatus for operating a

15 miniature refrigeration system, including a method for selecting an optimum fluid mixture for use as the primary cooling medium and then precooling the primary fluid mixture with a secondary closed loop Joule-Thomson refrigeration cycle to maximize the available cooling power of the fluid mixture.

The cooling power is an important design parameter of a cryosurgical

20 instrument. With greater cooling power, more rapid temperature decreases occur, and lower temperatures can be maintained at the probe tip during freezing. This ultimately leads to greater tissue destruction. The power of a mixed gas J-T cryosurgical device is a function of the enthalpy difference of the gas mixture and the mass flow rate. Pre-cooling certain gas mixtures will increase the enthalpy difference available for cooling

25 power. In addition, pre-cooling will increase the average mass flow rate by making the gas more dense.

Pre-cooling has two other important ramifications. First, it reduces the size of heat exchangers used in the probe. In the miniature environments envisioned for the used of this apparatus, severe size limitations will be placed upon the heat exchangers

30 used, especially the heat exchanger in the cold tip. For instance, a cardiac catheter necessarily is severely limited in diameter by the diameter of the blood vessels through which the catheter must pass. Further, maneuverability requirements dictate

that the catheter be somewhat flexible, and the cold tip heat exchanger will probably be somewhat stiff, if not rigid. Therefore, the allowable length of the cold tip heat exchanger is severely limited. Limitation of the size of the cold tip heat exchanger naturally limits the amount of heat which can be transferred in the heat exchanger.

5   This makes use of pre-cooling particularly beneficial. Second, mixed gas J-T cryosurgical devices require fixed size expansion elements, which can become partially or totally blocked by contaminants such as water or oil. This limits flow rate and decreases cooling power. Pre-cooling allows these contaminants to be cold-filtered and removed from circulation prior to reaching the expansion element.

10   The term "gas mixture" will be used to some extent in the present application, but it should be understood that this term is not intended to be limited to mixtures having no liquid components, in view of the well known fact that most compositions commonly referred to as gases actually have some liquid content at some temperatures and pressures. The primary closed loop refrigeration system has a primary loop

15   compressor for compressing a primary gas mixture to a pressure up to 420 psia. The method and apparatus of the present invention can be used equally well in a rigid hand held cryoprobe, or in a catheter.

        The high pressure primary gas mixture from the primary compressor is fed into a high pressure supply tube, such as an inner tube of a coaxial dual lumen tube leading

20   to the handle of a cryoprobe. The dual lumen tube in turn feeds the high pressure gas mixture into the inlet port at the proximal end of a miniature counterflow primary heat exchanger in the handle. The high pressure primary gas mixture passes through a high pressure supply passageway within the primary heat exchanger and exits through a port at the distal end of the primary heat exchanger. The high pressure passageway of

25   the primary heat exchanger is connected to the inlet of a primary high pressure passageway in a primary-to-secondary heat exchanger also located in the handle of the cryoprobe. The high pressure primary gas mixture passes through the high pressure passageway within the primary-to-secondary heat exchanger and exits through a port at the distal end of the primary-to-secondary heat exchanger.

30   The primary-to-secondary heat exchanger is part of the secondary closed loop Joule-Thomson refrigeration system which has a secondary compressor, and a secondary Joule-Thomson expansion element, in addition to the primary/secondary

6

heat exchanger. The secondary compressor compresses a secondary refrigerant, usually a single component fluid, to a pressure which can be relatively higher than that used in the primary loop. Since the secondary loop does not flow into the probe, a higher pressure can be used safely. Then, the high pressure secondary refrigerant

5   passes through a high pressure secondary passageway in the primary/secondary heat exchanger. The high pressure secondary refrigerant then passes through the secondary Joule-Thomson expansion element, in which the secondary refrigerant isenthalpically expands to a lower pressure and a lower temperature.

The low pressure secondary refrigerant then passes through a low pressure

10   secondary passageway in the primary/secondary heat exchanger and returns to the secondary compressor. The primary/secondary heat exchanger is constructed so as to interpose the secondary low pressure passageway between the primary high pressure passageway and the secondary high pressure passageway. This insures the transfer of heat from both of the high pressure passageways into the low pressure passageway.

15   The high pressure passageway of the primary-to-secondary heat exchanger can then be connected to the inlet of a high pressure passageway in a microminiature primary heat exchanger located in the probe, near the cold tip. The high pressure primary gas mixture passes through the high pressure passageway within the microminiature primary heat exchanger and exits through a port at the distal end of

20   the heat exchanger. The high pressure passageway is then connected to the inlet of the primary Joule-Thomson expansion element located in the cold tip, in which the gas mixture is isenthalpically expanded to a lower pressure and a temperature at least as low as 183K. The expansion element can have a second stage in which the gas mixture is further expanded isothermally to absorb additional heat from the

25   surroundings. If the first primary heat exchanger and the primary/secondary heat exchanger have sufficient capacity, it may not be necessary to incorporate the microminiature primary heat exchanger into the system, and the high pressure primary gas mixture can pass directly from the high pressure passageway of the primary/secondary heat exchanger to the primary Joule-Thomson expansion element.

30   The primary gas mixture exiting the primary Joule-Thomson expansion element is exposed to the inner surface of a heat transfer element mounted in the wall of an outer tube which is coaxial with the inner tube. The expanded primary gas

mixture cools the heat transfer element to a temperature of at least as low as 183K and then returns through the low pressure return passageway of the microminiature primary heat exchanger in the cold tip, and through the low pressure return passageway of the miniature primary heat exchanger in the probe handle. This cools

5   the primary high pressure gas from its original ambient temperature to a lower temperature. From the low pressure outlet of the miniature primary heat exchanger in the probe handle, the low pressure expanded primary gas mixture flows into the lumen of the outer coaxial tube, outside the inner high pressure tube, to return to the primary compressor.

10   Both the miniature primary heat exchanger and the primary/secondary heat exchanger are coiled tube heat exchangers. The miniature primary heat exchanger in the probe handle can be a coiled coaxial tube, with the inner lumen being the high pressure passageway and the outer lumen being the low pressure passageway. The secondary passageways of the primary/secondary heat exchanger can be a coiled

15   coaxial tube, with the inner lumen being the high pressure secondary passageway and the outer lumen being the low pressure secondary passageway. Attached to the side of this outer tube, in a parallel arrangement, is a tube which forms the high pressure primary passageway. The high pressure primary tube can have a plurality of inner tubes, which can be nested and placed in contact with the outer tube for improved heat

20   exchange. High pressure primary gas mixture flows in all of the nested tubes and in the interstitial spaces between the nested tubes and the outer tube. The secondary coaxial tube and the primary tube can be formed of metal and soldered together.

The microminiature heat exchanger in the cold tip can be a single coiled tube surrounded by a low pressure return passageway. Alternatively, it can have a

25   laminated construction of several different types. In one example of the laminated type, the microminiature heat exchanger is constructed of a plurality of plates and spacers stacked alternatingly along the axial dimension of the heat exchanger. The plates have a first plurality of holes establishing the high pressure passageway of the heat exchanger, and a second plurality of holes establishing the low pressure

30   passageway of the heat exchanger. The high pressure holes are segregated from the low pressure holes. Spacers with larger openings are stacked between the plates to

8

promote turbulent flow and insure effective heat exchange. The plates and spacers can be fastened together by a process such as diffusion bonding.

The primary and secondary Joule-Thomson expansion elements can be a sintered metal plug made by sintering a plurality of metal beads into a metal cup, to

5   provide the required pressure drop. Alternatively, the expansion element can be a properly sized orifice or some other type of restriction. The two different stages of the sintered plug expansion element, if present, can utilize different sizes of beads, different cross sectional areas, and different packing densities. The heat transfer element can take the optimum shape for matching the object or tissue to be cooled.

10   For example, a metal plug can be installed in the tip of the outer tube or catheter, for applying cooling through the extreme distal tip of the catheter. Alternatively, a relatively narrow metal strip can be mounted in a side wall of the catheter, near the distal tip, for applying cooling to a narrow strip of tissue.

The severe limitation on the size and capacity of the cold tip heat exchanger

15   dictates that the system be optimized by selection of a gas mixture which will have the appropriate thermodynamic properties to perform as well as possible. The goal of this selection process is to maximize the cooling power of the combination of the pre-cooling heat exchangers, the cold tip heat exchanger, and the primary Joule-Thomson expansion element. For a given gas mixture operating between selected high and low

20   pressures and between selected high and low temperatures, there is a limit to the amount of heat which can be transferred, even in a perfect heat exchanger. The best use of the apparatus of the present invention requires a method for selecting, from among a group of gas mixture candidates, a mixture which will maximize the performance ratio between the cooling power of the Joule-Thomson expansion

25   element and the heat transfer capacity of a perfect heat exchanger.

The method involves first compiling a list of component fluids, which will be combined in various mixtures to arrive at an optimum mixture. It is necessary for each fluid mixture to have a triple point below the lowest temperature to be encountered, to ensure that the fluid mixture can not possibly freeze in the apparatus.

30   Various methods could be employed to insure that each fluid mixture possesses this quality. One method is to insure that each of the component fluids has a triple point below the lowest temperature to be encountered. This would ensure that any mixture

of those fluids would meet this criterion. It is common, however, for a fluid mixture
to have a triple point below the triple points of several of its components. Therefore,
it would be feasible to use several component fluids having triple points above the
lowest temperature to be encountered, as long as the triple point of each fluid mixture
5   is computed to be below the lowest temperature to be encountered.

It is also necessary for the fluid mixture to possess a positive Joule-Thomson
coefficient, to ensure that a drop in pressure is accompanied by a drop in temperature.
As with the triple point criterion, this can be accomplished by ensuring that each
component fluid has a positive Joule-Thomson coefficient. However, it is also
10   possible for a fluid mixture to have a positive Joule-Thomson coefficient, even though
several of its component fluids have negative coefficients. Therefore, it would be
feasible to use several component fluids having negative coefficients, as long as the
coefficient of each fluid mixture is computed to be a positive value.

For each of the component fluids in this list, the molar enthalpy is known at a
15   plurality of data points over a selected range of temperatures and a selected range of
pressures, with these ranges including the temperatures and pressures at which the
fluid mixture will be pumped through the apparatus. Then, various mixtures of the
fluids are selected, with each mixture having up to a selected maximum number of
component fluids. Based upon the known thermodynamic properties of the
20   component fluids, the molar enthalpy of each fluid mixture is then calculated at a
plurality of data points over the selected range of temperatures and the selected range
of pressures.

For each fluid mixture, a series of calculations are then performed. It can be
assumed that the pressure drop through the heat exchanger, on either the high pressure
25   side or the low pressure side, is negligible. Alternatively, a starting pressure can be
chosen which takes into account the anticipated pressure drop in the heat exchanger.
For the low pressure in the selected pressure range, the molar enthalpy of the fluid
mixture at the low temperature in the selected temperature range is subtracted from
the molar enthalpy at the high temperature in the range, yielding a low pressure
30   enthalpy difference between the fluid mixture states at the two temperatures.
Similarly, for the high pressure in the selected pressure range, the molar enthalpy at
the low temperature is subtracted from the molar enthalpy at the high temperature,

yielding a high pressure enthalpy difference between the fluid mixture states at the two temperatures. The lesser of these two enthalpy differences is the maximum molar enthalpy difference which could be achieved in a perfect counterflow heat exchanger operating with the selected fluid mixture over the selected temperature range and
5   pressure range. The maximum possible heat transfer capacity of such a heat exchanger with the selected fluid mixture is the product of the molar flow rate of the fluid mixture and this molar enthalpy difference.

Then, for each selected fluid mixture, at a plurality of selected temperatures over the selected temperature range, the molar enthalpy of the fluid mixture at the
10   high pressure in the selected pressure range is subtracted from the molar enthalpy at the low pressure in the range, yielding a molar enthalpy difference between the fluid mixture states at the two pressures, for each of the plurality of temperatures. The plurality of temperatures at which this calculation is performed are selected at uniform intervals over the selected temperature range. As an example, if the selected
15   temperature range is from 120K to 270K, the intervals between the selected plurality of temperatures might be set at five degree increments, for a total of 30 intervals, and 31 selected temperatures. This calculation is then performed at each of the 31 temperatures. The higher the number of selected temperatures used, the greater will be the usefulness of the information calculated. The molar enthalpy difference
20   calculated at each of these selected temperatures is the enthalpy increase which would occur during
expansion of the selected fluid mixture from the high pressure to the low pressure, if the temperature were to remain constant.

In Joule-Thomson expansion, there is very little or no opportunity for heat
25   transfer to or from the fluid as it flows through the expansion element, no change in potential energy of the fluid, no work performed, and very little or no change in kinetic energy of the fluid. Therefore, the enthalpy states of the fluid before and after the expansion are essentially the same. As the pressure sharply decreases, the temperature of the fluid also sharply decreases, maintaining an essentially constant
30   enthalpy. This colder fluid then can be used to cool the surroundings. The maximum possible cooling power available through Joule-Thomson expansion over the selected pressure range, with the selected fluid mixture, is the product of the molar flow rate of

the fluid mixture and the lowest molar enthalpy difference calculated at any temperature over the selected temperature range.

Therefore, each fluid mixture in the group exhibits a maximum possible cooling power and a maximum possible heat transfer capacity. In order to optimize

5 the operation of the apparatus of the present invention, a fluid mixture is chosen from among the candidates described above, which will result in the highest performance ratio between the available cooling power and the available heat transfer across a heat exchanger. That is the optimum fluid mixture within the temperature and pressure ranges selected. It can be seen that, if the performance ratio is equal to or greater than

10 unity, meaning that the available cooling power is as great as the available heat transfer, then the maximum cooling possible over the desired temperature and pressure range can be achieved through Joule-Thomson expansion alone, and no heat exchangers are needed. If the highest performance ratio is less than unity, at least one heat exchanger will be required.

15

The novel features of this invention, as well as the invention itself, will be best understood from the attached drawings, taken along with the following description, in which similar reference characters refer to similar parts, and in which:

20   BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a graph of enthalpy vs. temperature for a typical gas mixture used with the present invention;

Figure 2 is a perspective view of one embodiment of the primary portion of the miniature refrigeration system;

25 Figure 3 is a partial section view of the distal end portion of the cryosurgical probe portion of the refrigeration system shown in Figure 2;

Figure 4 is an elevation view of a preferred embodiment of one configuration of heat exchanger plate used in the micro-miniature heat exchanger utilized in the cryosurgical probe shown in Figure 3;

30 Figure 5 is an elevation view of a second configuration of heat exchanger plate, showing a different angular orientation of holes from the orientation shown in Figure 4;

12

Figure 6 is an elevation view of a preferred embodiment of a spacer used in the micro-miniature heat exchanger used in the probe shown in Figure 3;

Figure 7 is an elevation view of a second embodiment of a spacer used in a second embodiment of the micro-miniature heat exchanger;

5   Figure 8 is an elevation view of a first configuration of plate used in the second embodiment of the micro-miniature heat exchanger;

Figure 9 is an elevation view of a second configuration of plate used in the second embodiment of the micro-miniature heat exchanger, showing the different orientation of high pressure and low pressure ports;

10   Figure 10 is a series of elevation views of plates and spacers used in the second embodiment of the micro-miniature heat exchanger, showing the flow of supply and return gas mixtures;

Figure 11 is a sectional view of the plurality of plates and spacers shown in Figure 10, showing the flow of supply and return gas mixtures;

15   Figure 12 is a perspective view of a third embodiment of the micro-miniature heat exchanger, prior to final shaping;

Figure 13 is a perspective view of the heat exchanger shown in Figure 12, after final shaping;

Figure 14 is a partial section view of a second embodiment of the distal end

20   portion of a cryosurgical probe, showing a narrow elongated heat transfer element;

Figure 15 is a section view of the second embodiment, taken along the line 15-15 in Figure 14;

Figures 16 through 32 show enthalpy tables and graphs for seventeen fluid mixtures, for exemplary purposes;

25   Figure 33 is a schematic of the primary and secondary closed loops of the present invention;

Figure 34 is a section view of the portion of the primary closed loop and the secondary closed loop of the present invention, as they could be arranged in the handle of a cryoprobe;

30   Figure 35 is a section view of a hand held cryoprobe according to the present invention;

Figure 36 is a transverse section view of the coaxial dual lumen tube used in the miniature primary heat exchanger located in the handle of the cryoprobe; and

Figure 37 is a transverse section view of the coiled multiple lumen tubes used in the primary/secondary heat exchanger.

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DETAILED DESCRIPTION OF THE INVENTION

The present invention lies in the appropriate use of a secondary closed loop Joule-Thomson refrigeration system to precool the primary high pressure gas mixture, before passage of the primary gas mixture through the primary Joule-Thomson
10   expansion element. This is intended to maximize the available cooling power at the tip of the cryosurgical probe.

Pre-cooling the primary fluid mixture prior to feeding it to the micro-miniature heat exchanger in the cold tip is the focus of the present invention. This pre-cooling could be done prior to introducing the primary fluid mixture into the catheter, by the
15   use of a conventional, relatively large, heat exchanger. However, for ease of handling and for maximum efficiency, the present invention focuses on the provision of pre-cooling near the treatment area, such as in the handle of a cryoprobe. This is because minimizing the length of the flow path of precooled fluid maximizes the efficiency of the pre-cooling system.

20   An important parameter in the design of a cryosurgical device is the cooling power which the refrigeration system can develop. The cooling power determines the rate of cooling in degrees per second, and the temperature which can be maintained at the probe tip during freezing of the tissue. The rate of freezing is important in achieving cell death, since more rapid freezing results in better formation of
25   intracellular ice crystals, resulting in cell lysis. The rate of freezing also determines the length of time required to perform a given procedure on the patient. The quicker the procedure, the less traumatic the procedure is to the patient.

The temperature which can be maintained at the probe cold tip determines the size of the ice ball formed in the surrounding tissue. This, of course, determines the
30   total volume of tissue destroyed at each location, and the speed with which the procedure can be completed. For example, if a first cryoprobe, using a given gas mixture, has 30 watts of cooling power, assume that it can maintain a cold tip

temperature of minus 100 degrees C, creating an ice ball of up to 4.5 cm diameter in 15 minutes, in a test gel. Because of the rapid temperature drop, a significant percentage of cell death would occur within a similar size ball of living tissue. By contrast, consider a second cryoprobe, using the same gas mixture, which has only 10

5　watts of cooling power. The second cryoprobe could only maintain a temperature of minus 50 degrees C, creating an ice ball only 2.5 cm diameter within 15 minutes. Therefore, the aforementioned high percentage of cell death would only occur in a 2.5 cm diameter ball of living tissue, rather than a 4.5 cm diameter ball. Furthermore, if the required size of the ice ball is only 2.5 cm, the first cryoprobe could achieve such

10　an ice ball within 5 minutes, rather than 15 minutes. So, by either standard, the first cryoprobe will achieve a better result, and more quickly, than the lower power second cryoprobe.

　　　　　In Joule-Thomson cryosurgical devices, high pressure fluid expands across a restriction of some kind, such as a small orifice, or a crimped tube. The sudden drop

15　in pressure results in a corresponding drop in temperature. The cooling power of the device is the product of the mass flow rate of the cryogen and the enthalpy difference at the different pressures and temperatures. The flow rate is a function of orifice size and the temperature and pressure of the cryogen. For a given orifice size, under non-choking conditions, the density of the cryogen is higher at higher pressures and lower

20　temperatures, resulting in a higher mass flow rate. The maximum flow rate is found at the point where the cryogen is a liquid. The enthalpy difference is also a function of the pressure and temperature, with the enthalpy difference between two conditions being higher at higher pressures and lower temperatures. For a given temperature and a given pressure, the maximum enthalpy difference between two conditions occurs at

25　the liquefaction point of the cryogen. One or more pre-cooling heat exchangers can be incorporated into the refrigeration system near the expansion element, to promote cooling or liquefaction of the warm, high pressure cryogen, thereby increasing the power of the system.

　　　　　Nitrous oxide is the most commonly used cryogen in Joule-Thomson

30　cryosurgical systems. If the high pressure of the system is above 4.5 MPa, nitrous oxide will liquefy upon expansion, without the help of a heat exchanger, and achieve the maximum cooling power. However, nitrous oxide must be operated at this high

pressure, and the lowest temperatures available are between minus 50 and minus 70 degrees C, which is relatively warm for some cryosurgical applications. Therefore, the safety and the efficiency of a nitrous oxide system are less than desirable for some applications, such as catheter ablation of heart tissue, and ablation of endometrial

5   tissue.

The fluid mixtures or cryogens discussed in this application operate at lower pressures, and they can achieve lower temperatures, making them both safer and more effective. For example, the mixture of 66% Krypton, 14% R142b, 10% R22, and 10% R23 can reach a temperature of minus 120 degrees C, from a pressure of 2.1 MPa. At

10   a flow rate of 0.6 grams per second, approximately 30 watts of cooling power is achieved. However, this mixture will not liquefy, and reach its maximum cooling power, without the aid of a heat exchanger.

This creates a problem, if this type of mixture is to be used. Since the mixture is in the warm, gaseous state upon startup of the refrigeration system, the early flow

15   rate is very low, and the power is very low. If the heat exchanger used is not very efficient, the initial cool down is very slow at overcoming the low flow rate. Further, the cold tip is typically placed within the patient, and in contact with the target tissue, before commencement of cooldown, placing a significant heat load on the tip. This means that cooldown can be unacceptably slow, and in some cases, it may not occur at

20   all.

Another problem that may occur is the clogging of the expansion element by contaminants. If present, water and oil will liquefy and freeze as the temperature of the cryogen drops. Because of the small size of the orifice or other expansion element, it can be plugged easily. In larger cryosystems, an adjustable orifice can be

25   used, to offset this clogging. However, in the small medical systems, adjustable orifices are too large and unwieldy to be used.

In some mixed gas Joule-Thomson systems, a small degree of pre-cooling can sometimes produce significant increases in cooling power. The selection of a fluid mixture and the use of a pre-cooler must therefore be coordinated.

30   In order to maximize the performance of mixed gas cryosurgical systems, and to eliminate the problems normally associated with slow cooldown rates and low cooling power, an independent closed loop Joule-Thomson secondary refrigeration

system is incorporated into the present invention. The secondary system uses a single refrigerant such as R13b1 to pre-cool the primary gas mixture in the handle of the cryoprobe, prior to flow of the primary gas mixture to the cold tip. The secondary system accomplishes this pre-cooling through a primary/secondary heat exchanger

5   placed as close as possible to the cold tip, to prevent excessive warming of the cooled primary gas mixture before it reaches the cold tip.

This pre-cooling causes the initial flow rate and the cooling power of the system to be higher, making the initial cooldown rate much faster. Selection of the optimal fluid mixture makes the pre-cooling more effective, maximizing the cooling

10 power. With some mixtures, and with pre-cooling, there may be no need for a heat exchanger at the cold tip next to the primary expansion element. A further advantage is that the pre-cooler may act as a cold filter, to eliminate contaminants such as oil and water, which may otherwise clog the expansion element as the system cools down. For this purpose, the a filter can be constructed with openings smaller than the

15 expansion element, but with the total opening area much larger, to avoid creating a significant pressure drop.

The optimization of the present invention also requires the selection of an optimum fluid mixture, since no known single gasses are capable of achieving the necessary cooling power at the required temperatures, given the size limitations and

20 pressure limitations imposed on systems intended for use in the selected applications. Several gas mixtures have been identified for use with the present invention, and it is anticipated that others will be identified as well. Appropriate gas mixtures may take various forms, and they may be either hydrocarbon-based or non-hydrocarbon-based. Some fluid mixtures function significantly better than other mixtures, so it is

25 important to be able to identify and select an optimum mixture from among a group of available mixtures. One mixture currently identified as useful for many applications is 30 percent Methane, 23 percent Nitrogen, 23 percent Isobutane, 19 percent Ethane, and 5 percent Propane. The temperature capability of isenthalpic expansion of such a gas mixture is illustrated by Figure 1, which shows enthalpy curves for this gas

30 mixture at pressures of 1 bar (14.5 psia.), 21 bar (305 psia.), and 41 bar (595 psia.). Isenthalpic expansion from one of the higher pressures to the lower pressure proceeds horizontally to the left across the graph, accompanied by a drop in temperature. The

lowest temperature attainable would be at the point where the curves cross, somewhere below 100K. The lower the temperature of the high pressure gas mixture, the lower the temperature which can be achieved by the isenthalpic expansion through the Joule-Thomson expansion element. It can also be seen from the graph that there is

5   little difference between the temperatures attainable by expanding from 41 bar and expanding from 21 bar. For example, assume that the heat exchanger used is capable of cooling the high pressure gas mixture to a temperature of 210 K, just upstream of the expansion element. If a high pressure of 21 bar is used, the isenthalpic expansion will result in a temperature of 180K. If the gas mixture is instead pressurized to 41

10   bar, the attainable temperature after isenthalpic expansion is still only about 173K. Further, the cooling power, or power, represented by the difference between the high pressure curve and the 1 bar curve at a given temperature is similar, whether the high pressure is 21 bar or 41 bar. Therefore, the added safety achieved by lowering the initial pressure to 21 bar, or approximately 300 psia, results in only a minor loss of

15   performance. Obviously, for a given gas mixture, the more efficient the heat exchange system, the lower the probe temperature that can ultimately be obtained, and the greater will be the cooling power.

Figure 2 shows the primary loop portion of a refrigeration system 10 according to the present invention, for a cryosurgical application. The primary portion of the

20   system 10 consists of a commercially available single stage compressor 12, a flexible dual lumen hose 14 connected to the inlet and outlet of the compressor 12, a steering handle 16, and a cryosurgical probe 18. The compressor 12 can be any of several compressors available, often using an aftercooler, an oil separator, and an adsorption filter. Alternatively, an oil free compressor could also be utilized. The hose 14 can be

25   any flexible dual lumen hose suitable for the pressures and chemical exposures involved, for the gas mixture used. The handle 16 can have a control expansion element installed, for the physician to use in throttling the flow rate of the gas mixture. Alternatively, the flow could be controlled via a foot switch that regulates flow at the compressor. The probe 18 is a coaxial catheter having an inner tube for conducting

30   the high pressure gas mixture from the outlet of the compressor 12 and for returning the expanded low pressure gas to the inlet of the compressor 12. The probe 18 has a distal end portion or region 20 in which the heat exchanger, expansion element, and

heat transfer element are located. The probe 18 is of suitable diameter, length, and flexibility to be inserted to the object to be cooled, such as through the vascular system of a patient into the heart.

Figure 3 shows a partial section view of the distal end portion 20 of the coaxial
5   catheter 18. The catheter 18 consists of an outer tube 22 and an inner tube 24. The outer tube 22 can be continuous to the end of the catheter 18, or it can have an extension 23, which should be considered for all practical purposes an integral part of the outer tube 22. The outer tube 22 is made according to known methods from a wire-braided polymer, such as a polyamide-ether copolymer. The inner tube 24 is
10 made from a wire-braided polyimide having a pressure capability sufficient for the maximum high pressure anticipated for the particular application. The inner tube 24 is connected by means of an inlet fitting 26 to the proximal end of a micro-miniature heat exchanger 28. Mounted to the distal end of the heat exchanger 28 is a primary Joule-Thomson expansion element 30. The distal end of the primary expansion
15 element 30 is exposed to a cavity 31 at the distal end of the outer tube 22 or extension 23, closed by a heat transfer element 32. The expanded gas mixture cools the inner surface 66 of the heat transfer element 32, thereby cooling the outer surface 68. The outer surface 68 is placed against the object to be cooled by the physician.

More specifically, the distal end of the inner high pressure tube 24 is
20 connected by means of the inlet fitting 26 to the high pressure inlet port 34 at the proximal end of the heat exchanger 28. This high pressure inlet port 34 leads to a high pressure supply passageway 36 through the heat exchanger, shown as the central axial portion of the heat exchanger 28 in this embodiment. The heat exchanger 28 also has a low pressure inlet port 38 at its distal end exposed to the cavity 31. This
25 low pressure inlet port 38 leads to a low pressure return passageway 40, shown as the outer annular portion of the heat exchanger, surrounding the high pressure passageway 36. The low pressure, low temperature gas mixture flowing through the low pressure passageway pre-cools the high pressure, higher temperature gas mixture flowing through the high pressure passageway. The heat exchanger 28 is constructed of
30 alternately stacked copper plates 42 and stainless steel spacers 44, diffusion bonded together. Other methods of attachment could be used. The heat exchanger 28 is shown, for the sake of simplicity in this figure, as having an outer skin over the plates

42 and spacers 44, but in actuality, the skin is optimally provided by an outer ring 45
on each spacer 44 being bonded to the extreme outer annular portion of each plate 42,
as will be made more clear below. The central portion of each plate 42 has a plurality
of holes 46 therethrough, which along with central openings in the spacers 44

5   establish the high pressure passageway 36 longitudinally through the heat exchanger
28 in the distal direction. Similarly, the outer portion of each plate 42 has a plurality
of holes 48 therethrough, which along with outer openings in the spacers 44 establish
the low pressure passageway 40 longitudinally through the heat exchanger 28 in the
proximal direction. The high pressure passageway 36 is separated from the low

10   pressure passageway 40 by an inner ring 47 on each spacer 44.

High pressure gas mixture passing through the heat exchanger 28 exits the
high pressure passageway at a high pressure outlet port 50 at the central distal portion
of the heat exchanger to enter the inlet 52 of the primary Joule-Thomson isenthalpic
expansion element 30. This primary expansion element 30 has a first stage 54 of a

15   first diameter, in which isenthalpic expansion to a second larger diameter takes place,
lowering the temperature of the gas mixture to the design temperature. The gas
mixture then passes through the second stage 56 in which isothermal expansion takes
place, leaving the gas mixture still at the desired temperature, but absorbing heat from
the surrounding structure in the process. The first stage 54 is constructed by filling a

20   metal cylinder 58 with a selected size of metal beads, at a selected packing density, to
achieve the desired rate of expansion of the gas. The beads are sintered in place in the
cylinder 58. Similarly, the second stage 56 is constructed by filling a second metal
cylinder 60 with a selected size of metal beads, at a selected packing density, to
achieve the desired rate of expansion of the gas. Typically, the beads in the second

25   stage 56 will have a larger surface area to enhance heat transfer.

The expanded primary gas mixture which passes through the heat exchanger
28 in the proximal direction exits the annular low pressure passageway 40 at a low
pressure outlet port 62 at the proximal end of the heat exchanger 28. This expanded
gas mixture enters the inner lumen 64 of the outer tube 22, surrounding the inner tube

30   24, to be returned to the primary compressor 12.

Figures 4 and 5 more clearly illustrate the structure of the plates 42 and their
angular orientation within the heat exchanger 28. Each plate 42 has a first plurality of

20

high pressure holes 46 through its central portion, and a second plurality of low pressure holes 48 through its outer annular portion. Typically, the diameter and spacing of the inner holes 46 are smaller than the diameter and spacing of the outer holes 48. Selection of hole diameter and spacing for the two different passageways is

5   designed for an optimization of minimum pressure drop and maximum heat transfer rate at the two different pressures, according to well known design principles. Figures 4 and 5 are also intended to show the relative angular orientation between adjacent plates 42. It can be seen that the two figures actually depict the same plate configuration, with the plate 42 in Figure 5 simply being rotated relative to the plate

10   42 in Figure 4. The hole pattern used in the plate 42 can be varied, with the objective being to maximize the heat exchange contact between the gas mixture and the plate 42. Gas does not flow from the high pressure portion of the plate to the low pressure portion, being prevented by contact between the plate 42 and the inner ring 47 of the interdisposed spacer 44, as shown earlier in Figure 3. The relative angular orientation

15   between adjacent plates 42 can also be varied according to the chosen hole pattern, with the objective being to maximize turbulence of the gas mixture, to promote heat transfer. It can be clearly seen from Figures 3, 4, and 5 that gas flowing through the heat exchanger 28 in either of the passageways 36, 40 follows a somewhat tortuous path, with a substantial portion of the flow path being involved in movement

20   transverse to the axis of the heat exchanger 28. In the embodiment shown, the transverse component of the flow results from the relative angular orientation between adjacent plates 42. This tortuous path promotes efficient heat transfer, allowing the micro-miniature heat exchanger 28 to achieve the required temperature drop to enable the desired isenthalpic expansion through the Joule-Thomson flow restriction

25   expansion element 30, ultimately producing the designed cooling temperature. Heat flow in this embodiment tends to be substantially radial.

Figure 6 shows the preferred embodiment of the spacer 44, which is interspersed between the plates 42. The spacer 44 has an outer ring 45 and an inner ring 47 supported in the desired concentric relationship by spokes 70. An inner

30   opening 72 within the inner ring 47 serves as a portion of the high pressure passageway 36 between plates 42. A plurality of outer openings 74 between the inner ring 47 and the outer ring 45 serve as a portion of the low pressure passageway 40

21

between plates 42. The inner ring 47 serves as a divider between the high and low pressure openings 72, 74.

      Figure 7 shows a second embodiment of the spacer 44' which can be used with a second embodiment of plates 42' shown in Figures 8 and 9. The spacer 44' has an

5   outer ring 45' and a high/low pressure divider 47'. This divider 47' separates the high pressure opening 72' from the low pressure opening 74'. It can be seen that this spacer 44' can be turned over from the orientation shown in Figure 7, to reverse the orientation of the divider 47', for reasons that will become apparent below. Figure 8 shows a plate 42' having a relatively small rectangular high pressure hole 46' and a

10   relatively large rectangular low pressure hole 48', with the long dimensions of the rectangular holes 46', 48' being vertically aligned. Figure 9 shows the same type of plate 42', with the rectangular holes 46', 48' being arranged horizontally. These two hole patterns and the two spacer orientations possible with the spacer 44' are used to create a series of adjacent plates 42' and spacers 44' as shown in Figure 10.

15   Figure 10 shows this series arranged from left to right as they would be arranged from the proximal end of the heat exchanger toward the low pressure end, in successive series. The HP arrows show the flow path of the high pressure gas mixture into the plane of the page, while the LP arrows show the path of the low pressure gas mixture out of the plane of the page. Figure 11 further illustrates this flow path, by

20   showing a vertical section through the stacked plates 42' and spacers 44'. Dashed lines are used to show the locations of hidden high and low pressure holes. Here again, it can be seen that the gas mixture follows a tortuous path through both the high pressure and low pressure passageways 36, 40, but in this embodiment, the transverse components of the flow are much more pronounced than in the first embodiment, and

25   the heat flow tends to be more axial than radial.

      Figures 12 and 13 show yet another embodiment of the microminiature heat exchanger, constructed of rolled sheets, rather than stacked plates and spacers. The inner tube 24 of the catheter 18 is shown connected to a labyrinthine high pressure passageway 36' etched into a first sheet 76. A constriction is also etched into the

30   outlet of the high pressure passageway 36', to form a Joule-Thomson expansion element 30'. A second sheet 80 has a low pressure passageway 40' etched therein, with an inlet 38' and an outlet 62'. Positioned in between the first sheet 76 and the

second sheet 80 are spacer sheets 78 to separate the high pressure and low pressure passageways 36', 40'. The sheets 76, 78, 80 can be laminated in the orientation shown and diffusion bonded together, or joined by some other suitable process. The assembly is then rolled as shown in Figure 13, to construct a cylindrical heat
5　　exchanger 28'.

Figures 14 and 15 show a second embodiment of the distal end portion of the catheter 18', having a slender elongated heat transfer element 32'. This embodiment illustrates that the end portion of the catheter can have a fluid tube 27 affixed to the expansion element 30, a fluid chamber 29, and insulation 25 between the fluid
10　　chamber 29 and the extension tube 23. This construction insures that the cooling power is applied primarily through the heat transfer element 32'.

The size and inherent heat transfer capacity of the heat exchanger are limited, regardless of the design used. In the miniature environments envisioned for the use of this apparatus, space is at a premium. Whether used in a cardiac catheter or on a
15　　printed circuit board, therefore, severe size limitations will be placed upon the heat exchanger. For instance, a cardiac catheter must be introduced into, and maneuvered through a blood vessel to the target area for application of cooling. Therefore, a cardiac catheter necessarily is severely limited in diameter by the diameter of the blood vessels through which the catheter must pass. Further, the catheter must be
20　　highly maneuverable to be able to pass through the vascular system under the control of the physician. These maneuverability requirements call for the catheter to be somewhat flexible, especially near its tip, where the cold tip heat exchanger will be located. Unfortunately, most designs of the cold tip heat exchanger will probably be somewhat stiff, if not rigid. Therefore, the length of the heat exchanger must be
25　　severely limited, in order to leave the catheter in that region somewhat flexible. Limiting the size of the heat exchanger, of course, will result in a commensurate limitation of the amount of heat which can be transferred in the heat exchanger. This type of severe limitation on the size and capacity of the cold tip heat exchanger suggests that the overall refrigeration system be kept at the highest possible level of
30　　performance by the use of a secondary closed loop Joule-Thomson refrigeration system. When appropriate precooling is combined with the optimum gas or fluid mixture, the system will perform cooling as well as possible, in spite of the size

limitations. The goal of this precooling system, in combination with the appropriate fluid mixture selection process, is to maximize the cooling power of the combination of the pre-cooling heat exchangers and the Joule-Thomson expansion elements.

For any particular gas mixture, and for any selected pressure range and temperature range, there is a theoretical limit to the amount of heat which can be transferred, even in a perfect heat exchanger. That limit is given by the equation

$$Q_{hx} = n[h(P,T_h) - h(P,T_c)]_{min}$$

where n is the molar flow rate, h is the molar enthalpy, T_h is the temperature at the hot end of a heat exchanger, T_c is the temperature at the cold end of the heat exchanger, and P is the pressure, with the value of Q_{hx} being calculated at both the high pressure and the low pressure. The subscript $_{min}$ denotes the fact that the value of Q_{hx} used is the lesser of the values computed at the two pressures.

Similarly, for that particular fluid mixture, and for that particular pressure and temperature range, there is a theoretical limit to the cooling power which can be achieved by even a perfect Joule-Thomson expansion element. That limit is given by the equation

$$Q_r = n[h(P_l,T) - h(P_h,T)]_{min}$$

where P_l is the low pressure, P_h is the high pressure, and T is the temperature, with the value of Q_r being calculated at a plurality of selected temperatures between the low and high temperatures at the extremes of the selected temperature range. The subscript $_{min}$ denotes the fact that the value of Q_r used is the lowest of the values computed at the plurality of selected temperatures.

The ratio of the theoretical cooling power to the theoretical heat transfer capacity, or Q_r / Q_{hx}, can be thought of as a performance ratio which is characteristic of that particular fluid mixture, over that particular pressure and temperature range. The present invention includes a method for selecting a fluid mixture from among a group of candidate mixtures, which will have the highest performance ratio of any fluid mixture in the candidate group.

First, a list of pure component fluids is compiled, from which the candidate fluid mixtures will be formulated. Each component fluid might be an elemental fluid, or it could be a compound of several elements. Each component fluid might be either organic or inorganic. One requirement is that the fluid mixture must have a triple

24

point below the lowest temperature in the selected temperature range, to prevent freezing of the fluid mixture in the apparatus. This requirement can be met by ensuring that each component fluid in the list has a triple point below the lowest temperature to be encountered. Alternatively, some of the component fluids can have

5   triple points within the anticipated temperature range, as long as the triple point of each of the formulated fluid mixtures has a triple point below the anticipated temperature range. A second requirement is that each fluid mixture must have a positive Joule-Thomson coefficient; in other words, a pressure drop in the fluid mixture must be accompanied by a temperature drop. One way of ensuring this is to

10 ensure that each of the component fluids on the list has a positive coefficient. Alternatively, some component fluids could have negative coefficients, as long as the coefficient of each fluid mixture has a positive coefficient.

For each of the component fluids in this list, the molar enthalpy must be known at a plurality of data points over the selected range of temperatures and the

15 selected range of pressures, with these selected ranges being the temperature and pressure ranges at which the fluid mixture will be pumped through the refrigeration apparatus.

Then, a plurality of mixtures of the component fluids are selected, with each fluid mixture having a number of component fluids, and with each component fluid

20 being present in a particular molar fraction. Any number of component fluids could theoretically be included in a fluid mixture. In actual practice, of course, computation capabilities will require that some limit be placed on the highest possible number of component fluids included in any one fluid mixture. Two fluid mixtures having the same component fluids, but with the component fluids being present in different

25 molar fractions, would be considered two different fluid mixtures. As few as two candidate fluid mixtures might be selected for comparison in the simplest case. However, any number of mixtures might be formulated, up to the maximum number that can be formulated from the component fluids under consideration. Based upon the known thermodynamic properties of each of the component fluids, the molar

30 enthalpy of each formulated fluid mixture is then calculated at a plurality of data points over the selected range of temperatures and the selected range of pressures.

25

One known method of calculating the molar enthalpy of each fluid mixture at a plurality of data points over the selected temperature and pressure ranges is the extended corresponding states method as used in the Mixture Property Database (DDMIX) program and the Thermophysical Properties of Hydrocarbon Mixtures

5   (SUPERTRAPP) program, both available from the National Institute of Standards and Technology (NIST). Enthalpy values and other thermophysical properties of the candidate fluid mixtures can be estimated, with the aid of these programs, through the use of approximate shape factors based on saturation boundary matching. A reference fluid is typically selected, with the thermophysical properties of the other fluids being

10   given in relation to the properties exhibited by the reference fluid. The refrigerant R134 has been found to serve as an appropriated reference fluid for these computations, but other fluids could also serve.

The component fluids selected must have a triple point below the low end of the selected temperature range, to eliminate the possibility of the formation of solids.

15   The database of component fluids can contain refrigerants, light hydrocarbons including alkanes and alkenes, and noble gases, including argon, krypton, and neon. The phase split and enthalpy content of each selected candidate fluid mixture are computed as a function of temperature and pressure.

For each candidate fluid mixture, a series of calculations are then performed.

20   It can sometimes be assumed that the pressure drop through the heat exchanger, on either the high pressure side or the low pressure side, is negligible. Alternatively, if an appreciable pressure drop is anticipated, a starting pressure can be selected which will take into account the pressure drop in the heat exchanger. For the low pressure in the selected pressure range, the molar enthalpy of the fluid mixture at the low temperature

25   in the selected temperature range is subtracted from the molar enthalpy at the high temperature in the range, yielding a low pressure enthalpy difference between the fluid mixture states at the two temperatures. Similarly, for the high pressure in the selected pressure range, the molar enthalpy at the low temperature is subtracted from the molar enthalpy at the high temperature, yielding a high pressure enthalpy difference between

30   the fluid mixture states at the two temperatures. The lesser of these two enthalpy differences is the theoretical molar enthalpy difference which could be achieved in a perfect counterflow heat exchanger operating with the selected fluid mixture over the

selected temperature range and pressure range. The theoretical heat transfer capacity of such a heat exchanger with the selected fluid mixture, over the selected temperature and pressure range, is the product of the molar flow rate of the fluid mixture and this theoretical molar enthalpy difference. The theoretical heat transfer capacity is
5   calculated for each candidate fluid mixture.

Then, a plurality of temperatures are selected at uniform increments over the selected temperature range. The number and size of the temperature increments can vary. A temperature increment of 5 degrees is often satisfactory. As an example, if the selected temperature range is from 120K to 270K, and if the size of the increment
10   is set at five degrees, this results in a total of 30 increments, and 31 selected temperatures. For each candidate fluid mixture, the molar enthalpy of the fluid mixture at the high end of the selected pressure range is subtracted from the molar enthalpy at the low end of the pressure range, yielding a molar enthalpy difference between the fluid mixture states at the two pressures. This calculation is performed at
15   each of the 31 selected temperatures. The higher the number of selected temperatures used, and the smaller the size of the increments, the greater will be the usefulness of the information calculated. The molar enthalpy difference calculated at each of these selected temperatures is the theoretical enthalpy increase which would occur during expansion of the candidate fluid mixture from the high pressure to the low pressure, at
20   that temperature, if the temperature were to remain constant.

In Joule-Thomson expansion, however, there is very little or no opportunity for heat transfer to or from the fluid as it flows through the expansion element, no change in potential energy of the fluid, no work performed, and very little or no change in kinetic energy of the fluid. Therefore, the enthalpy states of the fluid before
25   and after the expansion are essentially the same. As the pressure sharply decreases during expansion, the temperature of the fluid also sharply decreases, maintaining an essentially constant enthalpy. This colder fluid then can be used to cool the surroundings. In actuality, then, the temperature does not remain constant during expansion, and the theoretical cooling power available through Joule-Thomson
30   expansion of the candidate fluid mixture, in the selected temperature range, is a function of the lowest theoretical enthalpy difference at any of the selected temperatures. More specifically, the theoretical cooling power available through

27

Joule-Thomson expansion of the candidate fluid mixture is the product of the molar
flow rate of the fluid mixture and the lowest theoretical molar enthalpy difference
calculated at any temperature over the selected temperature range. The theoretical
cooling power is calculated for each candidate fluid mixture.

5   Therefore, each candidate fluid mixture in the group exhibits a theoretical
cooling power and a theoretical heat transfer capacity, over the selected temperature
and pressure range. The ratio of the theoretical cooling power to the theoretical heat
transfer capacity can be called a performance ratio which is characteristic of that
particular fluid mixture over that temperature and pressure range. In order to optimize

10   the operation of the apparatus of the present invention, a fluid mixture is chosen from
among the candidate mixtures, which will result in the highest performance ratio.
That is the optimum fluid mixture, among that group of candidates, within the
temperature and pressure ranges selected. It can be seen that, if the performance ratio
is equal to or greater than unity, meaning that the theoretical cooling power is as great

15   as the theoretical heat transfer capacity, then the maximum cooling possible over the
desired temperature and pressure range can be achieved through Joule-Thomson
expansion alone, and no heat exchanger is needed. If the highest performance ratio in
the group is less than unity, at least one heat exchanger will be required.

        Figures 16 through 32 show Tables A through Q of enthalpy values of various

20   fluid mixtures, derived through the extended corresponding states method. The
component fluids used in formulating the candidate fluid mixtures were Ar, CH_4,
C_2H_4, C_3H_4, Kr, N_2, NF_3 , 1-pentene, Isobutane, Isopentane, Propylene, R14, R22,
R23, R32, R124, and R142b. It has been found that various mixtures of these
component fluids can be useful in the operation of miniature mixed gas refrigeration

25   systems. The enthalpy values in each table are shown at a low pressure of 1.0 bar in
the column labeled Low H, and at a high pressure of 21.0 bar in the column labeled
High H. Based upon these enthalpy values, calculations are made to arrive at
calculated values of delta H at each incremental temperature. Then, according to a
method described below, based upon the selected temperature range, values of delta

30   H^* are calculated at each incremental temperature. In addition to the table of enthalpy
and related values, each Figure also shows a graph of delta H^* vs. temperature, and a
graph of Low H and High H vs. temperature. Tables A through H show enthalpy

28

values and delta H* between 150K and 300K, with the selected temperature range of
interest being from 150K to 270K. Tables I through M show enthalpy values and
delta H* between 120K and 270K, with the selected temperature range of interest
being 120K to 270K. Tables N through Q show enthalpy values and delta H* between

5   100K and 280K, with the selected temperature range of interest being 100K to 260K.

        The temperature ranges covered by the tables were arbitrarily selected to
demonstrate that the enthalpy values for a mixture can be given over any desired
temperature range, with the delta H* values in a given table being calculated based
upon the selected temperature range of interest. Comparisons between fluid mixtures

10   can be taken only from tables which have delta H* values calculated based on the
same selected temperature range. For instance, all of the tables include enthalpy
values over the range of 150K to 270K. However, only Tables A through H can be
used for comparing calculated values of delta H* based upon a selected temperature
range of 150K to 270K, because the values of delta H* in the other tables were

15   calculated based upon a different selected temperature range.

        Similarly, Tables I through Q all show enthalpy values over the range of 120K
to 270K, but only Tables I through M can be used for comparing calculated values of
delta H* based upon this selected temperature range. This is because the calculated
values of delta H* in Tables N through Q were calculated based upon a selected

20   temperature range of 100K to 260K. Listed values of delta H* which are outside the
selected temperature range for a given table are calculated by the method of the
present invention and shown in the table, but they are not pertinent to the selection of
a fluid mixture for use within the selected temperature range.

        The following discussion will specify selected temperature ranges which are

25   covered by the tables referenced. In all cases, the temperature increments are 5 Kelvin
degrees. H is molar enthalpy. The values of thermophysical properties are referenced
to the values for R134a. Each table lists the molar enthalpy values of the candidate
fluid mixture at increments of 5 degrees, for a low pressure of 1.0 bar, and for a high
pressure of 21.0 bar. Further, for each incremental temperature over the range, a delta

30   H is given, with delta H being the difference between the enthalpy values at the low
pressure and the high pressure at that temperature.

For the low pressure, on a given table, it can be seen that the enthalpy value at the low temperature in the selected range can be subtracted from the enthalpy value at the high temperature in the selected range, to give a low pressure enthalpy difference. This is the y value shown near the lower left hand corner of the table. A similar

5 calculation can be performed for the high pressure, yielding a high pressure enthalpy difference. This is the x value shown near the lower left hand corner. The lesser of the low pressure enthalpy difference and the high pressure enthalpy difference is the theoretical enthalpy difference available over that selected temperature range. This is the nh value shown near the lower left hand corner. The molar Gibbs free energy is

10 also shown.

For each incremental temperature, if the value shown in the delta H column is divided by the theoretical enthalpy difference, nh, the result is shown in the column designated delta H^*. Since the theoretical enthalpy difference, nh, is based upon a selected temperature range, the calculated values of delta H^* are based upon that

15 range, as well. The lowest value of delta H^* within the selected temperature range, for any given table, is the same as the theoretical cooling power divided by the theoretical heat transfer capacity, since the molar flow rate is the same in both terms. This value, delta H^*_{min}, is the performance ratio for that fluid mixture, over the selected temperature range.

20 By way of example, select a temperature range of 120K to 270K, and a pressure range of 1.0 bar to 21.0 bar. Tables I through M contain delta H^* values for five fluid mixtures over this selected temperature range. Over this selected temperature range, the fluid mixture having the highest value of delta H^*_{min} is addressed in Table J, and the value of delta H^*_{min} for that fluid mixture is 0.2180.

25 This means that, of the fluid mixtures addressed in the tables which show calculated delta H^* values based upon a selected temperature range of 120K to 270K, over this selected temperature and pressure range, the optimum fluid mixture is 43% Argon, 13% Krypton, 11% R14, 2% R22, 14% R23, 4% R124, and 13% Isopentane. In Tables I through M, the molar composition values of 50% or higher have a possible

30 error of +/- 10%, values from 20% to 49% have a possible error of +/- 7.5%, and values below 20% have a possible error of +/- 5%.

By way of a further example, select a temperature range of 150K to 270K. Tables A through H contain delta H* values calculated for seven fluid mixtures based upon this range. For the fluid mixtures addressed in the tables which show calculated delta H* values over this range, the fluid mixture having the highest value of delta

5   H^*_{min} is addressed in Table E, and the value of delta H^*_{min} for that fluid mixture is 0.3756. This means that, of the fluid mixtures addressed in these tables, over this selected temperature and pressure range, the optimum fluid mixture is 7% R22, 7% R23, 20% R142b, 55% Krypton, and 11% NF_3. In Tables A through H, the molar composition values have a possible error of +/- 10%.

10   Use of the tables can be further illustrated by showing a means of eliminating toxicity or flammability in the selected gas mixture. Noting that NF_3 is potentially toxic to humans, for instance, the fluid mixture used in the last example may not be desirable for use in a mixed gas refrigeration system which will be used in a heart catheter. A fluid mixture which is similar, but which does not include this component

15   fluid is addressed in Table C. It can be seen that the value of delta H^*_{min} for that fluid mixture over the same selected temperature range is 0.3580. This means that, of the fluid mixtures addressed in these tables, over this selected temperature and pressure range, the optimum non-toxic fluid mixture is 7.5% R22, 7.5% R23, 20% R142b, and 65% Krypton. Toxicity or flammability can therefore be eliminated by a slight change

20   in the gas mixture selected.

It can be seen that, for some of the primary fluid mixtures addressed in the tables, the minimum value of delta H* occurs in the upper part of the selected temperature range. For such a fluid mixture, pre-cooling of the primary fluid mixture with a secondary refrigeration system can lower the top end of the temperature range

25   to a level which results in a higher value of delta H^*_{min} as the primary mixture flows through the primary expansion element.

For example, consider the possibility of using a pre-cooler to lower the temperature of the fluid mixture from 270K to 260K prior to introducing the mixture into the catheter. The mixture addressed in Table B will show a proportional increase

30   in delta H^*_{min} of over 40%, which is almost twice the proportional increase of over 20% which would result in the mixture addressed in Table D. Therefore, in systems where it is possible to pre-cool the fluid mixture before introducing it into the micro-

31

miniature heat exchanger, and where it is desirable to use that pre-cooling to control
the performance of the system, the mixture in Table B might be more advantageous.

It should be noted that gases with similar boiling points are interchangeable in
a selected fluid mixture. For example, R124 can be substituted in the place of R142b

5   or Isobutane, and Nitrogen can be substituted in the place of Argon. The substitution
can be at an equal, or slightly different, percentage, with only slight changes in delta
H^*_{min}. A good example of this can be seen by examining Tables C and H. The
mixture in Table C is 7.5% R22, 7.5% R23, 20% R142b, and 65% Krypton, with a
delta H^*_{min} of 0.3580. In the mixture addressed in Table H, R32 has been substituted

10   in place of R22, and R124 has been substituted in place of R142b, to arrive at an
environmentally safer mixture, but the delta H^*_{min} has only dropped to 0.3491, a drop
of only about 2%.

Figure 33 shows a schematic of the dual closed loop refrigeration system 10 of
the present invention, incorporating the pre-cooling concept. The primary loop 100 is

15   similar in some respects to the primary loop described above in the non-precooled
system. The secondary loop 200 has been added for the purpose of maximizing the
pre-cooling effect. The primary loop 100 consists of a high pressure path 110 and a
low pressure path 120. A primary loop compressor 130 compresses the primary gas
mixture to a selected pressure and temperature, such as 420 psia and 300K. The high

20   pressure primary gas mixture then flows from the outlet 132 of the primary
compressor 130, through a first primary heat exchanger 140, which can be a miniature
heat exchanger located in the handle of a cryoprobe. Specifically, the high pressure
primary gas mixture passes through the high pressure passageway 142 of the first
primary heat exchanger 140, where it is cooled to a lower temperature, such as for

25   example 280K. Depending upon the reqired temperatures and cooling power, some
applications may not require the first primary heat exchanger 140.

The high pressure gas mixture then passes through a primary/secondary heat
exchanger 240, specifically through the high pressure primary passageway 170 of the
primary/secondary heat exchanger 240, where it is further cooled to a lower

30   temperature such as 220K. The high pressure primary gas mixture then passes
through a second primary heat exchanger 160, specifically through the high pressure
passageway 162, where it is still further cooled to, for example, 160K. This second

32

primary heat exchanger can be comparable to the laminated heat exchangers discussed above in the non-precooled systems. Depending upon the reqired temperatures and cooling power, some applications may not require the second primary heat exchanger 160.

5   The gas mixture then flows to the primary Joule-Thomson expansion element 150. After isenthalpic expansion in the primary expansion element 150, to a temperature such as 130K, the expanded low pressure gas mixture cools the target tissue T.

Then, the low pressure primary gas mixture passes back through a low
10   pressure passageway 164 in the second primary heat exchanger 160, where it is warmed to 220K, and through a low pressure passageway 144 in the first primary heat exchanger 140, where it is warmed to 300K. The low pressure gas mixture then returns to the inlet 134 of the primary compressor 130.

The secondary loop 200 consists of a high pressure path 210 and a low
15   pressure path 220. A secondary loop compressor 230 compresses the secondary refrigerant to a pressure which can be relatively higher than the pressure found in the primary system, since the secondary system does not enter the cannula of the probe. The high pressure secondary refrigerant then flows from the outlet 232 of the secondary compressor 230, through a primary/secondary heat exchanger 240, which
20   can also be a miniature heat exchanger located in the handle of the cryoprobe. Specifically, the high pressure secondary refrigerant passes through the secondary high pressure passageway 242 of the primary/secondary heat exchanger 240, where it is cooled to a lower temperature.

The high pressure secondary refrigerant then passes through a secondary Joule-
25   Thomson expansion element 250. After isenthalpic expansion in the secondary expansion element 250, the expanded low pressure secondary refrigerant passes back through a low pressure passageway 244 in the primary/secondary heat exchanger 240. The low pressure passageway 244 is situated so as to insulate the high pressure primary passageway 170 from the high pressure secondary passageway 242. This
30   insures that heat flows from the high pressure passageways to the low pressure passageway. The low pressure secondary refrigerant then returns to the inlet 234 of the secondary compressor 230.

33

Figure 34 shows the portion of the dual loop refrigeration system that might be located in the handle of a cryoprobe. The primary loop 100 enters the handle as a coaxial dual lumen tube, with the high pressure path 110 being in the inner lumen, and the low pressure path 120 being in the outer lumen. The first primary heat exchanger

5   140 is also constructed as a coaxial coiled tube, with the high pressure passageway 142 being in the inner lumen, and the low pressure passageway 144 being in the outer lumen. The details of the dual lumen coaxial tube are shown in Figure 36. Both the high and low pressure paths 110, 120 pass into a first splitting tee fitting 180. In the splitting tee fitting 180, the high pressure path 110 is split from the low pressure path

10   120. From the first tee fitting 180, the high pressure path 110 passes to the high pressure primary passageway 170 in the primary/secondary heat exchanger 240.

The primary/secondary heat exchanger 240 is constructed as a coiled multi-lumen tube, as shown in Figure 37. The high and low pressure paths 210, 220 pass through a dual lumen coaxial tube. The high pressure secondary path 210 passes

15   through the inner lumen, high pressure secondary passageway 242, and the low pressure secondary path 220 passes through the outer lumen, low pressure secondary passageway 244. Soldered to the outside of the low pressure secondary passageway 244 is the high pressure primary passageway 142. The high pressure primary passageway 142 can have a plurality of inner lumens 143, with the high pressure

20   primary gas mixture flowing through all of the inner lumens 143, and through the interstitial spaces between and around the inner lumens 143. This arrangement promotes improved heat transfer to the solder and to the low pressure secondary passageway 244.

After exiting the primary/secondary heat exchanger 240, the high pressure

25   primary path 110 flows through a high pressure primary connector 192, which can be connected to the cannula of the cryoprobe, and to the primary expansion element 150 in the cold tip. After expansion in the expansion element 150, the low pressure gas mixture flows back through a low pressure primary connector 194 to the tee fitting 180. In the tee fitting 180, the low pressure primary passageway 144 rejoins the high

30   pressure primary passageway 142 in a coaxial relationship to return to the primary compressor 130.

The secondary loop 200 also enters the cryoprobe handle, coming from the secondary compressor 230, as a coaxial dual lumen tube, with the high pressure path 210 being in the inner lumen, and the low pressure path 220 being in the outer lumen. The secondary high and low pressure paths 210, 220 pass through the

5   primary/secondary heat exchanger 240 as described above, and connect to a second splitting tee fitting 280. In the second tee fitting 280, the high pressure secondary path 210 splits from the low pressure secondary path 220 and passes through the secondary expansion element 250. After expansion in the secondary expansion element 250, the low pressure secondary refrigerant passes into the low pressure secondary path 220,

10   which rejoins the high pressure secondary path 210 in the second tee fitting 280.

Figure 35 shows how the apparatus of the present invention might be arranged in a rigid cryoprobe P, having a handle H. The primary and secondary closed loop systems 100, 200 enter the end of the handle H. The primary gas mixture passes through the first primary heat exchanger 140, while the first primary heat exchanger

15   140 is bypassed by the secondary refrigerant. Both the primary gas mixture and the secondary refrigerant pass through the primary/secondary heat exchanger 240 as described earlier. The secondary refrigerant is then isenthalpically expanded in the secondary expansion element 250 and returns through the primary/secondary heat exchanger 240. The secondary refrigerant then exits the handle H to return to the

20   secondary compressor 230. The primary gas mixture passes through the connectors 192, 194 to the cold tip CT. In the cold tip CT, the high pressure primary gas mixture passes through the microminiature primary heat exchanger 160, and then through the primary expansion element 150. The microminiature heat exchanger 160 is shown as a coiled high pressure tube, with the low pressure primary gas mixture returning

25   through the coils. Having expanded and cooled, the low pressure primary gas mixture flows back through the microminiature primary heat exchanger 160, and the first primary heat exchanger 140, before exiting the handle H to return to the primary compressor 130.

While the particular invention as herein shown and disclosed in detail is fully

30   capable of fulfilling the objects previously stated, it is to be understood that this disclosure is merely an illustration of the presently preferred embodiments of the invention and that no limitations are intended other than those described in the appended claims.

35

- 35a -

Throughout this specification and the claims which follow, unless the context requires otherwise, the word "comprise", and variations such as "comprises" or comprising", will be understood to imply the inclusion of a stated integer or step or group of integers or steps but not the exclusion of any other integer or step or group of integers or steps.

CLAIMS

We claim:

1.   A miniature mixed gas refrigeration system, comprising:

a closed primary loop for circulating a gas mixture, with a high pressure
primary flow path and a low pressure primary flow path, said primary
loop including a primary compressor, and a primary expansion element
for isenthalpically expanding said gas mixture from said high pressure
primary flow path to said low pressure primary flow path; and

a closed secondary loop for circulating a refrigerant, with a high pressure
secondary flow path and a low pressure secondary flow path, said
secondary   loop   including   a   secondary   compressor,   a
primary/secondary heat exchanger, and a secondary expansion element
for isenthalpically expanding said refrigerant from said high pressure
secondary flow path downstream of said primary/secondary heat
exchanger to said low pressure secondary flow path upstream of said
primary/secondary heat exchanger;

wherein said high pressure primary flow path, said high pressure secondary
flow path, and said low pressure secondary flow path pass through said
primary/secondary heat exchanger in a heat exchange relationship; and

wherein said low pressure primary flow path bypasses said primary/secondary
heat exchanger.

2.   A miniature mixed gas refrigeration system as recited in claim 1,
further comprising a primary heat exchanger, having high pressure and low pressure
primary flow paths, between said primary compressor and said primary/secondary
heat exchanger.

3.   A miniature mixed gas refrigeration system as recited in claim 2,
wherein said primary heat exchanger comprises a coaxial dual lumen coiled tube, with
said high pressure primary flow path connected to an inner said lumen and said low
pressure primary flow path connected to an outer said lumen.

36

1　　4.　　A miniature mixed gas refrigeration system as recited in claim 1,
2　further comprising a primary heat exchanger, having high pressure and low pressure
3　primary flow paths, between said primary/secondary heat exchanger and said primary
4　expansion element.

1　　5.　　A miniature mixed gas refrigeration system as recited in claim 1,
2　wherein said primary high pressure flow path in said primary/secondary heat
3　exchanger is insulated from said secondary high pressure flow path by said secondary
4　low pressure flow path.

1　　6.　　A miniature mixed gas refrigeration system as recited in claim 5,
2　wherein:
3　　　said secondary high and low pressure flow paths in said primary/secondary
4　　　　　heat exchanger are formed as a first tube having two coaxial lumens,
5　　　　　with an inner said lumen forming said secondary high pressure flow
6　　　　　path and an outer said lumen forming said secondary low pressure flow
7　　　　　path; and
8　　　said primary high pressure flow path in said primary/secondary heat exchanger
9　　　　　comprises a second tube mounted to an outer wall of said first tube in a
10　　　　　parallel arrangement.

37

AMENDED SHEET

1   7.   A miniature mixed gas refrigeration system, comprising:
2   a closed primary loop for circulating a gas mixture, with a high pressure
3   primary flow path and a low pressure primary flow path, said primary
4   loop including a primary compressor, a primary heat exchanger with
5   high pressure and low pressure primary flow paths, a primary
6   expansion element for isenthalpically expanding said gas mixture from
7   said high pressure primary flow path downstream of said primary heat
8   exchanger to said low pressure primary flow path upstream of said
9   primary heat exchanger; and
10   a closed secondary loop for circulating a refrigerant, with a high pressure
11   secondary flow path and a low pressure secondary flow path, said
12   secondary loop including a secondary compressor, a
13   primary/secondary heat exchanger, and a secondary expansion element
14   for isenthalpically expanding said refrigerant from said high pressure
15   secondary flow path downstream of said primary/secondary heat
16   exchanger to said low pressure secondary flow path upstream of said
17   primary/secondary heat exchanger;
18   wherein said high pressure primary flow path, said high pressure secondary
19   flow path, and said low pressure secondary flow path pass through said
20   primary/secondary heat exchanger in a heat exchange relationship; and
21   wherein said low pressure primary flow path bypasses said primary/secondary
22   heat exchanger.

1   8.   A miniature mixed gas refrigeration system as recited in claim 7,
2   further comprising a second primary heat exchanger having high pressure and low
3   pressure primary flow paths between said first primary heat exchanger and said
4   primary expansion element.

1   9.   A miniature mixed gas refrigeration system as recited in claim 7,
2   wherein said primary heat exchanger comprises a coaxial dual lumen coiled tube, with
3   said high pressure primary flow path connected to an inner said lumen and said low
4   pressure primary flow path connected to an outer said lumen.

38

1   10.   A miniature mixed gas refrigeration system as recited in claim 7,

2   wherein said primary high pressure flow path in said primary/secondary heat

3   exchanger is insulated from said secondary high pressure flow path by said secondary

4   low pressure flow path.

1   11.   A miniature mixed gas refrigeration system as recited in claim 10,

2   wherein:

3   said secondary high and low pressure flow paths in said primary/secondary

4   heat exchanger are formed as a first tube having two coaxial lumens,

5   with an inner said lumen forming said secondary high pressure flow

6   path and an outer said lumen forming said secondary low pressure flow

7   path; and

8   said primary high pressure flow path in said primary/secondary heat exchanger

9   comprises a second tube mounted to an outer wall of said first tube in a

10   parallel arrangement.

1   12.   A miniature mixed gas refrigeration system, comprising:

2   a probe having a proximal handle and a distal cold tip;

3   a closed primary loop for circulating a gas mixture, said primary loop

4   including:

5   a primary compressor connected to said probe;

6   a miniature primary expansion element adjacent said cold tip for

7   isenthalpically expanding said gas mixture from a high pressure

8   flow path of said primary loop to a low pressure flow path of

9   said primary loop; and

10   a primary heat exchanger in said handle, said primary heat exchanger

11   having high pressure and low pressure primary flow paths;

12   a heat transfer body in said cold tip, said heat transfer body having an inner

13   surface exposed to said expanded gas mixture and an outer surface

14   exposed to ambient, for transferring heat from ambient to said gas

15   mixture; and

16   a closed secondary loop for circulating a refrigerant, said secondary loop

17   including:

18   a secondary compressor connected to said probe;

19   a secondary expansion element in said handle for isenthalpically

20   expanding said refrigerant from a high pressure flow path of

21   said secondary loop to a low pressure flow path of said

22   secondary loop; and

23   a primary/secondary heat exchanger in said handle, said

24   primary/secondary heat exchanger having a high pressure

25   primary flow path, a high pressure secondary flow path, and a

26   low pressure secondary flow path;

27   wherein said low pressure primary flow path bypasses said

28   primary/secondary heat exchanger.

1   13.   A miniature mixed gas refrigeration system as recited in claim 12,

2 further comprising a second primary heat exchanger adjacent said cold tip, said

3 second primary heat exchanger having high pressure and low pressure primary flow

4 paths between said first primary heat exchanger and said primary expansion element.

14. A miniature mixed gas refrigeration system as recited in claim 12, wherein said primary heat exchanger comprises a dual lumen tube, with said high pressure flow path comprising a first said lumen and said low pressure flow path comprising a second said lumen.

15. A miniature mixed gas refrigeration system as recited in claim 14, wherein said first and second lumens are coaxial.

16. A miniature mixed gas refrigeration system as recited in claim 15, wherein said dual lumen coaxial tube forms a coil.

17. A miniature mixed gas refrigeration system as recited in claim 12, wherein said primary high pressure path in said primary/secondary heat exchanger is insulated from said secondary high pressure path by said secondary low pressure path.

18. A miniature mixed gas refrigeration system as recited in claim 17, wherein:
    said secondary high and low pressure paths in said primary/secondary heat
        exchanger are formed as a first tube having two coaxial lumens, with
        an inner said lumen forming said secondary high pressure path and an
        outer said lumen forming said secondary low pressure path; and
    said primary high pressure path in said primary/secondary heat exchanger
        comprises a second tube mounted to an outer wall of said first tube in a
        parallel arrangement.

19. A miniature mixed gas refrigeration system as recited in claim 12, wherein a high pressure portion of said primary loop comprises a tube having a plurality of high pressure lumens.

AMENDED SHEET

1   20.   A miniature mixed gas refrigeration system as recited in claim 19,

2   wherein said tube comprises:

3   an outer lumen; and

4   a plurality of inner lumens within said outer lumen, each said lumen having a

5   wall in contact with a wall of at least one other said lumen.

1   21.   A miniature mixed gas refrigeration system as recited in claim 20,

2   wherein each said inner lumen has a wall in contact with a wall of at least one other

3   said inner lumen and a wall in contact with a wall of said outer lumen.

1   22.   A miniature mixed gas refrigeration system, comprising:

2   a primary loop compressor for pressurizing a gas mixture to a pressure of

3   approximately 420 psia, said primary compressor having an inlet and

4   an outlet;

5   a dual lumen primary loop tube, said primary loop tube having a high pressure

6   lumen connected to an outlet of said primary compressor and a low

7   pressure lumen connected to an inlet of said primary compressor;

8   a primary loop heat exchanger attached to said primary loop tube, said primary

9   loop heat exchanger having a high pressure passageway connected to

10   said high pressure lumen and a low pressure passageway connected to

11   said low pressure lumen;

12   a primary loop expansion element connected to said high pressure passageway

13   of said primary loop heat exchanger for isenthalpically expanding said

14   gas mixture from said higher pressure to a lower pressure, said

15   expanded gas mixture thereby cooling to a temperature of no greater

16   than 183K, said expanded gas mixture being in fluid flow

17   communication with said low pressure passageway;

18   a secondary loop compressor for compressing a refrigerant, said secondary

19   compressor having an inlet and an outlet;

20   a dual lumen secondary loop tube, said secondary loop tube having a high

21   pressure lumen connected to an outlet of said secondary compressor

22   and a low pressure lumen connected to an inlet of said secondary

23   compressor;

42

24   a primary/secondary heat exchanger attached to a distal end of said secondary
25   loop tube, said primary/secondary heat exchanger having a primary
26   loop high pressure passageway connected to said primary loop high
27   pressure lumen, a secondary loop high pressure passageway connected
28   to said secondary loop high pressure lumen, and a secondary loop low
29   pressure passageway connected to said secondary loop low pressure
30   lumen; and
31   a secondary loop expansion element connected to said secondary loop high
32   pressure passageway of said primary/secondary heat exchanger for
33   isenthalpically expanding said refrigerant, said expanded gas mixture
34   being in fluid flow communication with said secondary loop low
35   pressure passageway;
36   wherein said low pressure primary flow path bypasses said primary/secondary
37   heat exchanger.

1   23.   A miniature mixed gas refrigeration system as recited in claim 22,
2   further comprising a cold tip primary loop heat exchanger, said cold tip primary loop
3   heat exchanger having a high pressure passageway connected to said high pressure
4   lumen of said primary loop tube between said primary/secondary heat exchanger and
5   said primary loop expansion element, and said cold tip primary loop heat exchanger
6   having a low pressure passageway connected to said low pressure lumen of said
7   primary loop tube between said first primary loop heat exchanger and said primary
8   loop expansion element.

1   24.   A miniature mixed gas refrigeration system as recited in claim 22,
2   wherein said primary loop heat exchanger comprises a dual lumen coaxial tube, with
3   said high pressure passageway comprising a first said lumen and said low pressure
4   passageway comprising a second said lumen.

1   25.   A miniature mixed gas refrigeration system as recited in claim 24,
2   wherein said dual lumen coaxial tube forms a coil.

1   26.   A miniature mixed gas refrigeration system as recited in claim 22,
2   wherein said primary loop high pressure passageway is insulated from said secondary
3   loop high pressure passageway by said secondary loop low pressure passageway.

1   27.   A miniature mixed gas refrigeration system as recited in claim 26,
2   wherein:
3   said secondary loop high and low pressure passageways are formed as a first
4   tube having two coaxial lumens, with an inner said lumen forming said
5   secondary loop high pressure passageway and an outer said lumen
6   forming said secondary loop low pressure passageway; and
7   said primary loop high pressure passageway comprises a second tube mounted
8   to an outer wall of said first tube in a parallel arrangement.

1   28.   A miniature mixed gas refrigeration system as recited in claim 27,
2   wherein said second tube comprises:
3   an outer lumen; and
4   a plurality of inner lumens within said outer lumen, each said lumen having a
5   wall in contact with a wall of at least one other said lumen.

44

AMENDED SHEET

29. A method for cooling a distal cold tip of a probe, comprising:

providing a closed primary loop, said primary loop including at least one
   primary heat exchanger and a primary expansion element distal of said
   primary heat exchanger;

providing a closed secondary loop, said secondary loop including a
   primary/secondary heat exchanger and a secondary expansion element
   distal of said primary/secondary heat exchanger;

compressing a refrigerant in said secondary loop;

cooling said refrigerant in said primary/secondary heat exchanger;

isenthalpically expanding said refrigerant to a lower temperature with said
   secondary expansion element;

warming said expanded refrigerant in said primary/secondary heat exchanger;

compressing a gas mixture in said primary loop with said primary compressor;

cooling said compressed gas mixture in said primary heat exchanger;

cooling said compressed gas mixture in said primary/secondary heat
   exchanger;

isenthalpically expanding said gas mixture with said primary expansion
   element to still further cool said gas mixture; and

applying said expanded gas mixture to the cold tip, to lower the temperature of
   the cold tip.

30. A method as recited in claim 29, further comprising solidifying liquid
contaminants of said gas mixture in said primary/secondary heat exchanger, thereby
removing said contaminants from said gas mixture prior to passage of said gas
mixture through said primary expansion element.

31.   A method for cooling a distal cold tip of a probe, comprising:

providing a closed primary loop, said primary loop including a primary

compressor, a primary heat exchanger distal of said primary

compressor, and a primary expansion element distal of said primary

heat exchanger;

providing a closed secondary loop, said secondary loop including a secondary

compressor, a primary/secondary heat exchanger distal of said

secondary compressor, and a secondary expansion element distal of

said primary/secondary heat exchanger;

compressing a refrigerant in said secondary loop with said secondary

compressor;

cooling said compressed refrigerant in a high pressure secondary side of said

primary/secondary heat exchanger;

isenthalpically expanding said refrigerant with said secondary expansion

element;

warming said expanded refrigerant in a low pressure secondary side of said

primary/secondary heat exchanger;

returning said expanded refrigerant to an inlet of said secondary compressor;

compressing a gas mixture in said primary loop with said primary compressor;

cooling said compressed gas mixture in a high pressure side of said primary

heat exchanger;

cooling said compressed gas mixture in a high pressure primary side of said

primary/secondary heat exchanger;

isenthalpically expanding said gas mixture with said primary expansion

element to still further cool said gas mixture;

applying said expanded gas mixture to the cold tip, to lower the temperature of

the cold tip;

warming said expanded gas mixture in a low pressure side of said primary

heat exchanger; and

returning said expanded gas mixture to an inlet of said primary compressor.

46

1   32.   A method as recited in claim 31, further comprising solidifying liquid
2   contaminants of said gas mixture in restrictions in said high pressure primary side of
3   said primary/secondary heat exchanger, thereby removing said contaminants from
4   said gas mixture prior to passage of said gas mixture through said primary expansion
5   element.

1   33.   A method as recited in claim 31, further comprising:
2   providing a distal primary heat exchanger between said primary/secondary
3   heat exchanger and said primary expansion element;
4   still further cooling said compressed gas mixture in a high pressure side of
5   said distal primary heat exchanger; and
6   warming said expanded gas mixture in a low pressure side of said distal
7   primary heat exchanger prior to passage of said expanded gas mixture
8   through said low pressure side of said first primary heat exchanger.

1   34.   A method for cooling a cold tip of a probe, comprising:
2   providing a gas mixture capable of isenthalpically expanding to a temperature
3   below 183K from a pressure of no more than 420 psia;
4   providing a closed primary loop having a compressor for pressurizing said gas
5   mixture to a pressure of no more than 420 psia, at least one primary
6   heat exchanger, and a primary expansion element adjacent to a metallic
7   heat transfer element in said cold tip;
8   providing a closed secondary loop having a compressor, a primary/secondary
9   heat exchanger, and a secondary expansion element;
10   placing said heat transfer element in contact with a remote body to be cooled;
11   compressing a refrigerant in said secondary loop;
12   conducting said compressed refrigerant to a high pressure secondary section of
13   said primary/secondary heat exchanger;
14   cooling said compressed refrigerant in said high pressure secondary section of
15   said primary/secondary heat exchanger;
16   isenthalpically expanding said refrigerant in said secondary expansion
17   element;
18   conducting said expanded refrigerant to a low pressure secondary section of
19   said primary/secondary heat exchanger;

47

20	warming said expanded refrigerant in said low pressure secondary section of
21	said primary/secondary heat exchanger;
22	compressing said gas mixture to no more than 420 psia;
23	conducting said compressed gas mixture to a high pressure section of said
24	primary heat exchanger;
25	cooling said compressed gas mixture in said high pressure section of said
26	primary heat exchanger;
27	conducting said compressed gas mixture to a high pressure primary section of
28	said primary/secondary heat exchanger;
29	cooling said compressed gas mixture in said high pressure primary section of
30	said primary/secondary heat exchanger;
31	isenthalpically expanding said gas mixture in said primary expansion element
32	to still further cool said gas mixture to below 183K;
33	absorbing heat from said heat transfer element by contact with said expanded
34	gas mixture, to cool said heat transfer element to below 180K; and
35	absorbing heat from said body to be cooled, by contact with said heat transfer
36	element.

1	35. A method as recited in claim 34, further comprising solidifying liquid
2	contaminants of said gas mixture in restrictions in said high pressure primary section
3	of said primary/secondary heat exchanger, thereby removing said contaminants from
4	said gas mixture prior to passage of said gas mixture through said primary expansion
5	element.

1	36. A method as recited in claim 34, further comprising:
2	providing a distal primary heat exchanger between said primary/secondary
3	heat exchanger and said primary expansion element;
4	still further cooling said compressed gas mixture in a high pressure side of
5	said distal primary heat exchanger; and
6	warming said expanded gas mixture in a low pressure side of said distal
7	primary heat exchanger prior to passage of said expanded gas mixture
8	through said low pressure side of said first primary heat exchanger.

- 49 -

37.   A miniature mixed gas refrigeration system, substantially according to the embodiment described in the specification with reference to and as illustrated in the accompanying figures.

38.   A method for cooling a distal cold tip of a probe, substantially according to the
5   embodiment described in the specification with reference to the accompanying figures.

39.   A method for cooling a cold tip of a probe, substantially according to the embodiment described in the specification with reference to the accompanying figures.

10   DATED this 3rd day of November, 1999

CRYOGEN, INC.
By Their Patent Attorneys
DAVIES COLLISON CAVE

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1/27
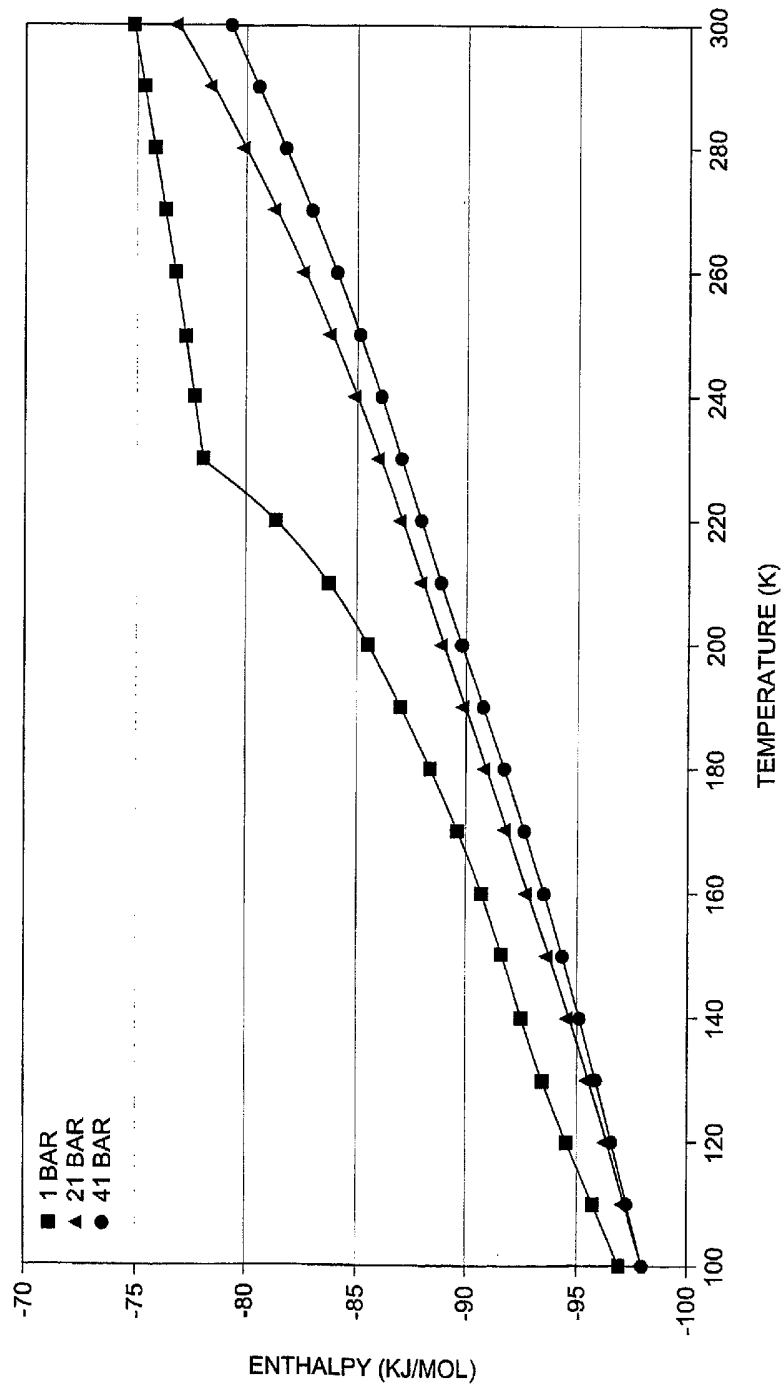
Fig. 1

2/27
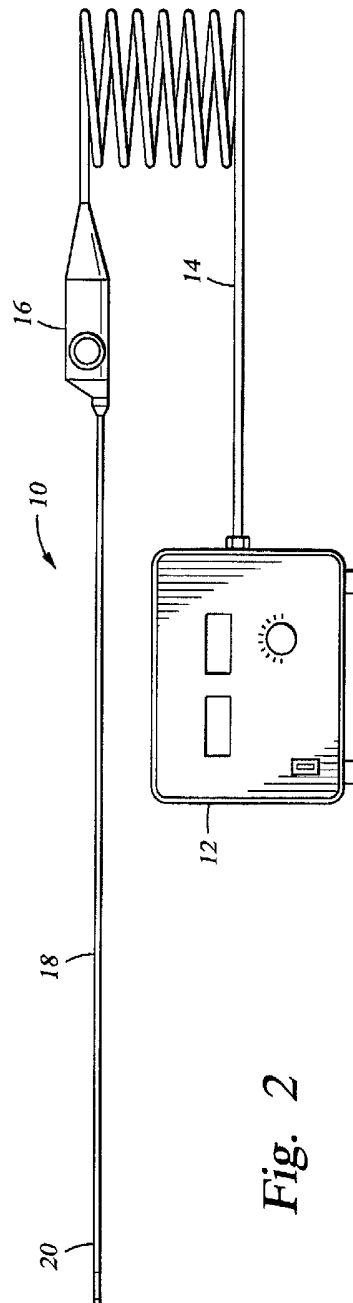
Fig. 2

Fig. 3

3/27

Fig. 5

Fig. 4

4/27
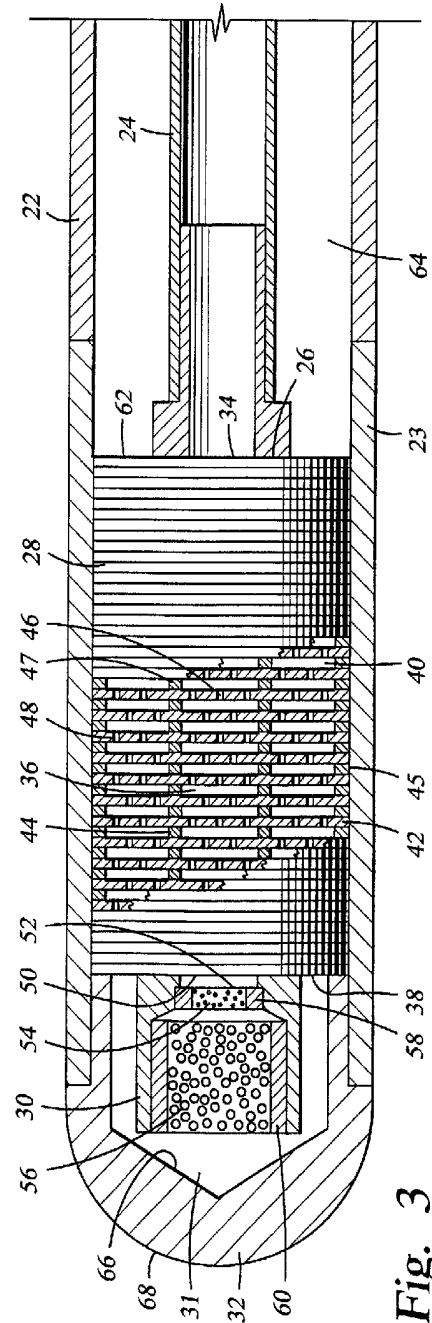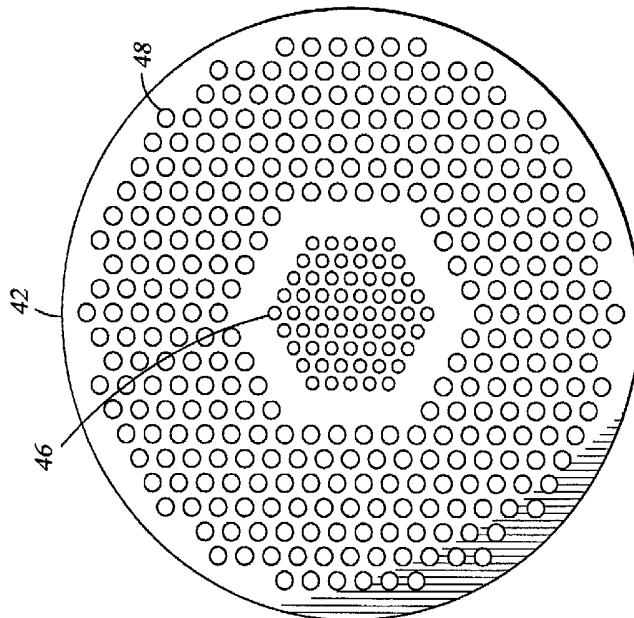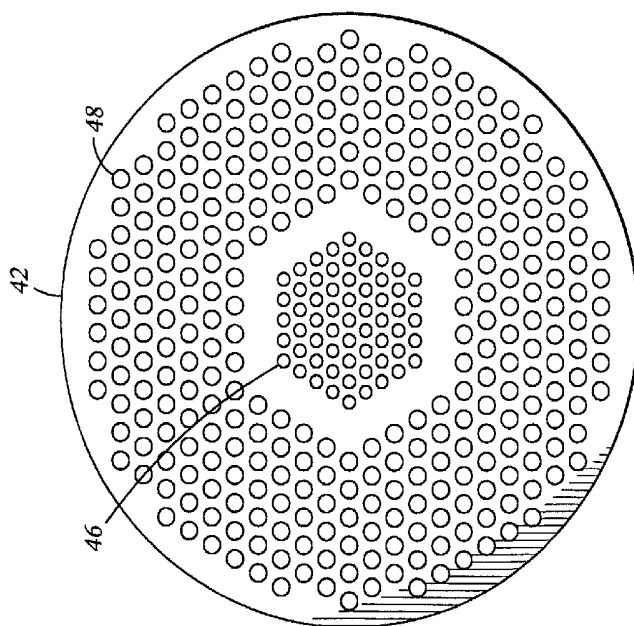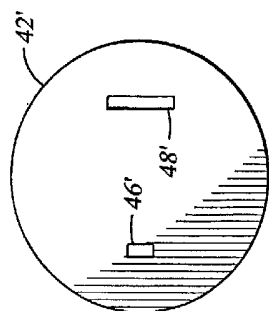
Fig. 9

Fig. 8

Fig. 7

Fig. 6

Fig. 10

Fig. 12

Fig. 11

Fig. 13

Fig. 14

Fig. 15

FIGURE 16

Components:R124; R32; NF3; Kr; Propylene
Compositions (mol fractions): 0.10; 0.10; 0.10; 0.60; 0.10
Low pressure= 1.00000000000000 bar
High pressure= 21.0000000000000 bar

Temp (K)	LowH (kJ/mol)	HighH (kJ/mol)	deltaH (kJ/mol)	deltaH* ()
150	-13.1194	-18.4616	5.3422	0.4454
155	-12.7058	-18.1661	5.4603	0.4544
160	-12.3244	-17.8461	5.5218	0.4604
165	-11.9461	-17.5319	5.5858	0.4657
170	-11.5471	-17.2133	5.6662	0.4724
175	-11.105	-16.8903	5.7852	0.4824
180	-10.6972	-16.5627	5.9655	0.4974
185	-10.0006	-16.2304	6.2298	0.5194
190	-9.2955	-15.8828	6.5873	0.5501
195	-8.47379	-15.0279	6.5541	0.5465
200	-7.54834	-13.624	6.0757	0.5066
205	-6.54721	-12.6403	6.0931	0.5080
210	-5.47959	-11.8566	6.3870	0.5325
215	-4.30547	-11.2067	6.9012	0.5754
220	-2.95841	-10.6094	7.6510	0.6379
225	-2.78037	-10.0444	7.2640	0.6057
230	-2.60126	-9.49189	6.8906	0.5745
235	-2.42148	-8.93797	6.5165	0.5433
240	-2.23983	-8.3721	6.1323	0.5113
245	-2.05628	-7.78595	5.7297	0.4777
250	-1.87262	-7.17281	5.3002	0.4419
255	-1.68776	-6.52717	4.8394	0.4035
260	-1.50168	-5.84457	4.3429	0.3621
265	-1.31435	-5.12126	3.8069	0.3174
270	-1.12578	-4.35361	3.2278	0.2691
275	-0.93695	-3.53721	2.6013	0.2169
280	-0.74486	-2.6657	1.9208	0.1602
285	-0.55251	-1.72946	1.1770	0.0981
290	-0.36889	-1.29838	0.9395	0.0783
295	-0.164	-1.06418	0.9002	0.0751
300	0.03215	-0.83197	0.8641	0.0720

TABLE A

Molar Composition Error +/- 0.10

Gibbs	1.92084
x	14.1080
y	11.9936
nh	11.99357

TABLE B

Components: R124; R32; NF3; Kr
Compositions (mol fractions): 0.10; 0.20; 0.10; 0.60
Low pressure= 1.0000000000000 bar
High pressure= 21.0000000000000 bar

Temp (K)	LowH (kJ/mol)	HighH (kJ/mol)	deltaH (kJ/mol)	deltaH* ( )
150	-12.9946	-18.1647	5.1702	0.4334
155	-12.6208	-17.8633	5.2425	0.4395
160	-12.2699	-17.5574	5.2876	0.4432
165	-11.9152	-17.2473	5.3321	0.4470
170	-11.5337	-16.9329	5.3992	0.4526
175	-11.1022	-16.6141	5.5119	0.4620
180	-10.5963	-16.2907	5.6944	0.4774
185	-9.98547	-15.9623	5.9768	0.5010
190	-9.24764	-15.6285	6.3809	0.5349
195	-8.37088	-14.5635	6.1926	0.5191
200	-7.37719	-13.2504	5.8732	0.4923
205	-6.31779	-12.235	6.0172	0.5044
210	-5.21813	-11.6123	6.3942	0.5360
215	-4.03412	-10.9897	6.9656	0.5831
220	-2.80933	-10.4181	7.6088	0.6378
225	-2.63924	-9.86871	7.2295	0.6060
230	-2.46913	-9.32229	6.8532	0.5745
235	-2.2969	-8.76524	6.4683	0.5422
240	-2.12389	-8.1872	6.0633	0.5083
245	-1.94938	-7.59021	5.6308	0.4720
250	-1.77461	-6.93844	5.1638	0.4329
255	-1.59884	-6.25828	4.6694	0.3906
260	-1.42203	-5.53828	4.1163	0.3451
265	-1.24417	-4.77862	3.5345	0.2963
270	-1.06527	-3.97975	2.9145	0.2443
275	-0.88531	-3.14019	2.2649	0.1890
280	-0.70428	-2.25457	1.5503	0.1300
285	-0.52218	-1.43715	0.9150	0.0767
290	-0.33901	-1.21481	0.8758	0.0734
295	-0.16477	-0.99472	0.8400	0.0704
300	0.03054	-0.77647	0.8070	0.0676

Molar Composition Error +/- 0.10

Gibbs	1.55029
x	14.1850
y	11.9293
nh	11.9928

FIGURE 17

Components: R22, R23, R142B, Kr				
Compositions (mol fractions): 0.076; 0.076; 0.20, 0.65				
Low pressure= 1.000000000000 bar				
High pressure= 21.00000000000000 bar				
Temp (K)	LowH (kJ/mol)	HighH (kJ/mol)	deltaH (kJ/mol)	deltaH* ()
150	-14.2194	-19.0992	4.8798	0.3808
155	-13.8298	-18.8068	4.9771	0.3884
160	-13.4414	-18.5094	5.0680	0.3955
165	-13.04	-18.2071	5.1671	0.4032
170	-12.6189	-17.8999	5.2810	0.4121
175	-12.1772	-17.5881	5.4109	0.4223
180	-11.7156	-17.2716	5.5559	0.4336
185	-11.2328	-16.9502	5.7174	0.4462
190	-10.7226	-16.6239	5.9013	0.4605
195	-10.1733	-15.46	5.2867	0.4126
200	-9.56916	-14.317	4.7478	0.3705
205	-8.8906	-13.4776	4.5870	0.3580
210	-8.11262	-12.7904	4.6778	0.3650
215	-7.20082	-12.1872	4.9864	0.3891
220	-6.10412	-11.6327	5.5285	0.4314
225	-4.74334	-11.1063	6.3630	0.4966
230	-2.99156	-10.5954	7.6039	0.5934
235	-2.38939	-10.0912	7.7018	0.6010
240	-2.21059	-9.58721	7.3766	0.5757
245	-2.03058	-9.07804	7.0475	0.5500
250	-1.84897	-8.55887	6.7099	0.5236
255	-1.66597	-8.02502	6.3591	0.4963
260	-1.48252	-7.47164	5.9891	0.4674
265	-1.29792	-6.89355	5.5956	0.4367
270	-1.11214	-6.28504	5.1729	0.4037
275	-0.92524	-5.63959	4.7144	0.3679
280	-0.73721	-4.9497	4.2125	0.3287
285	-0.54809	-4.20638	3.6583	0.2855
290	-0.36787	-3.39876	3.0409	0.2373
295	-0.1666	-2.51339	2.3468	0.1831
300	0.02571	-1.53327	1.5590	0.1217

Molar Composition Error +/- 0.10	
Gibbs	4.21249
x	12.8142
y	13.1073
hh	12.8142

TABLE C

FIGURE 18

Components: R22, R23, R142B, Kr
Compositions (mol fractions): 0.10; 0.10; 0.15; 0.65
Low pressure= 1.0000000000000 bar
High pressure= 21.000000000000 bar

Temp (K)	LowH (kJ/mol)	HighH (kJ/mol)	deltaH (kJ/mol)	deltaH* ()
150	-13.7135	-18.5658	4.8523	0.3837
155	-13.3063	-18.2746	4.9683	0.3929
160	-12.8895	-17.9789	5.0894	0.4025
165	-12.4473	-17.6786	5.2313	0.4137
170	-11.9737	-17.3739	5.4003	0.4271
175	-11.4695	-17.0648	5.5953	0.4426
180	-10.9396	-16.7511	5.8116	0.4596
185	-10.3853	-16.4328	6.0476	0.4783
190	-9.80097	-16.1096	6.3086	0.4989
195	-9.17417	-14.9785	5.8043	0.4590
200	-8.48875	-13.816	5.3272	0.4213
205	-7.72678	-12.9611	5.2344	0.4140
210	-6.86664	-12.2578	5.3912	0.4264
215	-5.87638	-11.6361	5.7598	0.4555
220	-4.7038	-11.0601	6.3563	0.5027
225	-3.26381	-10.5092	7.2454	0.5730
230	-2.47067	-9.97082	7.5002	0.5931
235	-2.29931	-9.43656	7.1373	0.5644
240	-2.12682	-8.90031	6.7735	0.5357
245	-1.95292	-8.3571	6.4042	0.5065
250	-1.77836	-7.80237	6.0240	0.4764
255	-1.60204	-7.23162	5.6296	0.4452
260	-1.42535	-6.64014	5.2148	0.4124
265	-1.2476	-6.02284	4.7752	0.3776
270	-1.06879	-5.37409	4.3053	0.3405
275	-0.88891	-4.68746	3.7986	0.3004
280	-0.70798	-3.95541	3.2474	0.2568
285	-0.52602	-3.16882	2.6428	0.2090
290	-0.34304	-2.3165	1.9736	0.1561
295	-0.15904	-1.38433	1.2253	0.0969
300	0.02594	-0.88885	0.9148	0.0723

Molar Composition Error +/- 0.10

Gibbs	3.24743
x	13.1917
y	12.6447
nh	12.64474

TABLE D

FIGURE 19

Components: R22, R23, R142B, Kr, NF3
Compositions (mol fractions): 0.07; 0.07; 0.20, 0.55, 0.11
Low pressure= 1.000000000000000 bar
High pressure= 21.000000000000000 bar

Temp (K)	LowH (kJ/mol)	HighH (kJ/mol)	deltaH (kJ/mol)	deltaH* ()
150	-14.7223	-19.757	5.0347	0.3766
155	-14.226	-19.446	5.2200	0.3894
160	-13.7659	-19.1299	5.3641	0.4002
165	-13.3153	-18.8089	5.4936	0.4099
170	-12.8606	-18.483	5.6224	0.4195
175	-12.3961	-18.1523	5.7563	0.4295
180	-11.9193	-17.817	5.8976	0.4400
185	-11.4266	-17.4768	6.0502	0.4514
190	-10.9099	-17.1317	6.2218	0.4642
195	-10.3562	-16.7814	6.4252	0.4794
200	-9.74923	-15.3998	5.6506	0.4216
205	-9.06869	-14.2976	5.2289	0.3901
210	-8.28911	-13.4345	5.1454	0.3839
215	-7.37544	-12.7065	5.3311	0.3977
220	-6.27596	-12.0594	5.7834	0.4315
225	-4.91111	-11.4618	6.5506	0.4887
230	-3.15377	-10.8943	7.7406	0.5775
235	-2.57666	-10.3442	7.7675	0.5795
240	-2.38455	-9.80196	7.4174	0.5534
245	-2.19101	-9.26038	7.0694	0.5274
250	-1.9956	-8.71318	6.7176	0.5012
255	-1.79909	-8.15462	6.3555	0.4742
260	-1.60082	-7.57907	5.9783	0.4460
265	-1.4017	-6.98074	5.5790	0.4162
270	-1.20118	-6.35345	5.1623	0.3844
275	-0.99928	-5.69032	4.6910	0.3500
280	-0.79601	-4.98353	4.1875	0.3124
285	-0.5914	-4.22388	3.6325	0.2710
290	-0.38547	-3.40032	3.0149	0.2249
295	-0.17824	-2.49922	2.3210	0.1732
300	0.03027	-1.50349	1.5338	0.1144

Molar Composition Error +/- 0.10

Gibbs	4.18762
x	13.4035
y	13.5211
nh	13.40352

TABLE E

FIGURE 20

Components: R22, R23, N2, Kr, isobutane
Compositions (mol fractions): 0.10; 0.10; 0.10; 0.60; 0.10
Low pressure= 1.000000000000000 bar
High pressure= 21.000000000000000 bar

Temp (K)	LowH (kJ/mol)	HighH (kJ/mol)	deltaH (kJ/mol)	deltaH* ()
150	-11.8985	-16.8519	4.9534	0.4549
155	-11.5004	-16.5573	5.0569	0.4644
160	-11.0788	-16.2085	5.1298	0.4711
165	-10.6222	-15.751	5.1288	0.4710
170	-10.1287	-15.2447	5.1160	0.4698
175	-9.60268	-14.6657	5.0631	0.4650
180	-9.04823	-13.9987	4.9505	0.4546
185	-8.46173	-13.2643	4.8026	0.4411
190	-7.83064	-12.5262	4.6955	0.4312
195	-7.13769	-11.8385	4.7008	0.4317
200	-6.36673	-11.2135	4.8468	0.4451
205	-5.50348	-10.6393	5.1358	0.4717
210	-4.52771	-10.0993	5.5716	0.5117
215	-3.39972	-9.57988	6.1802	0.5676
220	-2.65927	-9.07103	6.4118	0.5888
225	-2.49846	-8.6656	6.0671	0.5572
230	-2.33658	-8.05837	5.7218	0.5255
235	-2.17344	-7.54532	5.3719	0.4933
240	-2.0102	-7.02287	5.0127	0.4603
245	-1.84599	-6.48768	4.6417	0.4263
250	-1.68081	-5.93636	4.2556	0.3908
255	-1.5146	-5.36646	3.8509	0.3537
260	-1.34735	-4.77147	3.4241	0.3145
265	-1.17904	-4.1606	2.9716	0.2729
270	-1.00966	-3.49873	2.4891	0.2286
275	-0.83918	-2.81109	1.9717	0.1811
280	-0.6676	-2.08085	1.4133	0.1298
285	-0.4949	-1.32639	0.8315	0.0764
290	-0.32107	-1.11912	0.7981	0.0733
295	-0.14611	-0.91343	0.7673	0.0705
300	0.03	-0.70901	0.7390	0.0679

Molar Composition Error +/- 0.10

Gibbs	1.41325
x	13.3532
y	10.8888
nh	10.88883

TABLE F

FIGURE 21

Components: R22, R23, R142B, C1
Compositions (mol fractions): 0.085, 0.085, 0.19, 0.64
Low pressure= 1.000000000000 bar
High pressure= 21.000000000000 bar

Temp (K)	LowH (kJ/mol)	HighH (kJ/mol)	deltaH (kJ/mol)	deltaH* ()
150	-15.5479	-19.7834	4.2354	0.3174
155	-15.1772	-19.4327	4.2555	0.3189
160	-14.7833	-19.0785	4.2952	0.3219
165	-14.3597	-18.7209	4.3612	0.3289
170	-13.9042	-18.3599	4.4556	0.3339
175	-13.4186	-17.9954	4.5768	0.3430
180	-12.9063	-16.8948	3.9885	0.2989
185	-12.3665	-15.7975	3.4310	0.2571
190	-11.7969	-15.0348	3.2379	0.2427
195	-11.1853	-14.4143	3.2290	0.2420
200	-10.5164	-13.865	3.3486	0.2510
205	-9.77104	-13.3538	3.5828	0.2685
210	-8.92511	-12.8626	3.9375	0.2951
215	-7.94507	-12.3807	4.4356	0.3324
220	-6.78093	-11.901	5.1201	0.3837
225	-5.35132	-11.4188	6.0675	0.4547
230	-3.52892	-10.9304	7.4015	0.5547
235	-3.1502	-10.4329	7.2827	0.5458
240	-2.92926	-9.92347	6.9942	0.5242
245	-2.70637	-9.39943	6.6931	0.5016
250	-2.48245	-8.85779	6.3753	0.4778
255	-2.25693	-8.29522	6.0383	0.4526
260	-2.02981	-7.70789	5.6781	0.4256
265	-1.80107	-7.09141	5.2903	0.3965
270	-1.57072	-6.44068	4.8700	0.3650
275	-1.33874	-5.74968	4.4109	0.3306
280	-1.10513	-5.01121	3.9061	0.2928
285	-0.8699	-4.21658	3.3467	0.2508
290	-0.63304	-3.35503	2.7220	0.2040
295	-0.39455	-2.41314	2.0186	0.1513
300	2.256288	-2.64541	4.9017	0.3674

Molar Composition Error +/- 0.10

Gibbs	3.90508
x	13.3427
y	13.9772
nh	13.34269

TABLE G

FIGURE 22

Components: R32, R23, R124,Kr				
Compositions (mol fractions): 0.075; 0.075; 0.20; 0.65				
Low pressure= 1.000000000000000 bar				
High pressure= 21.000000000000000 bar				
Temp (K)	LowH (kJ/mol)	HighH (kJ/mol)	deltaH (kJ/mol)	deltaH* ()
150	-14.757	-19.555	4.7980	0.3639
155	-14.3453	-19.2247	4.8993	0.3814
160	-13.9315	-18.9287	4.9972	0.3686
165	-13.4992	-18.6074	5.1082	0.3768
170	-13.0392	-18.2807	5.2415	0.3866
175	-12.5477	-17.9489	5.4012	0.3984
180	-12.0236	-17.6119	5.5883	0.4122
185	-11.4656	-17.2696	5.8040	0.4281
190	-10.8703	-16.9218	6.0515	0.4464
195	-10.2322	-15.9191	5.6869	0.4195
200	-9.54152	-14.7186	6.1771	0.3819
205	-8.78189	-13.8337	5.0518	0.3726
210	-7.92464	-13.1059	5.1812	0.3822
215	-6.92364	-12.4634	5.5397	0.4086
220	-5.708	-11.8696	6.1606	0.4544
225	-4.17042	-11.2999	7.1295	0.6259
230	-2.76992	-10.7435	7.9735	0.5881
235	-2.57827	-10.19	7.6117	0.5614
240	-2.38571	-9.63273	7.2470	0.5345
245	-2.19084	-9.06635	6.8755	0.5071
250	-1.99536	-8.48618	6.4908	0.4788
255	-1.79793	-7.88777	6.0898	0.4492
260	-1.59985	-7.26644	5.6666	0.4180
265	-1.40046	-6.61694	5.2165	0.3848
270	-1.19972	-5.93313	4.7334	0.3491
275	-0.99766	-5.20755	4.2099	0.3105
280	-0.79424	-4.43107	3.6368	0.2683
285	-0.58951	-3.5923	3.0028	0.2215
290	-0.38345	-2.67699	2.2935	0.1692
295	-0.17607	-1.66707	1.4910	0.1100
300	0.03261	-0.93195	0.9646	0.0711

Molar Composition Error +/- 0.10

Gibbs	3.63683
x	13.6219
y	13.5573
nh	13.55732

TABLE H

FIGURE 23

FIGURE 24

Components: N2; CH4; C2H4; C3H4; Isobutane
Compositions (mol fractions): 0.23; 0.30; 0.19; 0.05; 0.23
Low pressure= 1.000000000000000 bar
High pressure= 21.0000000000000 bar

Temp (K)	LowH (kJ/mol)	HighH (kJ/mol)	deltaH (kJ/mol)	deltaH* ()
120	-24.9804	-27.1677	2.1873	0.1465
125	-24.3717	-26.8281	2.4564	0.1634
130	-23.847	-26.4851	2.6381	0.1755
135	-23.3826	-26.1383	2.7558	0.1833
140	-22.9494	-25.8704	2.7210	0.1810
145	-22.527	-25.0962	2.5692	0.1709
150	-22.0969	-24.5498	2.4529	0.1632
155	-21.6484	-24.0176	2.3692	0.1576
160	-21.1696	-23.4944	2.3247	0.1547
165	-20.6537	-22.9793	2.3256	0.1547
170	-20.0996	-22.474	2.3745	0.1580
175	-19.5137	-21.98	2.4663	0.1641
180	-18.9085	-21.4971	2.5886	0.1722
185	-18.2968	-21.0237	2.7269	0.1814
190	-17.6849	-20.5571	2.8722	0.1911
195	-17.0694	-20.0942	3.0249	0.2012
200	-16.4382	-19.6318	3.1936	0.2125
205	-15.7739	-19.1669	3.3930	0.2257
210	-15.0551	-18.6971	3.6420	0.2423
215	-14.2556	-18.2202	3.9646	0.2638
220	-13.3422	-17.7347	4.3926	0.2922
225	-12.2699	-17.2393	4.9694	0.3306
230	-10.9745	-16.733	5.7585	0.3831
235	-9.35925	-16.2149	6.8556	0.4561
240	-8.21757	-15.6842	7.4665	0.4968
245	-7.99298	-15.1397	7.1567	0.4761
250	-7.74665	-14.58	6.8334	0.4546
255	-7.50827	-14.003	6.4948	0.4321
260	-7.26777	-13.406	6.1383	0.4084
265	-7.02511	-12.7855	5.7604	0.3832
270	-6.78022	-12.1369	5.3567	0.3564

Molar Composition Error: for X>0.50 +/- 0.10; for X between 0.20-0.49 +/- 0.75; for X<0.20 +/- 0.05
X= molar ratio of fluid in a mixture

TABLE I

Gibbs	6.83336
x	15.0307
y	18.2002
nh	15.03074

Components: Ar; Kr; R14; R23; R22; R124; Isopentane
Compositions (mol fractions): 0.43; 0.13; 0.11; 0.14; 0.02; 0.04; 0.13
Low pressure= 1.000000000000 bar
High pressure= 21.00000000000 bar

Temp (K)	LowH (kJ/mol)	HighH (kJ/mol)	deltaH (kJ/mol)	deltaH* ()
120	-120.237	-124.009	3.7724	0.2486
125	-119.74	-123.668	3.9283	0.2589
130	-119.275	-123.322	4.0469	0.2667
135	-118.819	-122.972	4.1537	0.2737
140	-118.682	-122.619	3.9367	0.2594
145	-118.183	-122.261	4.0778	0.2687
150	-117.698	-121.687	3.9894	0.2629
155	-117.207	-120.847	3.6398	0.2399
160	-116.689	-120.737	3.4477	0.2272
165	-116.132	-119.497	3.3654	0.2218
170	-115.541	-118.899	3.3583	0.2213
175	-114.94	-118.329	3.3889	0.2233
180	-114.355	-117.778	3.4232	0.2256
185	-113.803	-117.242	3.4385	0.2266
190	-113.288	-116.718	3.4294	0.2260
195	-112.801	-116.203	3.4018	0.2242
200	-112.328	-115.694	3.3658	0.2218
205	-111.858	-115.189	3.3315	0.2196
210	-111.377	-114.686	3.3087	0.2181
215	-110.876	-114.183	3.3073	0.2180
220	-110.343	-113.681	3.3379	0.2200
225	-109.767	-113.18	3.4130	0.2249
230	-109.135	-112.683	3.5481	0.2338
235	-108.427	-112.189	3.7629	0.2480
240	-107.618	-111.701	4.0833	0.2691
245	-106.675	-111.219	4.5438	0.2995
250	-105.55	-110.74	5.1907	0.3421
255	-104.608	-110.265	5.6570	0.3728
260	-104.392	-109.791	5.3992	0.3558
265	-104.173	-109.315	5.1420	0.3389
270	-103.953	-108.835	4.8827	0.3218

Molar Composition Error: for X>0.50 +/- 0.10; for X between 0.20-0.49 +/- 0.75; for X<0.20 +/- 0.05
X= molar ratio of fluid in a mixture

TABLE J

Gibbs	5.19065
x	15.1737
y	16.2840
nh	15.17371

FIGURE 25

Components: Ar; Kr; R14; R23; R22; R124, 1-Pentene				
Compositions (mol fractions): 0.43; 0.13; 0.11; 0.14; 0.02; 0.04; 0.13				
Low pressure= 1.000000000000 bar				
High pressure= 21.000000000000 bar				
Temp (K)	LowH (kJ/mol)	HighH (kJ/mol)	deltaH (kJ/mol)	deltaH* ()
120	-120.556	-124.176	3.6197	0.2364
125	-120.019	-123.807	3.7880	0.2474
130	-119.495	-123.437	3.9417	0.2576
135	-119.198	-123.065	3.8674	0.2526
140	-118.645	-122.693	4.0474	0.2644
145	-118.128	-122.319	4.1905	0.2737
150	-117.628	-121.669	4.0410	0.2639
155	-117.125	-120.818	3.6933	0.2412
160	-116.597	-120.097	3.4999	0.2286
165	-116.031	-119.446	3.4150	0.2231
170	-115.433	-118.839	3.4051	0.2224
175	-114.826	-118.26	3.4331	0.2242
180	-114.237	-117.702	3.4647	0.2263
185	-113.684	-117.161	3.4770	0.2271
190	-113.169	-116.534	3.4644	0.2263
195	-112.685	-116.117	3.4325	0.2242
200	-112.218	-115.609	3.3908	0.2215
205	-111.787	-115.106	3.3489	0.2187
210	-111.289	-114.605	3.3159	0.2166
215	-110.805	-114.106	3.3006	0.2156
220	-110.296	-113.609	3.3127	0.2164
225	-109.751	-113.114	3.3634	0.2197
230	-109.157	-112.623	3.4667	0.2264
235	-108.497	-112.138	3.6408	0.2378
240	-107.749	-111.659	3.9095	0.2553
245	-106.882	-111.186	4.3039	0.2811
250	-105.853	-110.719	4.8655	0.3178
255	-104.604	-110.255	5.6514	0.3691
260	-104.351	-109.793	5.4417	0.3554
265	-104.137	-109.331	5.1939	0.3392
270	-103.921	-108.865	4.9443	0.3229

COMMENT: Isobutane may replace some of the R124
Nitrogen up to 21.5% may be added to replace an equal percentage of Argon

Molar Composition Error: for X>0.50 +/- 0.10; for X between 0.20-0.49 +/- 0.75; for X<0.20 +/- 0.05
X= molar ratio of fluid in a mixture

TABLE K

Gibbs	4.86551
x	15.3106
y	16.6362
nh	15.31056

FIGURE 26

Components: Ar; Kr; R14; R23; R124
Compositions (mol fractions): 0.35; 0.20; 0.05; 0.10; 0.30
Low pressure= 1.000000000000 bar
High pressure= 21.000000000000 bar

Temp (K)	LowH (kJ/mol)	HighH (kJ/mol)	deltaH (kJ/mol)	deltaH* ()
120	-66.5391	-69.7716	3.2325	0.2103
125	-66.0343	-69.4494	3.4151	0.2222
130	-65.5588	-69.12	3.5612	0.2317
135	-65.1903	-68.7832	3.5929	0.2338
140	-64.8243	-68.4391	3.6148	0.2352
145	-64.3802	-68.0878	3.7076	0.2412
150	-63.9652	-67.7297	3.7745	0.2456
155	-63.5322	-67.1359	3.6047	0.2345
160	-63.096	-66.3876	3.2917	0.2142
165	-62.6384	-65.7178	3.0794	0.2004
170	-62.158	-65.0973	2.9393	0.1912
175	-61.6561	-64.5106	2.8545	0.1867
180	-61.139	-63.9496	2.8105	0.1829
185	-60.612	-63.4092	2.7972	0.1820
190	-60.0744	-62.8857	2.8113	0.1829
195	-59.5173	-62.3756	2.8584	0.1860
200	-58.9233	-61.8756	2.9523	0.1921
205	-58.2676	-61.3821	3.1145	0.2026
210	-57.5167	-60.8921	3.3755	0.2196
215	-56.6258	-60.4028	3.7770	0.2457
220	-55.5323	-59.9116	4.3793	0.2849
225	-54.1429	-59.4165	5.2735	0.3431
230	-52.3088	-58.9154	6.6067	0.4298
235	-49.7786	-58.4066	8.6280	0.5614
240	-49.5454	-57.8879	8.3425	0.5428
245	-49.3112	-57.3571	8.0459	0.5235
250	-49.0751	-56.8115	7.7364	0.5033
255	-48.8369	-56.2476	7.4106	0.4921
260	-48.5968	-55.6613	7.0645	0.4596
265	-48.3547	-55.048	6.6933	0.4365
270	-48.1105	-54.4017	6.2912	0.4093

COMMENT: Nitrogen up to 17.5% may be added to replace an equal percentage of Argon
Isobutane maybe used to replace some of the R124

Molar Composition Error: for X>0.50 +/- 0.10; for X between 0.20-0.49 +/- 0.75; for X<0.20 +/- 0.05
X= molar ratio of fluid in a mixture

TABLE L

Gibbs	7.73641
x	15.3699
y	18.4236
nh	15.36994

FIGURE 27

Components: Ar; C2H4; Isopentane
Compositions (mol fractions): 0.60; 0.25; 0.15
Low pressure= 1.0000000000000 bar
High pressure= 21.000000000000 bar

Temp (K)	LowH (kJ/mol)	HighH (kJ/mol)	deltaH (kJ/mol)	deltaH* ()
120	-15.3092	-19.9572	4.6480	0.3303
125	-15.1214	-19.6237	4.5023	0.3199
130	-14.9308	-19.2876	4.3568	0.3096
135	-15.4002	-18.9491	3.5489	0.2522
140	-15.0219	-18.6087	3.5868	0.2549
145	-14.5957	-17.3819	2.7862	0.1980
150	-14.1017	-16.5616	2.4599	0.1748
155	-13.5229	-15.9355	2.4126	0.1714
160	-12.8563	-15.4078	2.5515	0.1813
165	-12.1304	-14.9353	2.8049	0.1993
170	-11.4159	-14.4945	3.0786	0.2188
175	-10.7857	-14.0712	3.2866	0.2335
180	-10.261	-13.6558	3.3949	0.2412
185	-9.82152	-13.2416	3.4201	0.2430
190	-9.43831	-12.8234	3.3851	0.2405
195	-9.08758	-12.3977	3.3101	0.2352
200	-8.75162	-11.9618	3.2102	0.2281
205	-8.41668	-11.5145	3.0978	0.2201
210	-8.07081	-11.0558	2.9850	0.2121
215	-7.70253	-10.8874	2.8848	0.2050
220	-7.29965	-10.1127	2.8131	0.1999
225	-6.84842	-9.63664	2.7882	0.1981
230	-6.3325	-9.16467	2.8322	0.2013
235	-5.73179	-8.70168	2.9699	0.2110
240	-5.02084	-8.25083	3.2300	0.2295
245	-4.16632	-7.81303	3.6467	0.2591
250	-3.12314	-7.38711	4.2640	0.3030
255	-1.85106	-6.97044	5.1194	0.3638
260	-1.64803	-6.56958	4.9116	0.3490
265	-1.44317	-6.15078	4.7076	0.3345
270	-1.23644	-5.74025	4.5038	0.3200

Molar Composition Error: for X>0.50 +/- 0.10; for X between 0.20-0.49 +/- 0.75; for X<0.20 +/- 0.05
X= molar ratio of fluid in a mixture

TABLE M

Gibbs	4.26397
x	14.2169
y	14.0727
nh	14.07274

FIGURE 28

Components: AR; C1; C2; R23; R22; R142B
Compositions (mol fractions) 0.50; 0.15; 0.15; 0.075; 0.025; .10
Low pressure= 1.000000000000000 bar
High pressure= 21.000000000000000 bar

Temp (K)	LowH (kJ/mol)	HighH (kJ/mol)	deltaH (kJ/mol)	deltaH* ()
100	-15.7278	-18.6507	2.9228	0.2049
105	-14.6267	-18.3688	3.7421	0.2624
110	-14.1284	-18.0831	3.9547	0.2773
115	-13.8726	-17.7934	3.9209	0.2749
120	-13.7766	-17.4999	3.7233	0.2610
125	-13.4564	-17.2028	3.7464	0.2627
130	-13.1539	-16.9023	3.7484	0.2628
135	-12.8463	-16.5987	3.7524	0.2631
140	-12.5159	-16.2922	3.7763	0.2648
145	-12.1458	-15.5947	3.4489	0.2418
150	-11.7178	-14.584	2.8662	0.2009
155	-11.2155	-13.8621	2.6466	0.1856
160	-10.6292	-13.2847	2.6555	0.1862
165	-9.97023	-12.7897	2.8194	0.1977
170	-9.27946	-12.3435	3.0640	0.2148
175	-8.61739	-11.9258	3.3084	0.2319
180	-8.01893	-11.5228	3.5039	0.2457
185	-7.47822	-11.1248	3.6466	0.2557
190	-6.96747	-10.7245	3.7570	0.2634
195	-6.45549	-10.3163	3.8608	0.2707
200	-5.91227	-9.89587	3.9836	0.2793
205	-5.3063	-9.46043	4.1541	0.2912
210	-4.60026	-9.00851	4.4083	0.3091
215	-3.74615	-8.54036	4.7942	0.3361
220	-2.84917	-8.05806	5.2089	0.3652
225	-2.67997	-7.56522	4.8853	0.3425
230	-2.5097	-7.06622	4.5565	0.3195
235	-2.33832	-6.56481	4.2265	0.2963
240	-2.16583	-6.06292	3.8971	0.2732
245	-1.99221	-5.55997	3.5678	0.2501
250	-1.81745	-5.05302	3.2366	0.2268
255	-1.64153	-4.53725	2.8957	0.2030
260	-1.46445	-4.00652	2.5421	0.1782
265	-1.2862	-3.4538	2.1676	0.1520
270	-1.10678	-2.87123	1.7645	0.1237
275	-0.92618	-2.2501	1.3239	0.0928
280	-0.74441	-1.59057	0.8362	0.0586

Gibbs	2.54207
x	14.6441
y	14.2634
nh	14.26339

TABLE N

FIGURE 29

Components: AR; C1; C2; R142B
Compositions (mol fractions) 0.50; 0.15; 0.20; 0.15
Low pressure= 1.00000000000000 bar
High pressure= 21.0000000000000 bar

Temp (K)	LowH (kJ/mol)	HighH (kJ/mol)	deltaH (kJ/mol)	deltaH* ()
100	-16.0767	-19.1129	3.0361	0.2145
105	-14.9267	-18.8351	3.9084	0.2761
110	-14.3206	-18.5533	4.2326	0.2990
115	-14.016	-18.2671	4.2511	0.3003
120	-13.785	-17.9767	4.1917	0.2961
125	-13.7884	-17.6822	3.8938	0.2750
130	-13.4742	-17.3839	3.9097	0.2762
135	-13.1579	-17.082	3.9241	0.2772
140	-12.8183	-16.7768	3.9584	0.2796
145	-12.44	-16.067	3.6270	0.2562
150	-12.0085	-15.0329	3.0244	0.2136
155	-11.5147	-14.2901	2.7764	0.1960
160	-10.9632	-13.6955	2.7323	0.1930
165	-10.3803	-13.1867	2.8064	0.1982
170	-9.81017	-12.73	2.9199	0.2063
175	-9.28701	-12.305	3.0180	0.2132
180	-8.81726	-11.8982	3.0810	0.2176
185	-8.39469	-11.5003	3.1156	0.2201
190	-7.96443	-11.1045	3.1401	0.2218
195	-7.53017	-10.7062	3.1761	0.2243
200	-7.06501	-10.3023	3.2473	0.2294
205	-6.50967	-9.89071	3.3810	0.2388
210	-5.86961	-9.47099	3.6115	0.2551
215	-5.06028	-9.04363	3.9834	0.2814
220	-4.06158	-8.60998	4.5584	0.3220
225	-2.7839	-8.17179	5.3879	0.3806
230	-2.60749	-7.73052	5.1230	0.3619
235	-2.42986	-7.28673	4.8569	0.3431
240	-2.25097	-6.83966	4.5887	0.3241
245	-2.07081	-6.38708	4.3163	0.3049
250	-1.88938	-5.92549	4.0361	0.2851
255	-1.70667	-5.45028	3.7436	0.2644
260	-1.52269	-4.95603	3.4333	0.2425
265	-1.33742	-4.43659	3.0992	0.2189
270	-1.15087	-3.88508	2.7342	0.1931
275	-0.96305	-3.29377	2.3307	0.1646
280	-0.77394	-2.65383	1.8799	0.1328

Gibbs	3.43334
x	14.1668
y	14.5540
nh	14.15684

TABLE O

FIGURE 30

Components: AR; C1; C2;C3; R142B
Compositions (mol fractions) 0.50; 0.10; 0.20; 0.05; 0.15
Low pressure= 1.00000000000000 bar
High pressure= 21.0000000000000 bar

Temp (K)	LowH (kJ/mol)	HighH (kJ/mol)	deltaH (kJ/mol)	deltaH* ()
100	-21.782	-25.3245	3.5426	0.2478
105	-21.079	-25.0429	3.9350	0.2762
110	-20.6596	-24.7573	4.0977	0.2866
115	-20.3296	-24.4674	4.1379	0.2894
120	-20.1345	-24.1732	4.0387	0.2825
125	-20.3072	-23.8746	3.5674	0.2495
130	-19.9943	-23.5718	3.5775	0.2502
135	-19.6816	-23.2649	3.5833	0.2506
140	-19.3506	-22.9543	3.6037	0.2521
145	-18.9869	-22.2668	3.2799	0.2294
150	-18.5774	-21.3137	2.7363	0.1914
155	-18.1134	-20.6163	2.5029	0.1751
160	-17.5907	-20.0487	2.4580	0.1719
165	-17.019	-18.5558	2.5368	0.1774
170	-16.4232	-19.1084	2.6852	0.1878
175	-15.8331	-18.6889	2.8558	0.1998
180	-15.2662	-18.2857	3.0194	0.2112
185	-14.7208	-17.8904	3.1696	0.2217
190	-14.1821	-17.4971	3.3150	0.2319
195	-13.6303	-17.1013	3.4711	0.2428
200	-13.0432	-16.6996	3.6564	0.2557
205	-12.3957	-16.2895	3.8938	0.2724
210	-11.6556	-15.8693	4.2136	0.2947
215	-10.7798	-15.4379	4.6581	0.3258
220	-9.70741	-14.9951	5.2877	0.3698
225	-8.34929	-14.5409	6.1916	0.4331
230	-7.90451	-14.0758	6.1713	0.4317
235	-7.7194	-13.6	5.8806	0.4113
240	-7.53287	-13.1135	5.5806	0.3903
245	-7.34491	-12.6162	8.2703	0.3686
250	-7.16551	-12.1036	4.9481	0.3461
255	-6.96467	-11.5757	4.6110	0.3225
260	-6.77236	-11.0277	4.2564	0.2976
265	-6.5786	-10.4549	3.8763	0.2711
270	-6.38339	-9.85116	3.4578	0.2426
275	-6.18672	-9.20963	3.0229	0.2114
280	-5.98869	-8.5219	2.5333	0.1772

Gibbs	4.25538
x	14.2968
y	15.0096
mh	14.2968

TABLE P

FIGURE 31

Components: AR; C1; C2;NF3; R142B
Compositions (mol fractions) 0.60; 0.10; 0.18; 0.05; 0.17
Low pressure= 1.00000000000000 bar
High pressure= 21.0000000000000 bar

Temp (K)	LowH (kJ/mol)	HighH (kJ/mol)	deltaH (kJ/mol)	deltaH* ()
100	-16.4526	-19.7971	3.3446	0.2338
105	-15.6948	-19.515	3.8202	0.2671
110	-15.2244	-19.2285	4.0041	0.2799
115	-14.9408	-18.9375	3.9967	0.2794
120	-15.0444	-18.6419	3.5975	0.2515
125	-14.6549	-18.3418	3.6870	0.2577
130	-14.2691	-18.0375	3.7683	0.2634
135	-13.8815	-17.7291	3.8476	0.2690
140	-13.4805	-17.4169	3.9363	0.2752
145	-13.057	-16.7731	3.7161	0.2598
150	-12.6995	-15.7929	3.1934	0.2232
155	-12.0996	-15.0713	2.9716	0.2077
160	-11.5605	-14.4778	2.9173	0.2039
165	-11.0013	-13.957	2.9557	0.2066
170	-10.4537	-13.4802	3.0265	0.2116
175	-9.94467	-13.0305	3.0859	0.2157
180	-9.47896	-12.5974	3.1184	0.2180
185	-9.04385	-12.1734	3.1295	0.2188
190	-8.61807	-11.7634	3.1353	0.2192
195	-8.17762	-11.3338	3.1562	0.2206
200	-7.69705	-10.912	3.2149	0.2247
205	-7.14803	-10.4862	3.3382	0.2334
210	-6.49681	-10.0559	3.5591	0.2488
215	-5.70017	-9.62113	3.9210	0.2741
220	-4.6991	-9.18244	4.4833	0.3134
225	-3.40782	-8.74067	5.3329	0.3728
230	-2.68557	-8.29635	5.6108	0.3922
235	-2.50202	-7.84927	5.3473	0.3738
240	-2.31708	-7.39822	5.0812	0.3552
245	-2.13069	-6.94082	4.8101	0.3363
250	-1.94291	-6.47366	4.5308	0.3167
255	-1.75372	-5.99241	4.2387	0.2963
260	-1.56312	-5.49195	3.9288	0.2746
265	-1.37112	-4.96646	3.5953	0.2513
270	-1.17771	-4.40939	3.2317	0.2259
275	-0.98292	-3.81329	2.8304	0.1979
280	-0.78674	-3.16965	2.3829	0.1666

Gibbs	3.92883
x	14.3052
y	14.8894
nh	14.30518

TABLE Q

FIGURE 32

24/27

Fig. 33

Fig. 34

Fig. 35

Fig. 37

Fig. 36