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(54) NATURAL GAS LIQUEFACTION PROCESS FOR LNG

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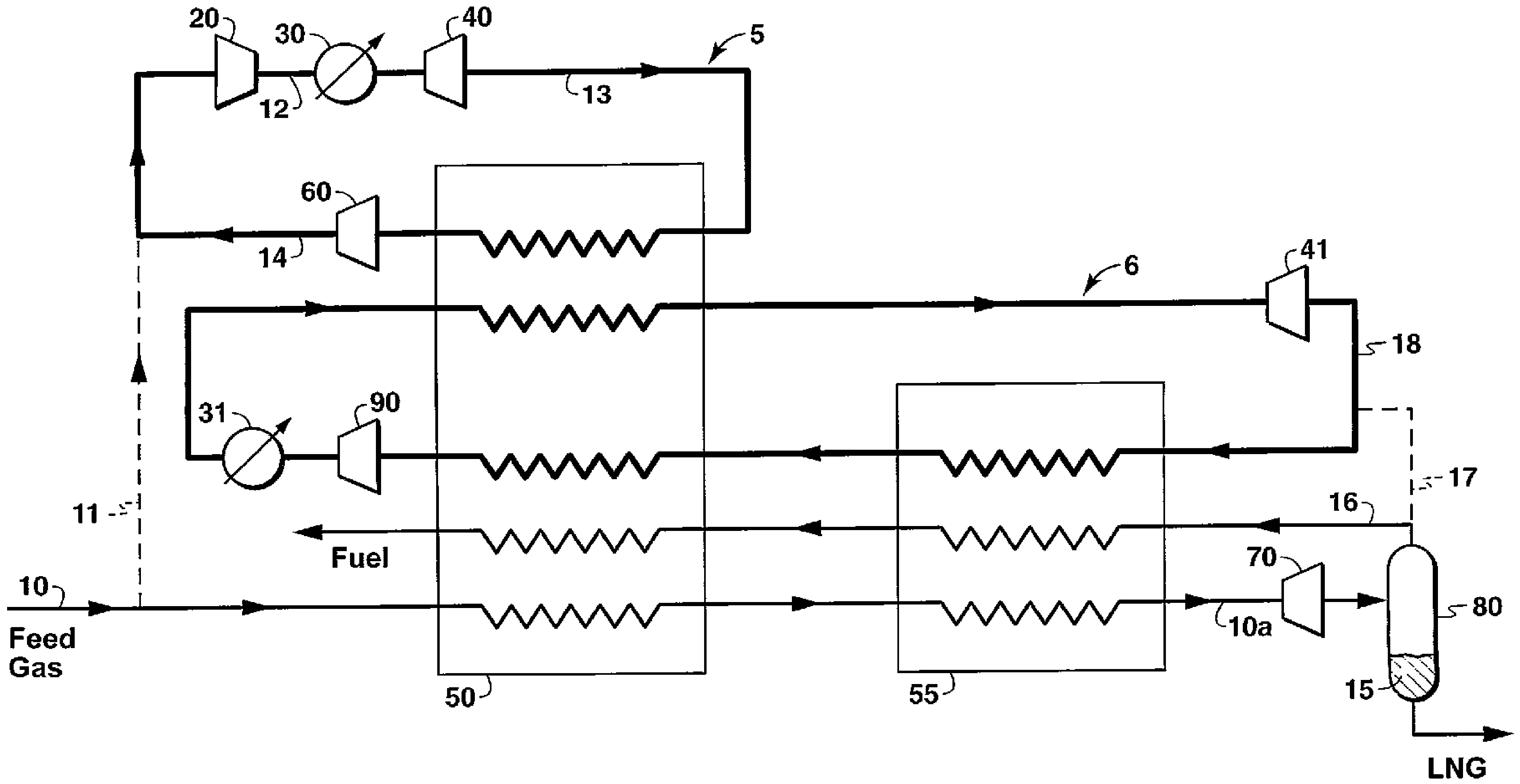
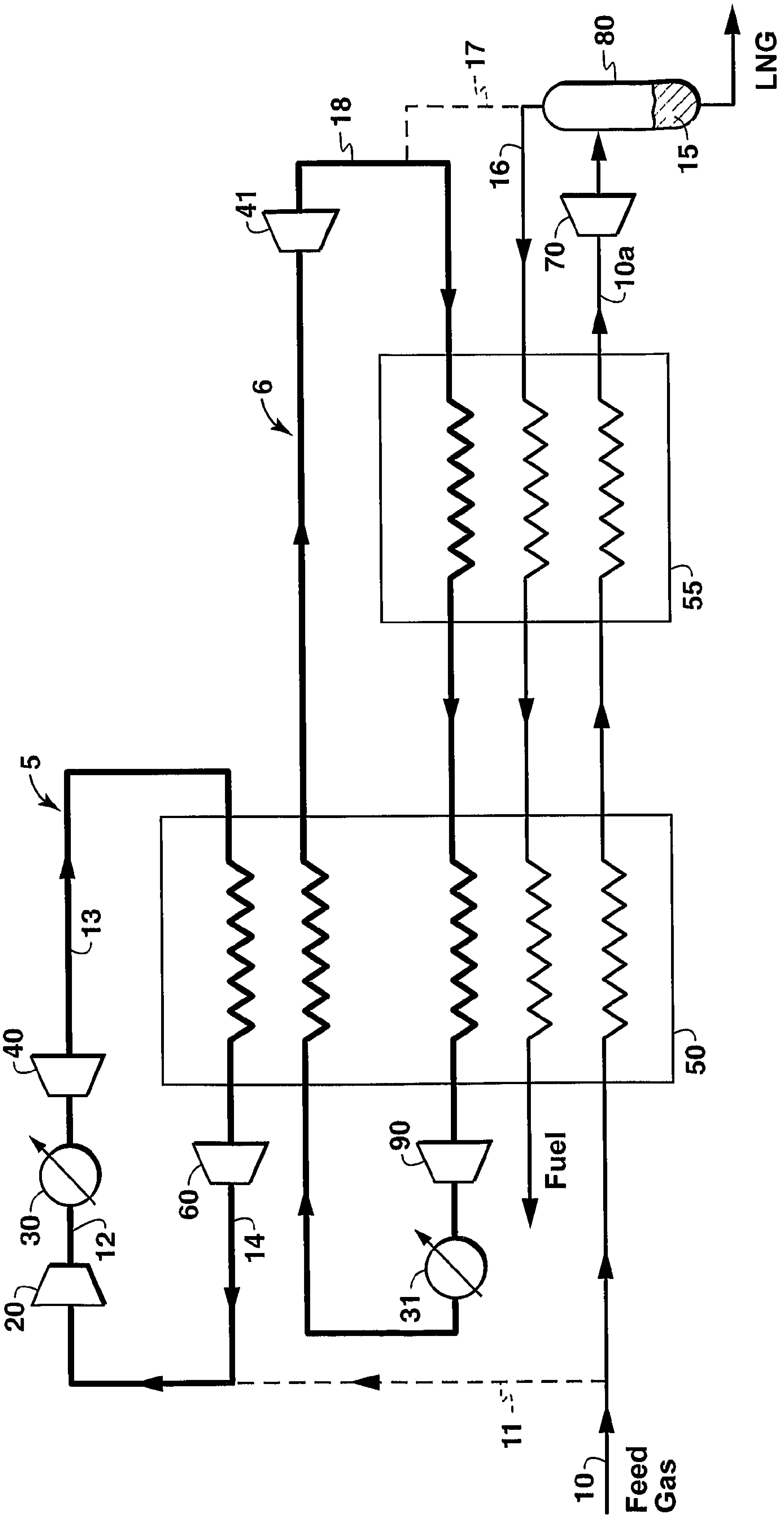
(57) ABSTRACT

Embodiments of this invention relate to a process for liquefaction of natural gas and other methane-rich gas streams, and more particularly to a process for producing liquefied natural gas (LNG). In a first step of the process, a first fraction of the feed gas is withdrawn, compressed to a pressure greater than or equal to 1500 psia, cooled and expanded to a lower pressure to cool the withdrawn first fraction. The remaining fraction of the feed stream is cooled by indirect heat exchange with the expanded first fraction in a first heat exchange process. In a second step a separate stream comprising flash vapor is compressed, cooled and expanded to a lower pressure providing another cold stream. This cold stream is used to cool the remaining feed gas stream in a second indirect heat exchange process. The expanded stream exiting from the second heat exchange process is used for supplemental cooling in the first indirect heat exchange step. The remaining feed gas is subsequently expanded to a lower pressure, thereby partially liquefying this feed gas stream. The liquefied fraction of this stream is withdrawn from the process as LNG having a temperature corresponding to the bubble point pressure.

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10
11
20
12
30
40
13
5
60
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90
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Fuel
50
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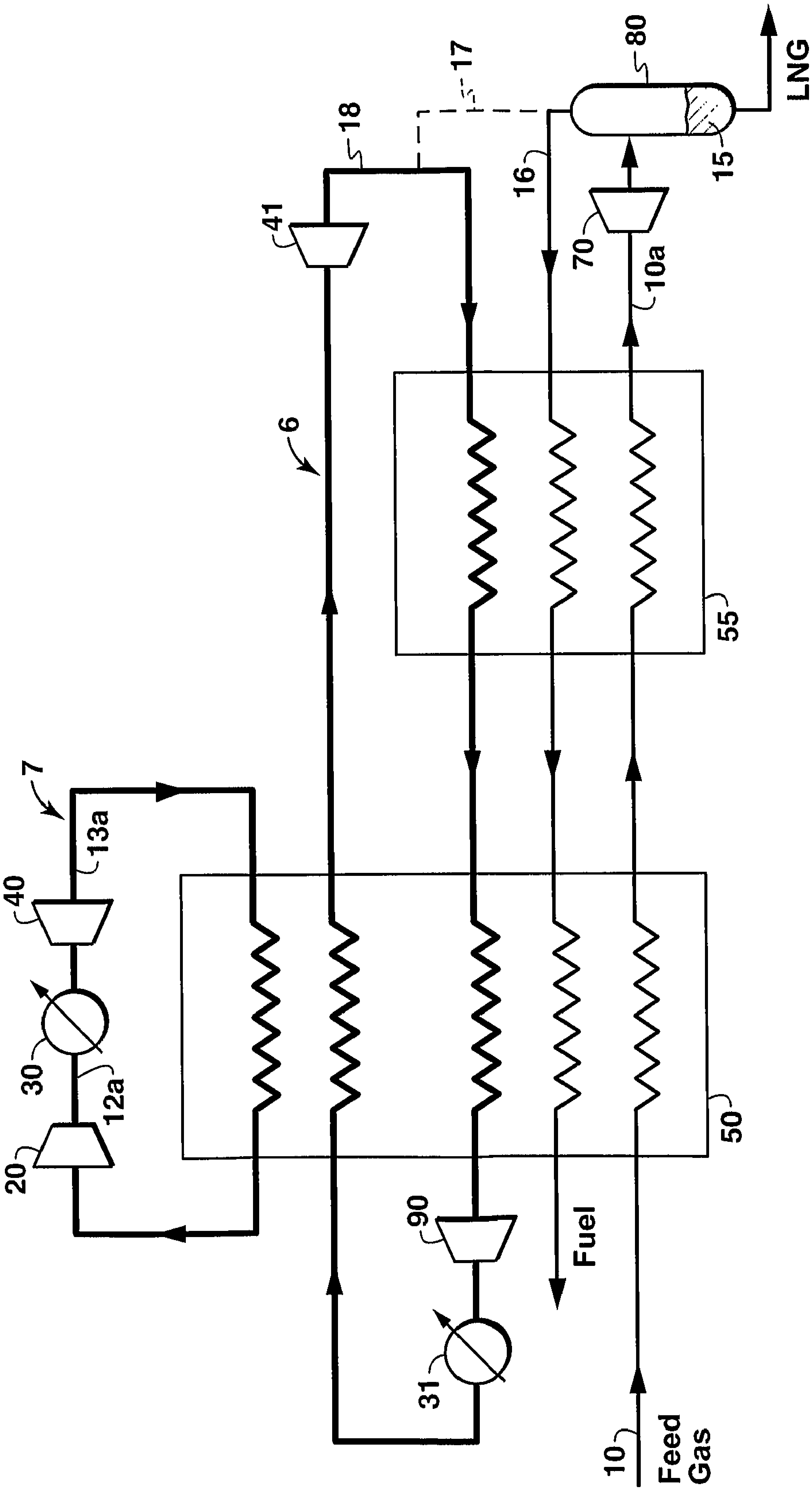
18
17
80
LNG
15
16
70
10a
55

FIG. 1


LNG
80
17
18
15
16
41
70
10a
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55
7
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40
30
12a
20
50
90
Fuel
31
10
Feed Gas

FIG. 2

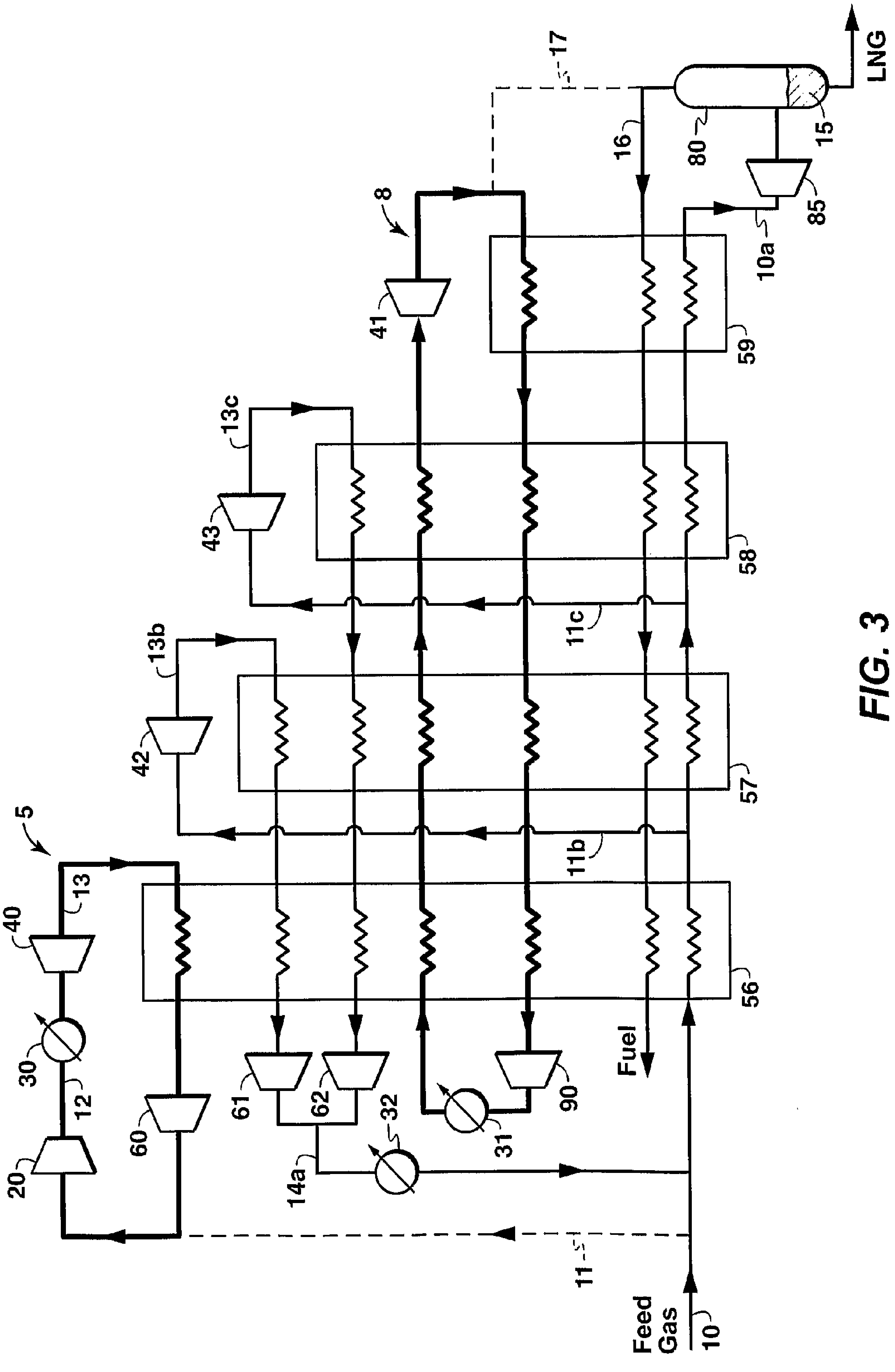

Feed Gas
10
11
20
12
30
40
13
5
60
14a
32
61
62
31
90
Fuel
56
11b
42
13b
57
11c
43
13c
58
41
8
59
10a
85
80
15
16
17
LNG

FIG. 3

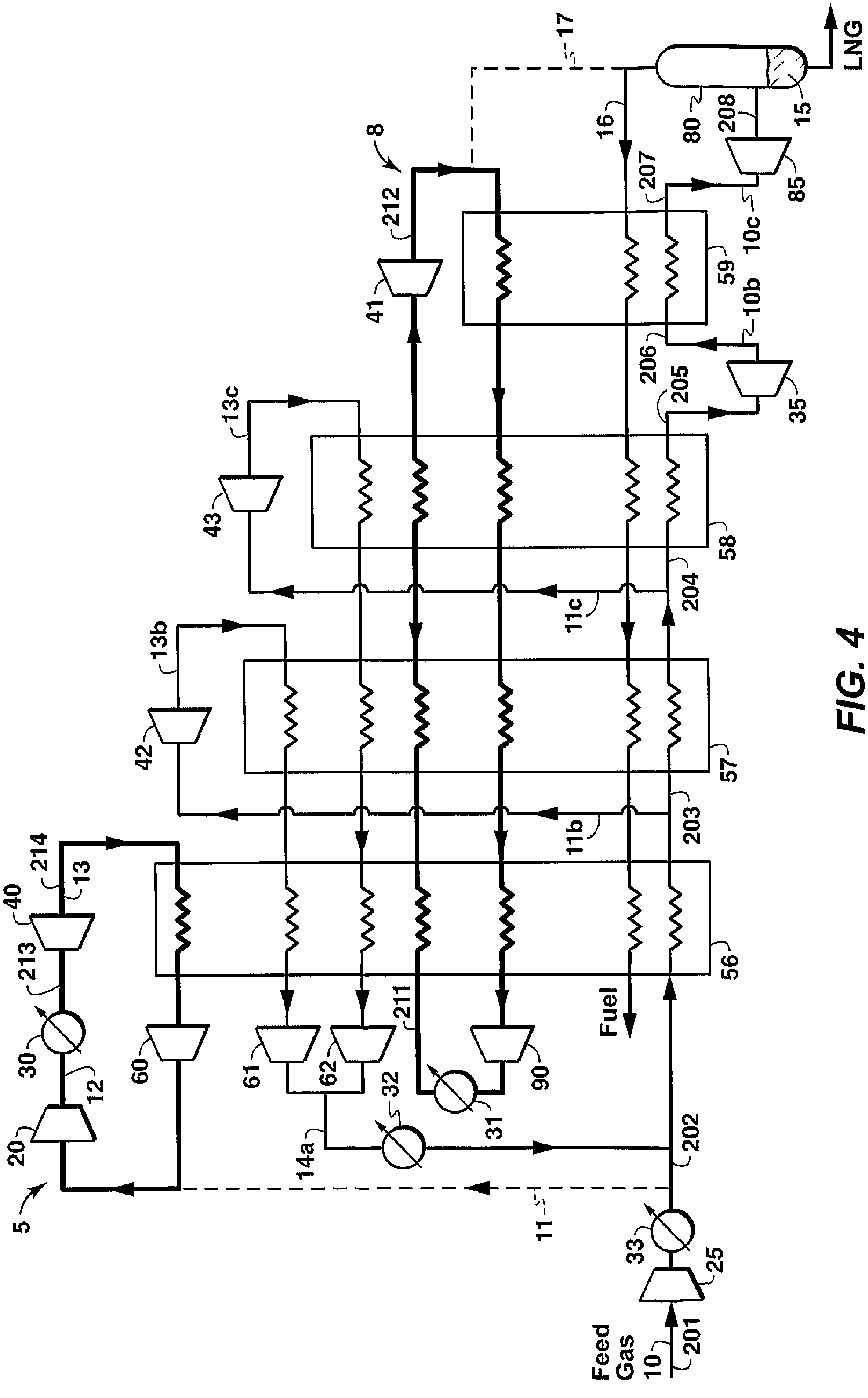
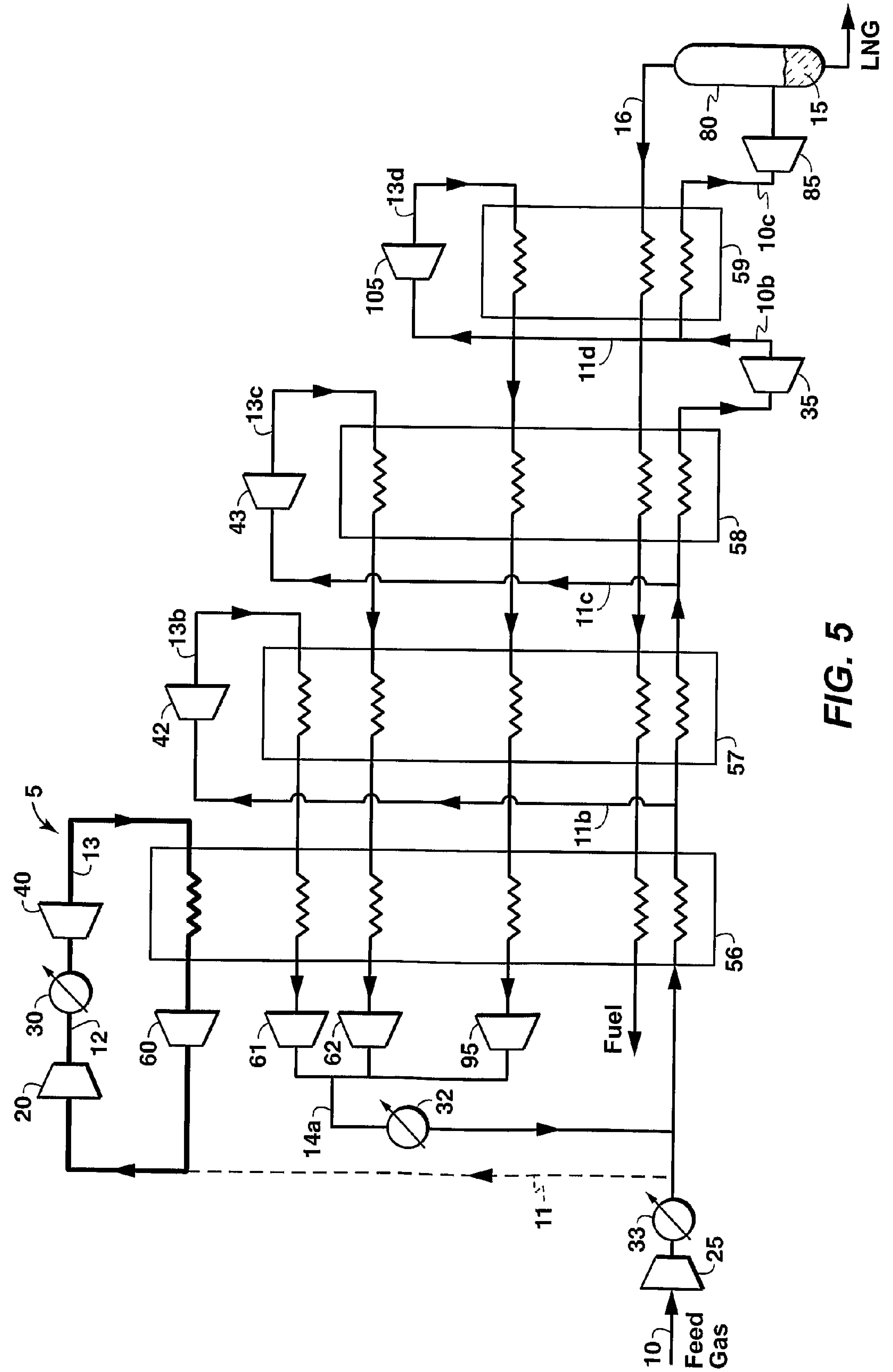

5
20
12
30
213
40
214
13
60
61
62
14a
32
211
31
90
11
33
25
Feed Gas
10
201
202
Fuel
56
203
11b
42
13b
57
204
11c
43
13c
58
41
212
8
17
205
35
206
10b
59
207
10c
85
208
16
80
15
LNG

FIG. 4


5
20
12
30
40
13
60
61
62
95
32
14a
11
33
25
10
Feed Gas
Fuel
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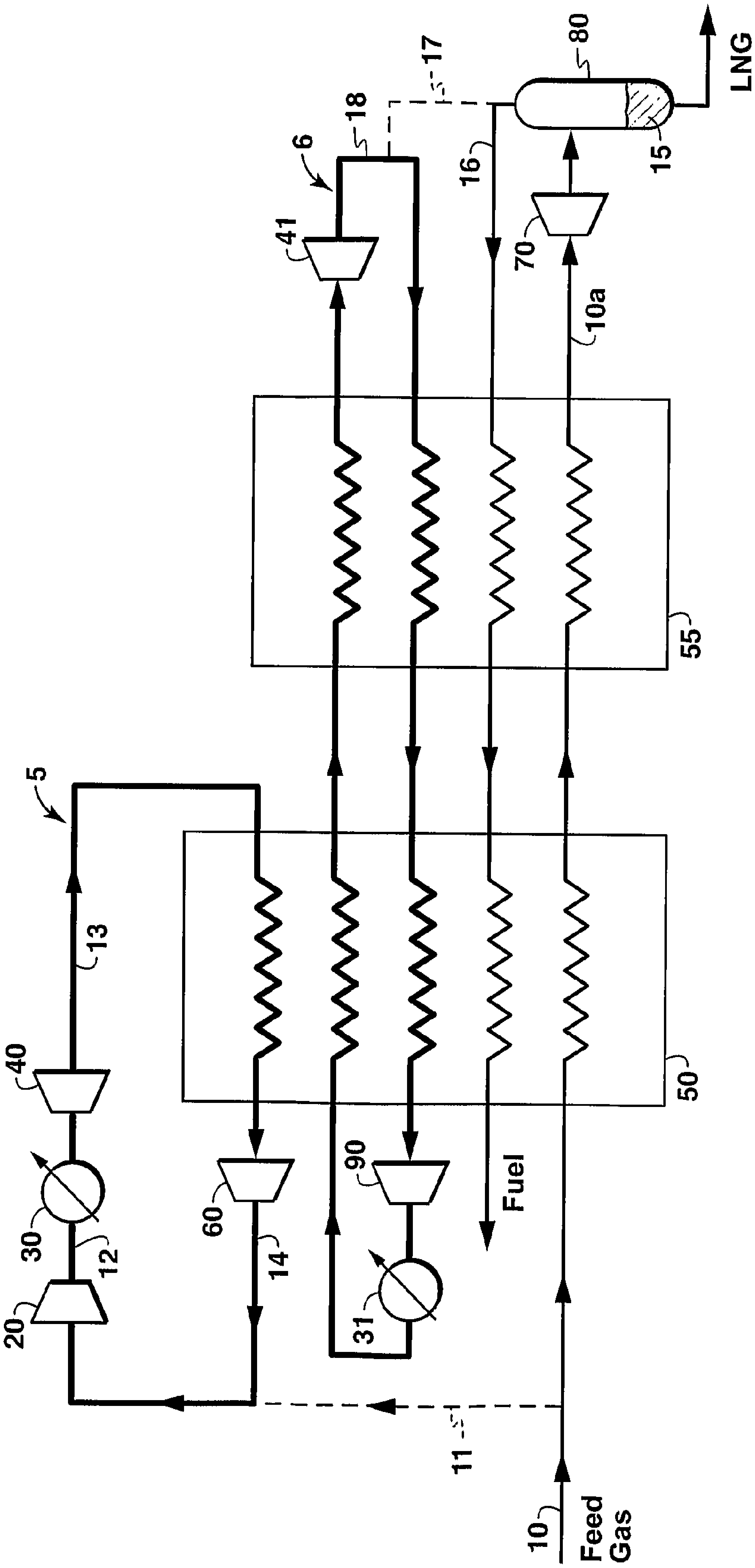
11b
42
13b
57
11c
43
13c
58
35
11d
10b
105
13d
59
10c
85
16
80
15
LNG

FIG. 5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Feed Gas
11
20
12
30
40
13
5
60
14
50
90
31
Fuel
55
41
6
18
17
16
70
10a
80
15
LNG

FIG. 6

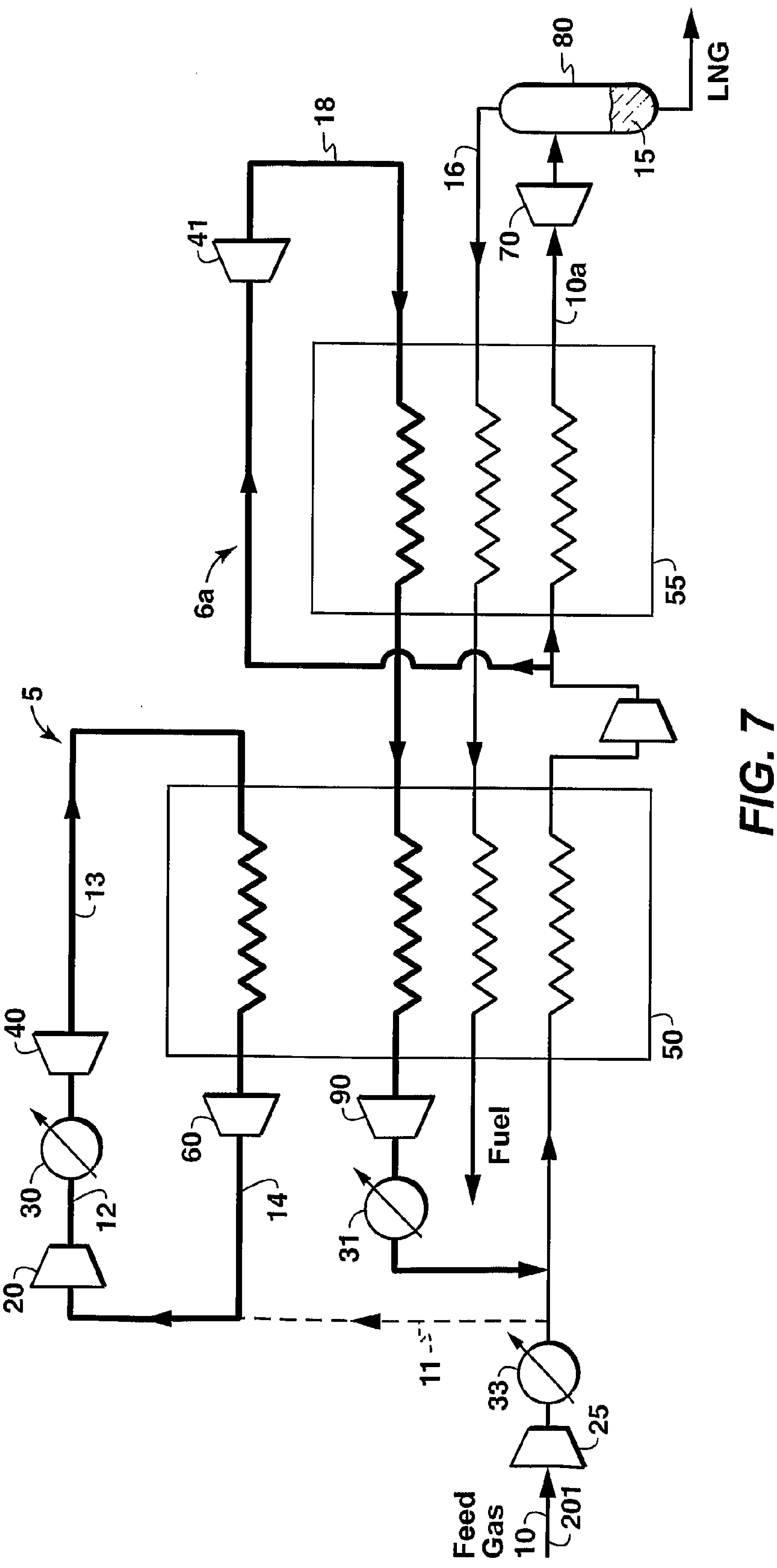
80
LNG
18
16
15
41
70
10a
6a
55
5
13
40
30
12
20
60
14
90
31
Fuel
50
11
33
25
Feed Gas
10
201

FIG. 7

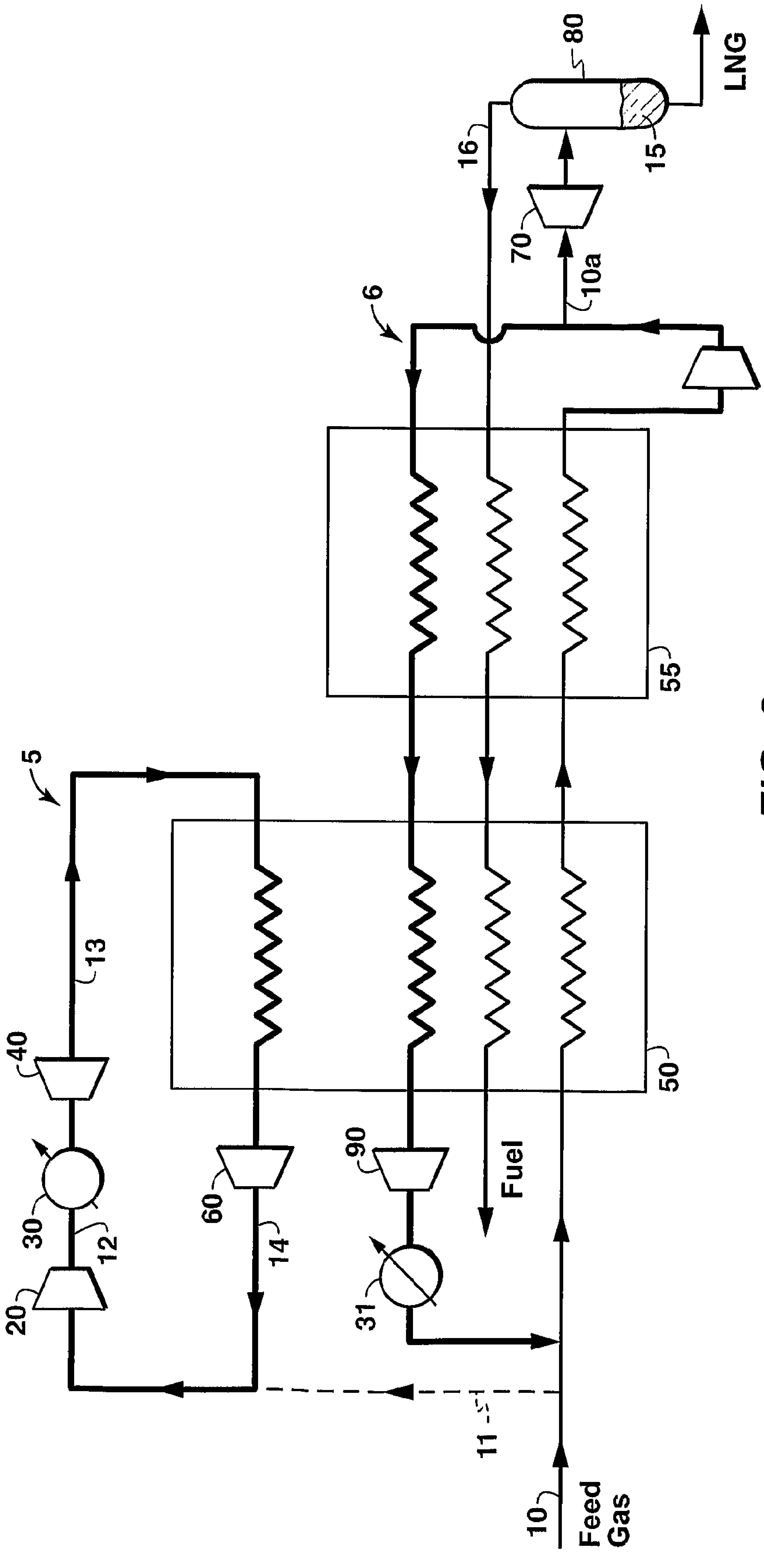
LNG
80
15
16
70
10a
6
55
5
13
40
30
12
20
60
14
90
31
50
Fuel
11
10
Feed Gas

FIG. 8

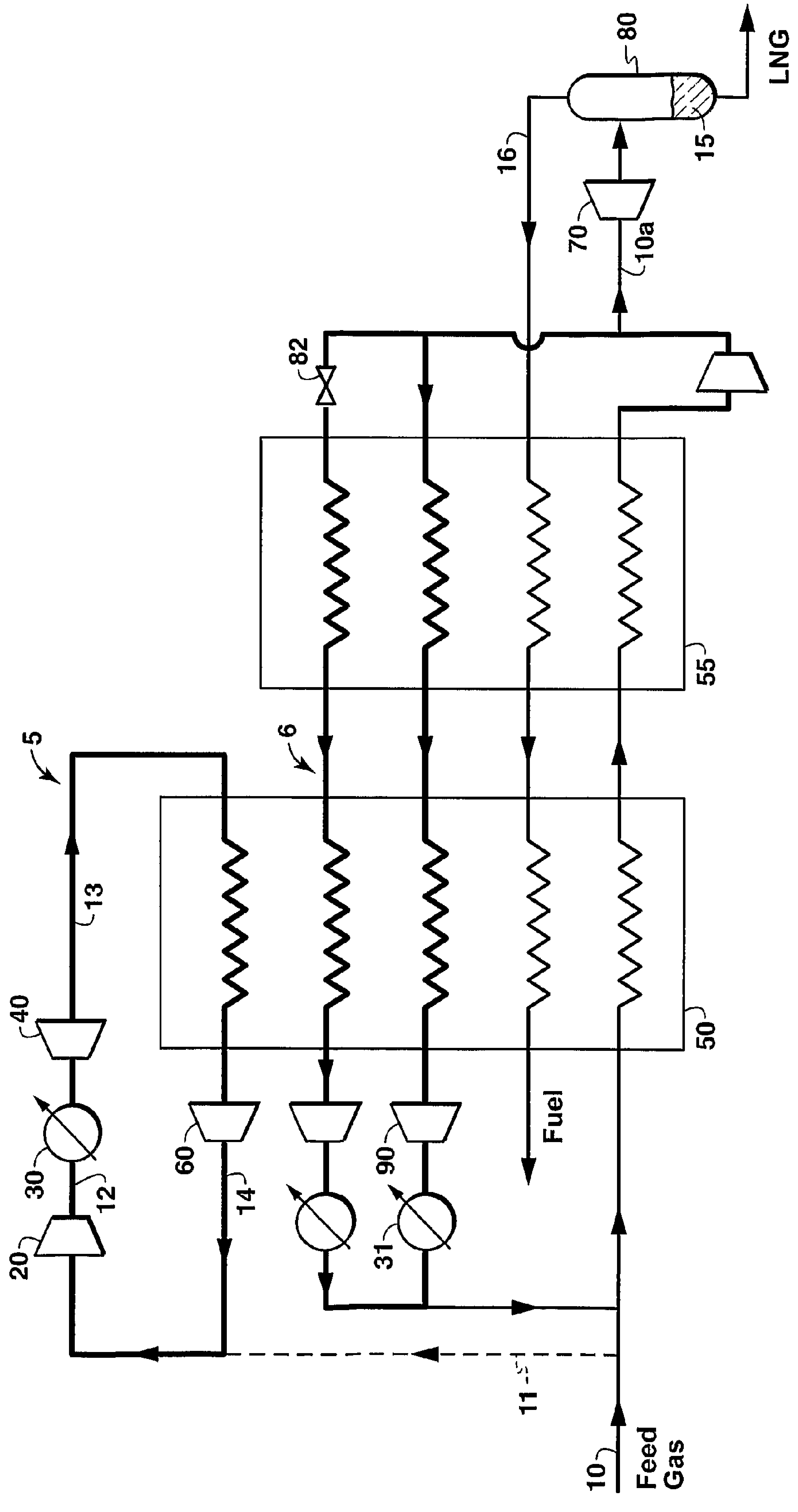
80
LNG
15
16
70
10a
82
55
50
5
6
13
40
30
12
20
60
14
90
31
Fuel
11
10
Feed Gas

FIG. 9

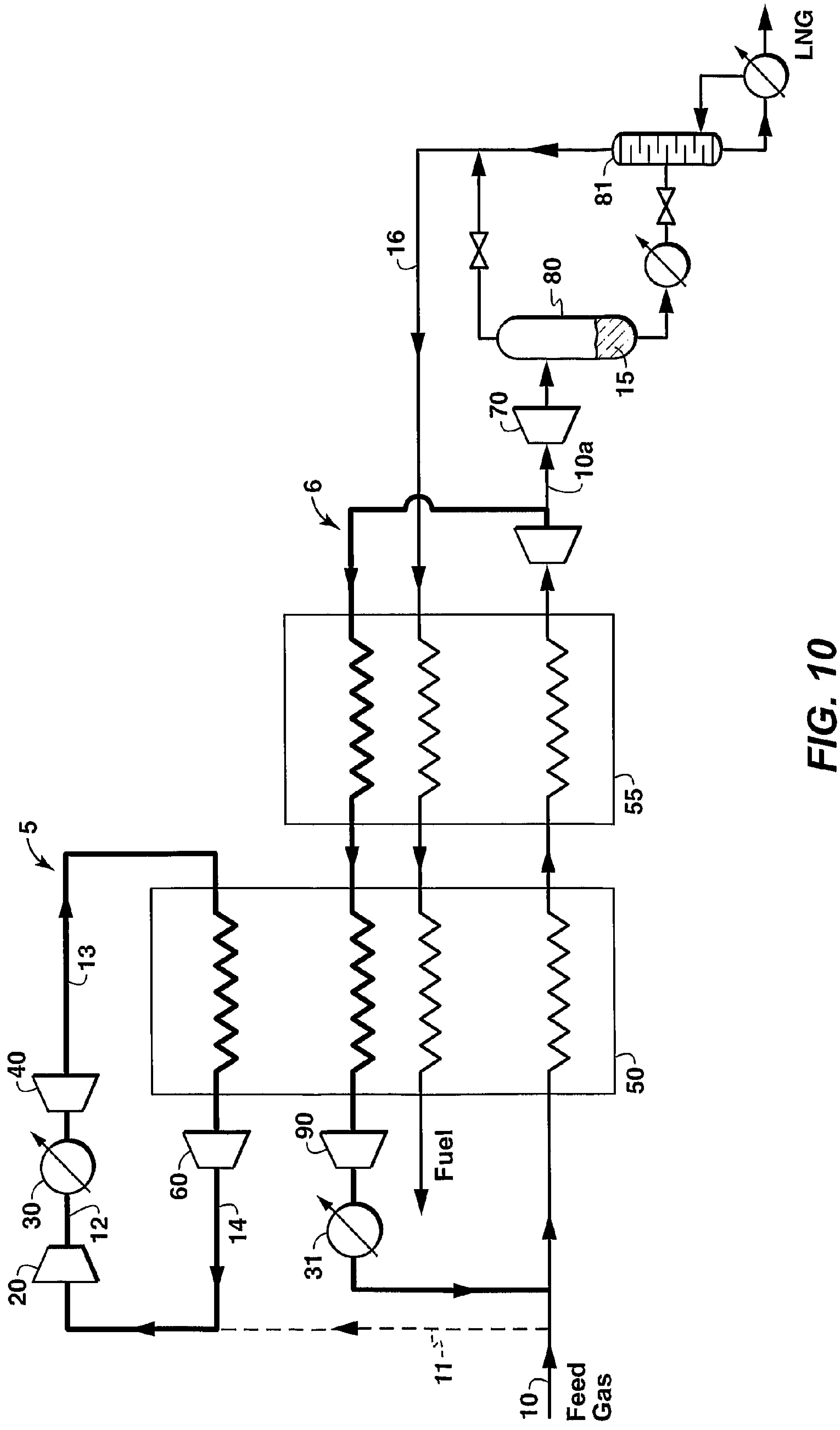
10
Feed Gas
11
5
20
12
30
40
13
14
60
50
31
90
Fuel
55
6
10a
70
15
80
16
81
LNG

FIG. 10

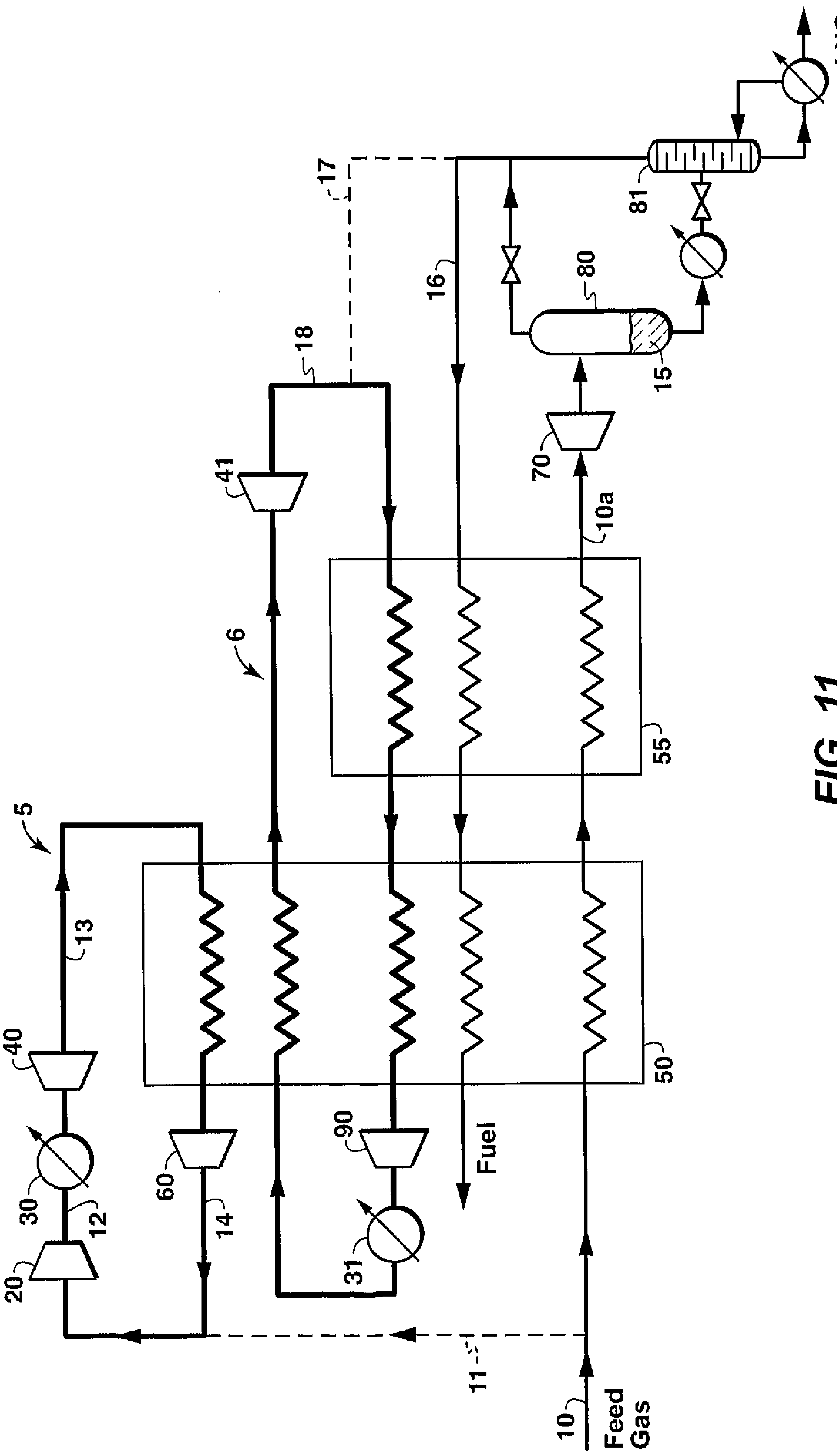
5
13
40
30
12
20
60
14
90
31
11
Fuel
50
6
41
18
17
16
55
70
10a
80
15
81
LNG
10
Feed Gas

FIG. 11

NATURAL GAS LIQUEFACTION PROCESS FOR LNG

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of U.S. Provisional Application No. 60/706,798, filed 9 Aug., 2005, and U.S. Provisional Application No. 60/795,101, filed 26 Apr. 2006.

TECHNICAL FIELD

[0002] Embodiments of the invention relate to a process for liquefaction of natural gas and other methane-rich gas streams, and more particularly to a process for producing liquefied natural gas (LNG).

BACKGROUND

[0003] Because of its clean burning qualities and convenience, natural gas has become widely used in recent years. Many sources of natural gas are located in remote areas, great distances from any commercial markets for the gas. Sometimes a pipeline is available for transporting produced natural gas to a commercial market. When pipeline transportation is not feasible, produced natural gas is often processed into liquefied natural gas (which is called "LNG") for transport to market.

[0004] In the design of an LNG plant, one of the most important considerations is the process for converting the natural gas feed stream into LNG. Currently, the most common liquefaction processes use some form of refrigeration system. Although many refrigeration cycles have been used to liquefy natural gas, the three types most commonly used in LNG plants today are: (1) the "cascade cycle," which uses multiple single component refrigerants in heat exchangers arranged progressively to reduce the temperature of the gas to a liquefaction temperature; (2) the "multi-component refrigeration cycle," which uses a multi-component refrigerant in specially designed exchangers; and (3) the "expander cycle," which expands gas from feed gas pressure to a low pressure with a corresponding reduction in temperature. Most natural gas liquefaction cycles use variations or combinations of these three basic types.

[0005] The refrigerants used may be a mixture of components such as methane, ethane, propane, butane, and nitrogen in multi-component refrigeration cycles. The refrigerants may also be pure substances such as propane, ethylene, or nitrogen in "cascade cycles." Substantial volumes of these refrigerants with close control of composition are required. Further, such refrigerants may have to be imported and stored imposing logistics requirements. Alternatively, some of the components of the refrigerant may be prepared, typically by a distillation process integrated with the liquefaction process.

[0006] The use of gas expanders to provide the feed gas cooling thereby eliminating or reducing the logistical problems of refrigerant handling has been of interest to process engineers. The expander system operates on the principle that the feed gas can be allowed to expand through an expansion turbine, thereby performing work and reducing the temperature of the gas. The low temperature gas is then heat exchanged with the feed gas to provide the refrigeration needed. Supplemental refrigeration is typically needed to fully liquefy the feed gas and this may be provided by a refrigerant system. The power obtained from the expansion is usually used to supply part of the main compression power used in the refrigeration cycle. The typical expander cycle for making LNG operates at the feed gas pressure, typically under about 6,895 kPa (1,000 psia).

[0007] Previously proposed expander cycles have all been less efficient thermodynamically, however, than the current natural gas liquefaction cycles based on refrigerant systems. Expander cycles have therefore not offered any installed cost advantage to date, and liquefaction cycles involving refrigerants are still the preferred option for natural gas liquefaction.

[0008] Because expander cycles result in a high recycle gas stream flow rate and high inefficiency for the pre-cooling (warm) stage, gas expanders have typically been used to further cool feed gas after it has been pre-cooled to temperatures well below −20° C. using an external refrigerant in a closed cycle, for example. Thus, a common factor in most proposed expander cycles is the requirement for a second, external refrigeration cycle to pre-cool the gas before the gas enters the expander. Such a combined external refrigeration cycle and expander cycle is sometimes referred to as a "hybrid cycle." While such refrigerant-based pre-cooling eliminates a major source of inefficiency in the use of expanders, it significantly reduces the benefits of the expander cycle, namely the elimination of external refrigerants. Additional cooling may also be required after the expander cooling and may be provided by another external refrigerant system, such as nitrogen or a cold mixed refrigerant.

[0009] Accordingly, there is still a need for an expander cycle that eliminates the need for external refrigerants and has improved efficiency, at least comparable to that of technologies currently in use.

SUMMARY

[0010] Embodiments of the present invention provide a process for liquefying natural gas and other methane-rich gas streams to produce liquefied natural gas (LNG) and/or other liquefied methane-rich gases. The term natural gas as used in this specification, including the appended claims, means a gaseous feed stock suitable for manufacturing LNG. The natural gas could comprise gas obtained from a crude oil well (associated gas) or from a gas well (non-associated gas). The composition of natural gas can vary significantly. As used herein, natural gas is a methane-rich gas containing methane (C_1) as a major component.

[0011] In one or more embodiments of the method for producing LNG herein, a first step is carried out in which a first fraction of the feed gas is withdrawn, compressed, cooled and expanded to a lower pressure to cool the withdrawn first fraction. The remaining fraction of the feed stream is cooled by indirect heat exchange with the expanded first fraction in a first heat exchange process. In a second step, involving a sub-cooling loop, a separate stream comprised of the flash vapor is compressed, cooled and expanded to a lower pressure providing another cold stream. This cold stream is used to cool the remaining feed gas stream in a second indirect heat exchange process, which constitutes the sub-cooling heat exchange process. The expanded stream exiting from the second heat exchange process is used for supplemental cooling in the first indirect heat exchange step. The remaining feed gas is subsequently expanded to a lower pressure, thereby partially liquefying this feed gas stream. The liquefied fraction of this stream is withdrawn from the process as LNG having a temperature corresponding to the bubble point pressure. The vapor fraction of this stream is returned to supplement the cooling provided in the indirect heat exchange steps. The warmed cooling gases from the various sources are compressed and recycled.

[0012] In one or more other embodiments according to the present invention, a process for liquefying a gas stream rich in methane is provided, said process comprising providing a gas stream rich in methane at a pressure less than 1,000 psia; providing a refrigerant at a pressure of less than 1,000 psia; compressing said refrigerant to a pressure greater than or equal to 1500 psia to provide a compressed refrigerant; cooling said compressed refrigerant by indirect heat exchange with a cooling fluid; expanding said compressed refrigerant to further cool said compressed refrigerant, thereby producing an expanded, cooled refrigerant; passing said expanded, cooled refrigerant to a heat exchange area; and passing said gas stream through said heat exchange area to cool at least part of said gas stream by indirect heat exchange with said expanded, cooled refrigerant, thereby forming a cooled gas stream. In one or more other specific embodiments, providing the refrigerant at a pressure of less than 1,000 psia comprises withdrawing a portion of the gas for use as the refrigerant. In other embodiments, the portion of the gas stream to be used as the refrigerant is withdrawn from the gas stream before the gas stream is passed to the heat exchange area. In still other embodiments, the process according to the present invention further comprises providing at least a portion of the refrigeration duty for the heat exchange area using a closed loop charged with flash vapor produced in the process for liquefying the gas stream rich in methane. Additional embodiments according to the present invention will be apparent to those skilled in the art.

BRIEF DESCRIPTION OF THE DRAWINGS

[0013] FIG. **1** is a schematic flow diagram of one embodiment for producing LNG in accordance with the process of this invention.

[0014] FIG. **2** is a schematic flow diagram of a second embodiment for producing LNG that is similar to the process shown in FIG. **1**, except that the gaseous refrigerant in the compressed, cooled and expanded loop is de-coupled from the feed gas and may therefore have a different composition than the feed gas.

[0015] FIG. **3** is a schematic flow diagram of a third embodiment for producing LNG in accordance with the process of this invention that uses a plurality of work expansion steps for improved efficiency.

[0016] FIG. **4** is a schematic flow diagram of a fourth embodiment for producing LNG in accordance with the process of this invention that uses a plurality of work expansion steps similar to FIG. **3**, but also incorporates an additional expansion step as well as compression of the feed gas to improve performance of the expansion steps.

[0017] FIG. **5** is a schematic flow diagram of a fifth embodiment for producing LNG in accordance with the process of this invention that is similar to the embodiment shown in FIG. **4**, but utilizes an additional side stream and expansion of process gas to provide sub-cooling.

[0018] FIG. **6** is another embodiment similar to the embodiments shown in FIG. **1** and FIG. **2** in which the refrigerant for the sub-cooling loop is cooled in the sub-cooling heat exchanger prior to expansion.

[0019] FIG. **7** is another embodiment in which the sub-cooling loop is coupled to the feed gas.

[0020] FIG. **8** is another embodiment showing an alternative arrangement for the sub-cooling loop.

[0021] FIG. **9** is a similar embodiment to that of FIG. **8** but using split expanded streams through the sub-cooler wherein an expansion valve, Joules-Thompson valve, or similar expansion device is used for improved efficiency in the sub-cooler.

[0022] FIG. **10** is another embodiment in which a nitrogen rejection stage has been integrated for situations in which nitrogen rejection may be needed.

[0023] FIG. **11** is yet another embodiment in which the refrigerant for the sub-cooling loop is derived from the flash vapor from the nitrogen rejection unit and is therefore rich in nitrogen content.

DETAILED DESCRIPTION

[0024] Embodiments of the present invention provide a process for natural gas liquefaction using primarily gas expanders and eliminating the need for external refrigerants. That is, in some embodiments disclosed herein, the feed gas itself (e.g., natural gas) is used as the refrigerant in all refrigeration cycles. Such refrigeration cycles do not require supplemental cooling using external refrigerants (i.e., refrigerants other than the feed gas itself or gas that is produced at or near the LNG process plant) as typical proposed gas expander cycles do, yet such refrigeration cycles have a higher efficiency. In one or more embodiments, cooling water or air are the only external sources of cooling fluids and are used for compressor inter-stage or after cooling.

[0025] FIG. **1** illustrates one embodiment of the present invention in which an expander loop **5** (i.e., an expander cycle) and a sub-cooling loop **6** are used. For clarity, expander loop **5** and sub-cooling loop **6** are shown with double-width lines in FIG. **1**. In this specification and the appended claims, the terms “loop” and “cycle” are used interchangeably. In FIG. **1**, feed gas stream **10** enters the liquefaction process at a pressure less than about 1200 psia, or less than about 1100 psia, or less than about 1000 psia, or less than about 900 psia, or less than about 800 psia, or less than about 700 psia, or less than about 600 psia. Typically, the pressure of feed gas stream **10** will be about 800 psia. Feed gas stream **10** generally comprises natural gas that has been treated to remove contaminants using processes and equipment that are well known in the art. Before it is passed to a heat exchanger, a portion of feed gas stream **10** is withdrawn to form side stream **11**, thus providing, as will be apparent from the following discussion, a refrigerant at a pressure corresponding to the pressure of feed gas stream **10**, namely any of the above pressures, including a pressure of less than about 1000 psia. Thus, in the embodiment shown in FIG. **1**, a portion of the feed gas stream is used as the refrigerant for expander loop **5**. Although the embodiment shown in FIG. **1** utilizes a side stream that is withdrawn from feed gas stream **10** before feed gas stream **10** is passed to a heat exchanger, the side stream of feed gas to be used as the refrigerant in expander loop **5** may be withdrawn from the feed gas after the feed gas has been passed to a heat exchange area. Thus, in one or more embodiments, the present method is any of the other embodiments herein described, wherein the portion of the feed gas stream to be used as the refrigerant is withdrawn from the heat exchange area, expanded, and passed back to the heat exchange area to provide at least part of the refrigeration duty for the heat exchange area.

[0026] Side stream **11** is passed to compression unit **20** where it is compressed to a pressure greater than or equal to about 1500 psia, thus providing compressed refrigerant stream **12**. Alternatively, side stream **11** is compressed to a pressure greater than or equal to about 1600 psia, or greater than or equal to about 1700 psia, or greater than or equal to about 1800 psia, or greater than or equal to about 1900 psia, or greater than or equal to about 2000 psia, or greater than or equal to about 2500 psia, or greater than or equal to about 3000 psia, thus providing compressed refrigerant stream **12**. As used in this specification, including the appended claims, the term "compression unit" means any one type or combination of similar or different types of compression equipment, and may include auxiliary equipment, known in the art for compressing a substance or mixture of substances. A "compression unit" may utilize one or more compression stages. Illustrative compressors may include, but are not limited to, positive displacement types, such as reciprocating and rotary compressors for example, and dynamic types, such as centrifugal and axial flow compressors, for example.

[0027] After exiting compression unit **20**, compressed refrigerant stream **12** is passed to cooler **30** where it is cooled by indirect heat exchange with a suitable cooling fluid to provide a compressed, cooled refrigerant. In one or more embodiments, cooler **30** is of the type that provides water or air as the cooling fluid, although any type of cooler can be used. The temperature of compressed refrigerant stream **12** as it emerges from cooler **30** depends on the ambient conditions and the cooling medium used and is typically from about 35° F. to about 105° F. Cooled compressed refrigerant stream **12** is then passed to expander **40** where it is expanded and consequently cooled to form expanded refrigerant stream **13**. In one or more embodiments, expander **40** is a work-expansion device, such as gas expander producing work that may be extracted and used for compression.

[0028] Expanded refrigerant stream **13** is passed to heat exchange area **50** to provide at least part of the refrigeration duty for heat exchange area **50**. As used in this specification, including the appended claims, the term "heat exchange area" means any one type or combination of similar or different types of equipment known in the art for facilitating heat transfer. Thus, a "heat exchange area" may be contained within a single piece of equipment, or it may comprise areas contained in a plurality of equipment pieces. Conversely, multiple heat exchange areas may be contained in a single piece of equipment.

[0029] Upon exiting heat exchange area **50**, expanded refrigerant stream **13** is fed to compression unit **60** for pressurization to form stream **14**, which is then joined with side stream **11**. It will be apparent that once expander loop **5** has been filled with feed gas from side stream **11**, only make-up feed gas to replace losses from leaks is required, the majority of the gas entering compressor unit **20** generally being provided by stream **14**. The portion of feed gas stream **10** that is not withdrawn as side stream **11** is passed to heat exchange area **50** where it is cooled, at least in part, by indirect heat exchange with expanded refrigerant stream **13**. After exiting heat exchange area **50**, feed gas stream **10** is passed to heat exchange area **55**. The principal function of heat exchange area **55** is to sub-cool the feed gas stream. Thus, in heat exchange area **55** feed gas stream **10** is sub-cooled by sub-cooling loop **6** (described below) to produce sub-cooled stream **10*a***. Sub-cooled stream **10*a*** is then expanded to a lower pressure in expander **70**, thereby partially liquefying sub-cooled stream **10*a*** to form a liquid fraction and a remaining vapor fraction. Expander **70** may be any pressure reducing device, including, but not limited to a valve, control valve, Joule Thompson valve, Venturi device, liquid expander, hydraulic turbine, and the like. Partially liquefied sub-cooled stream **10*a*** is passed to surge tank **80** where the liquefied fraction **15** is withdrawn from the process as LNG having a temperature corresponding to the bubble point pressure. The remaining vapor fraction (flash vapor) stream **16** is used as fuel to power the compressor units and/or as a refrigerant in sub-cooling loop **6** as described below. Prior to being used as fuel, all or a portion of flash vapor stream **16** may optionally be passed from surge tank **80** to heat exchange areas **50** and **55** to supplement the cooling provided in such heat exchange areas.

[0030] Referring again to FIG. **1**, a portion of flash vapor **16** is withdrawn through line **17** to fill sub-cooling loop **6**. Thus, a portion of the feed gas from feed gas stream **10** is withdrawn (in the form of flash gas from flash gas stream **16**) for use as the refrigerant in sub-cooling loop **6**. It will again be apparent that once sub-cooling loop **6** is fully charged with flash gas, only make-up gas (i.e., additional flash vapor from line **17**) to replace losses from leaks is required. In sub-cooling loop **6**, expanded stream **18** is discharged from expander **41** and drawn through heat exchange areas **55** and **50**. Expanded flash vapor stream **18** (the sub-cooling refrigerant stream) is then returned to compression unit **90** where it is re-compressed to a higher pressure and warmed. After exiting compression unit **90**, the re-compressed sub-cooling refrigerant stream is cooled in cooler **31**, which can be of the same type as cooler **30**, although any type of cooler may be used. After cooling, the re-compressed sub-cooling refrigerant stream is passed to heat exchange area **50** where it is further cooled by indirect heat exchange with expanded refrigerant stream **13**, sub-cooling refrigerant stream **18**, and, optionally, flash vapor stream **16**. After exiting heat exchange area **50**, the re-compressed and cooled sub-cooling refrigerant stream is expanded through expander **41** to provide a cooled stream which is then passed through heat exchange area **55** to sub-cool the portion of the feed gas stream to be finally expanded to produce LNG. The expanded sub-cooling refrigerant stream exiting from heat exchange area **55** is again passed through heat exchange area **50** to provide supplemental cooling before being re-compressed. In this manner the cycle in sub-cooling loop **6** is continuously repeated. Thus, in one or more embodiments, the present method is any of the other embodiments disclosed herein further comprising providing cooling using a closed loop (e.g., sub-cooling loop **6**) charged with flash vapor resulting from the LNG production (e.g., flash vapor **16**).

[0031] It will be apparent that in the embodiment illustrated in FIG. **1** (and in the other embodiments described herein) that as feed gas stream **10** passes from one heat exchange area to another, the temperature of feed gas stream **10** will be reduced until ultimately a sub-cooled stream is produced. In addition, as side streams are taken from feed gas stream **10**, the mass flow rate of feed gas stream **10** will be reduced. Other modifications, such as compression, may also be made to feed gas stream **10**. While each such modification to feed gas stream **10** could be considered to produce a new and different stream, for clarity and ease of illustration, the feed gas stream will be referred to as feed gas stream **10** unless otherwise indicated, with the understanding that passage through heat exchange areas, the taking of side streams, and other modifications will produce temperature, pressure, and/or flow rate changes to feed gas stream **10**.

[0032] FIG. **2** illustrates another embodiment of the present invention that is similar to the embodiment shown in FIG. **1**, except that expander loop **5** has been replaced with expander loop **7**. The other items in FIG. **2** have been previously described above. Expander loop **7** is shown with double-width lines in FIG. **2** for clarity. Expander loop **7** utilizes substantially the same equipment as expander loop **5** (for example, compressor **20**, cooler **30**, and expander **40**, all of which have been described above). The gaseous refrigerant in expander loop **7** however, is de-coupled from the feed gas and may therefore have a different composition than the feed gas. That is, expander loop **7** is essentially a closed loop and is not connected to feed gas stream **10**. The refrigerant for expander loop **7** is therefore not necessarily the feed gas, although it may be. Expander loop **7** may be charged with any suitable refrigerant gas that is produced at or near the LNG process plant in which expander loop **7** is utilized. For example, the refrigerant gas used to charge expander loop **7** could be a feed gas, such as natural gas, that has only been partially treated to remove contaminants.

[0033] Like expander loop **5**, expander loop **7** is a high pressure gas loop. Stream **12*a*** exits compression unit **20** at a pressure greater than or equal to about 1500 psia, or greater than or equal to about 1600 psia, or greater than or equal to about 1700 psia, or greater than or equal to about 1800 psia, or greater than or equal to about 1900 psia, or greater than or equal to about 2000 psia, or greater than or equal to about 2500 psia, or greater than or equal to about 3000 psia. The temperature of compressed refrigerant stream **12*a*** as it emerges from cooler **30** depends on the ambient conditions and the cooling medium used and is typically about from about 35° F. to about 105° F. Cooled compressed refrigerant stream **12*a*** is then passed to expander **40** where it is expanded and further cooled to form expanded refrigerant stream **13*a***. Expanded refrigerant stream **13*a*** is passed to heat exchange area **50** to provide at least part of the refrigeration duty for heat exchange area **50**, where feed gas stream **10** is at least partially cooled by indirect heat exchange with expanded refrigerant stream **13*a***. Upon exiting heat exchange area **50**, expanded refrigerant stream **13*a*** is returned to compression unit **20** for re-compression. In any of the embodiments described herein, expander loops **5** and **7** may be used interchangeably. For example, in an embodiment utilizing expander loop **5**, expander loop **7** may be substituted for expander loop **5**.

[0034] FIG. **3** shows another embodiment for producing LNG in accordance with the process of the invention. The process illustrated in FIG. **3** utilizes a plurality of work expansion cycles to provide supplemental cooling for the feed gas and other streams. The use of such work expansion cycles results in overall improved efficiency for the liquefaction process. Referring to FIG. **3**, feed gas stream **10** again enters the liquefaction process at the pressures described above. In the particular embodiment shown in FIG. **3**, side stream **11** is fed to expander loop **5** in the manner previously described, but it will be apparent that closed expander loop **7** could be utilized in the place of expander loop **5**, in which case side stream **11** would not be necessary. Expander loop **5** operates in the same manner as described above for the embodiment shown in FIG. **1**, except that expanded refrigerant stream **13** is passed through heat exchange area **56**, described in detail below, to provide at least a part of the refrigeration duty for heat exchange area **56**.

[0035] The portion of feed gas stream **10** that is not withdrawn as side stream **11** is passed to heat exchange area **56** where it is cooled, at least in part, by indirect heat exchange with expanded refrigerant stream **13** and other streams described below. After exiting heat exchange area **56**, feed gas stream **10** is passed through heat exchange areas **57** and **58** where it is further cooled by indirect heat exchange with additional streams described below. In the present embodiment, first and second work expansion cycles are utilized for improved efficiency as follows: before feed gas stream **10** enters heat exchange area **57**, side stream **11*b*** is taken from feed gas stream **10**. After feed gas stream **10** exits heat exchange area **57**, but before it enters heat exchange area **58**, side stream **11*c*** is taken from feed gas stream **10**. Thus, side streams **11*b*** and **11*c*** are taken from feed gas stream **10** at different stages of feed gas stream cooling. That is, each side stream is withdrawn from the feed gas stream at a different point on the cooling curve of the feed gas such that each successively withdrawn side stream has a lower initial temperature than the previously withdrawn side stream.

[0036] Side stream **11*b***, which is part of the first work expansion cycle, is passed to expander **42** where it is expanded and consequently cooled to form expanded stream **13*b***. Expanded stream **13*b*** is passed through heat exchange areas **56** and **57** to provide at least part of the refrigeration duty for heat exchange areas **56** and **57**. Similarly, side stream **11*c***, which is part of the second work expansion cycle, is passed to expander **43** where it is expanded and consequently cooled to form expanded stream **13*c***. Expanded stream **13*c*** is then passed through heat exchange areas **56**, **57**, and **58** to provide at least part of the refrigeration duty for heat exchange areas **56**, **57**, and **58**. Accordingly, feed gas stream **10** is also cooled in heat exchange areas **56** and **57** by indirect heat exchange with expanded streams **13*b*** and **13*c***. In heat exchange area **58** feed gas stream **10** is also cooled by additional indirect heat exchange with expanded stream **13*c***.

[0037] Upon exiting heat exchange area **56**, expanded streams **13*b*** and **13*c*** are passed to compression units **61** and **62**, respectively, where they are re-compressed and combined to form stream **14*a***. Stream **14*a*** is cooled by cooler **32** prior to being re-combined with feed gas stream **10**. Cooler **32** can be the same type of cooler or cooler types as coolers **30** and **31**. Expanders **42** and **43** are work expansion devices of the type well know to those of skill in the art. Illustrative, non-limiting examples of suitable work expansion devices include liquid expanders and hydraulic turbines. Thus, in the embodiment shown in FIG. **3**, the feed gas stream is further cooled using a plurality of work expansion devices. It will be apparent to those of ordinary skill in the art that additional work expansion cycles can be added to the embodiment illustrated in FIG. **3**, or that a single work expansion cycle could be employed. Generally, therefore, one or more work expansion devices may be employed in the manner described above. Each of the work expansion devices expands a portion of the feed gas stream and thereby cools such portion, wherein each of the portions of the feed gas stream expanded in the work expansion devices is withdrawn from the feed gas stream at a different stage of feed gas stream cooling (i.e., at a different feed gas stream temperature).

[0038] In one or more other embodiments according to the present invention, the work expansion devices are utilized by withdrawing one or more side streams from the feed gas stream; passing said one or more side streams to one or more work expansion devices; expanding said one of more side streams to expand and cool said one or more side streams, thereby forming one or more expanded, cooled side streams; passing said one or more expanded, cooled side streams to at least one heat exchange area; passing said gas stream through said at least one heat exchange area; and at least partially cooling said gas stream by indirect heat exchange with said one or more expanded, cooled side streams.

[0039] Referring again to FIG. **3**, feed gas stream **10**, after being cooled in heat exchange areas **56**, **57**, and **58**, is then passed to heat exchange area **59** where it is further cooled to produce sub-cooled stream **10***a*. The principal function of heat exchange area **59** is to sub-cool feed gas stream **10**. Sub-cooled stream **10***a* is then expanded to a lower pressure in expander **85**, thereby partially liquefying sub-cooled stream **10***a* to form a liquid fraction and a remaining vapor fraction. Expander **85** may be any pressure reducing device, including, but not limited to a valve, control valve, Joule Thompson valve, Venturi device, liquid expander, hydraulic turbine, and the like. Partially liquefied sub-cooled stream **10***a* is passed to surge tank **80** where the liquefied fraction **15** is withdrawn from the process as LNG having a temperature corresponding to the bubble point pressure. The remaining vapor fraction (flash vapor) stream **16** is used as fuel to power the compressor units and/or as a refrigerant in sub-cooling loop **8** in a manner substantially the same as previously described for sub-cooling loop **6**. As can be seen from FIG. **3**, sub-cooling loop **8** is similar to sub-cooling loop **6**, except that sub-cooling loop **8** supplies cooling to four heat exchange areas (heat exchange areas **56**, **57**, **58**, and **59**).

[0040] FIG. **4** illustrates yet another embodiment of the present invention. The embodiment shown in FIG. **4** is substantially the same as the embodiment shown in FIG. **3**, except that compression unit **25** and expander **35** have been added. Expander **35** may be any type of liquid expander or hydraulic turbine. Expander **35** is placed between heat exchange areas **58** and **59** such that feed gas stream **10** flows from heat exchange area **58** into expander **35** where it is expanded, and consequently cooled to produce expanded feed gas stream **10***b*. Stream **10***b* then is passed to heat exchange area **59** where it is sub-cooled to produce sub-cooled stream **10***c*. By expanding and consequently cooling feed gas stream **10** in expander **35** to produce stream **10***b*, the overall cooling load on sub-cooling loop **8** is advantageously reduced. Thus, in one or more embodiments, the present method is any of the other embodiments disclosed herein further comprising expanding at least a portion of the cooled feed gas stream to produce a cooled, expanded feed gas stream (e.g., stream **10***b*); and further cooling the cooled, expanded feed gas stream by indirect heat exchange with a closed loop (e.g., sub-cooling loop **6** or **8**) charged with flash vapor resulting from the LNG production (e.g., flash vapor **16**).

[0041] Continuing to refer to FIG. **4**, compression unit **25** is utilized to increase the pressure of feed gas stream **10** prior to entry into the liquefaction process. Thus, feed gas stream **10** is passed to compression unit **25** where it is compressed to a pressure above the feed gas supply pressure or, in one or more other embodiments, to a pressure greater than about 1200 psia. Alternatively, feed gas stream **10** is compressed to a pressure greater than or equal to about 1300 psia, or greater than or equal to about 1400 psia, or greater than or equal to about 1500 psia, or greater than or equal to about 1600 psia, or greater than or equal to about 1700 psia, or greater than or equal to about 1800 psia, or greater than or equal to about 1900 psia, or greater than or equal to about 2000 psia, or greater than or equal to about 2500 psia, or greater than or equal to about 3000 psia. After compression, feed gas stream **10** is passed to cooler **33** where it is cooled prior to being passed to heat exchange area **56**. It will be appreciated that to the extent compression unit **25** is used to compress feed gas stream **10** (and, hence, side stream **11**) to a lower pressure than that desired for compressed refrigerant stream **12**, compression unit **20** may be used to boost the pressure.

[0042] The compression of feed gas stream **10** as described above provides three benefits. First, by increasing the pressure of the feed gas stream, the pressures of side streams **11***b* and **11***c* are also increased, with the result that the cooling performance of work expansion devices **42** and **43** is enhanced. Second, the heat transfer coefficient in the heat exchange areas is improved. Thus, in one or more embodiments, the process for producing LNG described herein is carried out according to any of the other embodiments describe herein wherein the feed gas is compressed to the pressures described above prior to entry into a heat exchange area. In still other embodiments, the present method comprises providing supplemental cooling for the feed gas stream from a plurality of work expansion devices, each of the work expansion devices expanding a portion of the feed gas stream and thereby cooling the portion to form one or more expanded, cooled side streams, wherein each of the portions of the feed gas stream expanded in the work expansion devices is withdrawn from the feed gas stream at a different stage of feed gas stream cooling (i.e., at a different feed gas stream temperature); and cooling said feed gas stream by indirect heat exchange with said one or more expanded, cooled side streams.

[0043] In still other embodiments, each of the above-described portions of feed gas has a pressure, prior to expansion, greater than about 1200 psia, or greater than or equal to about 1300 psia, or greater than or equal to about 1400 psia, or greater than or equal to about 1500 psia, or greater than or equal to about 1600 psia, or greater than or equal to about 1700 psia, or greater than or equal to about 1800 psia, or greater than or equal to about 1900 psia, or greater than or equal to about 2000 psia, or greater than or equal to about 2500 psia, or greater than or equal to about 3000 psia. In yet other embodiments, the present method is any of the other embodiments described herein further comprising compressing the feed gas stream to any of the pressures described above to produce a pressurized feed gas stream; feeding the pressurized feed gas stream to a work expansion device, or to a plurality of work expansion devices; expanding the compressed feed gas stream through the work expansion device, or through a plurality of work expansion devices, to provide supplemental cooling for the feed gas stream.

[0044] A third benefit obtained by compression the feed gas stream as described above is that the cooling capacity of expander **35** is improved, with the result that expander **35** is able to even further reduce the cooling load on sub-cooling loop **8**. It will be appreciated that compression unit **25** and/or expander **35** could also be advantageously added to other embodiments described herein to provide similar reductions in the cooling load on the sub-cooling loops utilized in those embodiments or other improvements in cooling, and that compression unit **25** and expander **35** may be used independently of each other in any embodiment herein. Moreover, it will also be appreciated that the cooling capacity of expander **35** (or the work expansion devices **42** and **43**) will be improved, even without compression of the feed stream, to the extent the feed stream is supplied at a pressure above the bubble point pressure of the LNG. For example, if the feed gas is supplied at any of the pressures described above resulting from compression of the feed gas, the benefit of such pressure will obviously be obtainable without additional compression. Therefore, in interpreting this specification, including the appended claims, the use of work expansion devices and/or expander **35** to expand streams having pressures above about 1200 psia should not be construed as requiring the use or presence of compression unit **25** or of any other compressor or compression step.

[0045] FIG. **5** is a schematic flow diagram of a fifth embodiment for producing LNG in accordance with the process of this invention that is similar to the embodiment shown in FIG. **4**, but utilizes yet another expansion step to provide sub-cooling. Referring to FIG. **5**, it will be seen that sub-cooling loop **8** is not present in the embodiment shown in FIG. **5**. Instead, side stream **11***d* is taken from stream **10***b* and passed to expansion device **105** where it is expanded and consequently cooled to form expanded stream **13***d*. Expansion device **105** is a work-producing expander, many types of which are readily available. Illustrative, non-limiting examples of such devices include liquid expanders and hydraulic turbines. Expanded stream **13***d* is passed through heat exchange areas **59**, **58**, **57**, and **56** to provide at least part of the refrigeration duty for those heat exchange areas. As can be seen from FIG. **5**, stream **10***b* is also cooled by indirect heat exchange with expanded stream **13***d*, as well as by the flash vapor stream **16**. Thus, in one or more embodiments, the inventive process further comprises expanding at least a portion of the cooled gas stream (feed gas stream **10**) in expander **35** before the final heat exchange step (for example, prior to heat exchange area **59**) to produce an expanded, cooled gas stream (for example, stream **10***b*); passing a portion of said expanded, cooled gas stream to a work-producing expander; further expanding said expanded, cooled gas stream in said work-producing expander; and passing the stream emerging from said work-producing expander (for example, stream **13***d*) to a heat exchange area to further cool said expanded, cooled gas stream by indirect heat exchange in said heat exchange area.

[0046] Upon exiting heat exchange area **56**, expanded stream **13***d* is passed to compression unit **95** where it is re-compressed and combined with the streams emerging from compression units **61** and **62** to form part of stream **14***a*, which is cooled and then re-cycled to feed stream **10** as before.

[0047] A further embodiment shown in FIG. **6** is similar to the embodiment shown in FIG. **1** and described above, except that sub-cooling loop **6** has been modified such that after exiting heat exchange area **50**, the re-compressed and cooled sub-cooling refrigerant stream is further cooled in heat exchange area **55** prior to being expanded through expander **41**. This embodiment is favorable where a cooling fluid is used that does not present much condensation after expander **41**.

[0048] FIG. **7** depicts another embodiment in which sub-cooling loop **6***a* uses a portion of feed gas **10**. The portion of feed gas **10** is re-pressurized in compressor **25** and cooled in cooler **33** from 201, in the same fashion as in FIG. **4**.

[0049] FIG. **8** is another embodiment similar to FIG. **7** showing an alternative arrangement for the sub-cooling loop **6**. Depending on the composition of feed gas **10**, an additional compressor (not shown) may be used to prevent condensation in the sub-cooling loop or to ensure adequate line pressures.

[0050] FIG. **9** depicts an embodiment for use with certain feed gas **10** compositions and/or pressures. To better match the cooling curve of the feed gas **10** being cooled for LNG collection, to the cooling curve of that portion of feed gas **10** being used for cooling in sub-cooling heat exchange area **55**, it may be necessary to further expand a split of the portion of the refrigerant gas going to the sub-cooling loop **6**. This is accomplished using an expansion valve **82** or other expander (e.g., a Joules-Thompson valve) to provide supplemental cooling in sub-cooling loop **6**.

[0051] FIG. **10** represents another embodiment showing the integration of a nitrogen rejection stage using distillation column **81** or equivalent device, for the case where nitrogen rejection is needed, based on feed gas **10** composition. This may be needed to meet the nitrogen specification of product LNG for transmission and end use.

[0052] FIG. **11** represents another embodiment showing the integration of a nitrogen rejection unit, where the flash vapor from the nitrogen rejection unit is used as refrigerant for the sub-cooling loop. The resulting refrigerant is therefore rich in nitrogen.

EXAMPLE

[0053] A hypothetical mass and energy balance was carried out to illustrate the embodiment shown in FIG. **4**, and the results are shown in the Table below. The data were obtained using a commercially available process simulation program called HYSYS™ (available from Hyprotech Ltd. of Calgary, Canada); however, other commercially available process simulation programs can be used to develop the data, including for example HYSIM™, PROII™, and ASPEN PLUS™, which are familiar to those of ordinary skill in the art. This example assumed that feed gas stream **10** had the following composition in mole percent: C_1: 90.25%; C_2: 5.70%; C_3: 0.01%; N_2: 4.0%; He: 0.04%. The data presented in the Table are offered to provide a better understanding of the embodiment shown in FIG. **4**, but the invention is not to be construed as unnecessarily limited thereto. The temperatures, pressures, and flow rates can have many variations in view of the teachings herein. The specific temperature, pressure, and flow rate calculated for state points 201 through 214 (at the locations shown in FIG. **4**) are set forth in the Table.

[0054] In one embodiment of the inventive method, by controlling the temperature of the stream emerging from the final heat exchange area, the volume of flash vapor stream **16** is controlled to match the fuel requirements of the compression units and other equipment. For example, referring to FIG. **4**, the temperature at state point 207 can be controlled to produce more or less flash vapor (stream **16**) depending on the fuel requirements. Higher temperatures at state point 207 will result in the production of more flash vapor (and hence more available fuel), and vice-versa. Alternatively, the temperature may be adjusted such that the flash vapor flow rate is higher than the fuel requirement, in which case the excess flow above the fuel flow requirement may be recycled after compression and cooling.

TABLE

State Point	Temperature (deg. F.)	Pressure (psia)	Flow (lb-mole/hr)
201	262	985	3.35×10^5
202	100	1500	1.08×10^6
203	−36	1480	4.85×10^5
204	−130	1470	3.35×10^5
205	−213	1460	3.35×10^5
206	−229	48	3.35×10^5
207	−236	42	3.35×10^5
208	−254	18	3.35×10^5
209	−217	71	3.12×10^5
210	−140	420	2.29×10^4
211	100	126	2.57×10^4
212	−240	44	2.57×10^4
213	100	3000	8.57×10^5
214	−40	895	8.57×10^5

[0055] A person skilled in the art, particularly one having the benefit of the teachings herein, will recognize many modifications and variations to the specific embodiments disclosed above. For example, features shown in one embodiment may be added to other embodiments to form additional embodiments. Thus, the specifically disclosed embodiments and example should not be used to limit or restrict the scope of the invention, which is to be determined by the claims that follow.

1. A process for liquefying a gas stream rich in methane, said process comprising:

providing said gas stream at a pressure less than 1,000 psia;

providing a refrigerant at a pressure of less than 1,000 psia;

compressing said refrigerant to a pressure greater than or equal to 1500 psia to provide a compressed refrigerant;

cooling said compressed refrigerant by indirect heat exchange with a cooling fluid;

expanding said compressed refrigerant to further cool said compressed refrigerant, thereby producing an expanded, cooled refrigerant;

passing said expanded, cooled refrigerant to a heat exchange area; and

passing said gas stream through said heat exchange area to cool at least part of said gas stream by indirect heat exchange with said expanded, cooled refrigerant, thereby forming a cooled gas stream.

2. The process of claim **1** wherein providing said refrigerant at a pressure of less than 1,000 psia comprises withdrawing a portion of said gas stream for use as said refrigerant.

3. The process of claim **2** wherein said portion of said gas stream is withdrawn before said gas stream is passed to said heat exchange area.

4. The process of claim **2** wherein said portion of said gas stream is withdrawn from said heat exchange area.

5. The process of claim **1** further comprising providing at least a portion of the refrigeration duty for said heat exchange area using a closed loop charged with a flash vapor produced in said process for liquefying a gas stream rich in methane.

6. The process of claim **5** further comprising:

expanding at least a portion of said cooled gas stream to produce an expanded, cooled gas stream; and

further cooling said expanded, cooled gas stream by indirect heat exchange with said closed loop charged with the flash vapor.

7. The process of claim **1** further comprising:

expanding at least a portion of said cooled gas stream to produce an expanded, cooled gas stream; and

further cooling said expanded, cooled gas stream by indirect heat exchange in one or more additional heat exchange areas.

8. The process of claim **1** further comprising:

cooling said gas stream using a plurality of work expansion devices, each of said work expansion devices expanding a portion of the feed gas stream and thereby cooling said portion to form one or more expanded, cooled side streams, wherein each of said portions of the feed gas stream expanded in said work expansion devices is withdrawn from said feed gas stream at a different stage of feed gas stream cooling; and

cooling said feed gas stream by indirect heat exchange with said one or more expanded, cooled side streams.

9. The process of claim **1** further comprising:

withdrawing one or more portions of said gas stream;

passing each of said one or more portions of said gas stream to one or more work expansion devices and expanding each of said one of more portions of said gas stream to expand and cool said one or more portions, thereby forming one or more expanded, cooled side streams;

passing said one or more expanded, cooled side streams to at least one heat exchange area;

passing said gas stream through said at least one heat exchange area; and

at least partially cooling said gas stream by indirect heat exchange with said one or more expanded, cooled side streams.

10. The process of claim **6**, **7**, **8**, or **9** wherein said gas stream is first compressed to a pressure above the gas supply pressure.

11. The process of claim **1** further comprising an expansion stage of said cooled gas stream before a final heat exchange step and prior to expansion to produce LNG.

12. The process of claim **1** further comprising:

expanding at least a portion of said cooled gas stream before a final heat exchange step to produce an expanded, cooled gas stream;

passing a portion of said expanded, cooled gas stream to a work-producing expander and further expanding said portion of said expanded, cooled gas stream in said work-producing expander; and

passing the stream emerging from said work-producing expander to a heat exchange area to further cool the balance of said expanded, cooled gas stream by indirect heat exchange in said heat exchange area.

13. The process of claim **1** wherein said refrigerant is compressed to a pressure greater than or equal to 3,000 psia to provide a compressed refrigerant.

14. The process of claim **1** wherein said heat exchange area comprises multiple heat exchange chambers.

15. The process of claim **1** further comprising:

a sub-cooling heat exchange area receiving said gas stream and cooled by expansion of a second refrigerant to provide a sub-cooled gas stream;

followed by final expansion of said sub-cooled gas stream and recovery of LNG.

16. The process of claim **15** wherein said second refrigerant is a portion of said gas stream rich in methane.

17. The process of claim **15** wherein said second refrigerant is sub-cooled in said sub-cooling heat exchange area prior to expansion of said second refrigerant.

18. The process of claim **16** wherein said gas stream rich in methane is re-pressurized before passing through said heat exchange area, said cooled gas stream is expanded, and a portion of said expanded, cooled gas stream is further expanded and used as said second refrigerant in said sub-cooling heat exchange area.

19. The process of claim **15** wherein a portion of said sub-cooled gas stream is expanded and a portion thereof is said second refrigerant.

20. The process of claim **19** wherein said portion of said sub-cooled gas stream is split into two partial streams, one of said partial streams is further expanded, and both of said partial streams comprise said second refrigerant.

21. The process of claim **1** further comprising rejecting nitrogen with LNG recovery.

22. A process for liquefying a gas stream rich in methane, said process comprising:

providing said gas stream at a pressure less than 1,000 psia;
providing a refrigerant in a closed loop;
compressing said refrigerant to a pressure greater than or equal to 1500 psia to provide a compressed refrigerant;
cooling said compressed refrigerant by indirect heat exchange with a cooling fluid;
expanding said compressed refrigerant to further cool said compressed refrigerant, thereby producing an expanded, cooled refrigerant;
passing said expanded, cooled refrigerant to a heat exchange area; and
passing said gas stream through said heat exchange area to cool at least part of said gas stream by indirect heat exchange with said expanded, cooled refrigerant.

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