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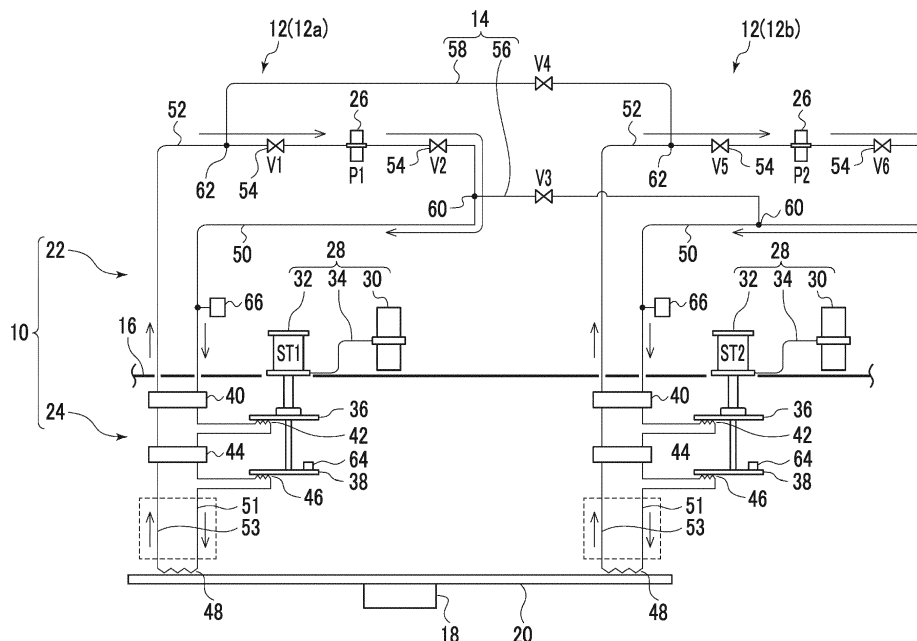
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(54) **CRYOGENIC SYSTEM**

(57) The continuity of the cooling operation of a cryogenic system is improved. A cryogenic system (10) includes a cryogenic cooling unit (20), a plurality of refrigerant circulation loops (12) which cool the cryogenic cooling unit (20) by heat exchange between the cryogenic cooling unit (20) and a refrigerant and each of which includes a circulation pump (26) circulating the refrigerant and a refrigerator (28) cooling the refrigerant, and a connection line (14) that connects the plurality of refrigerant circulation loops (12) to allow the refrigerant to be circulated. The connection line (14) is adapted to be switch-

able to a connected state from an unconnected state, isolates the plurality of refrigerant circulation loops (12) from each other in the unconnected state so that the circulation pump (26) of each refrigerant circulation loop (12) circulates the refrigerant in the refrigerant circulation loop (12), and connects the plurality of refrigerant circulation loops (12) in the connected state so that the circulation pump (26) of at least one refrigerant circulation loop (12) circulates the refrigerant in at least one of the other refrigerant circulation loops (12) as well.

FIG. 1



Description

BACKGROUND OF THE INVENTION

Field of the Invention

[0001] Certain embodiments of the present invention relate to a cryogenic system.

[0002] Priority is claimed to Japanese Patent Application No. 2017-207999, filed October 27, 2017, the entire content of which is incorporated herein by reference.

Description of Related Art

[0003] In the past, cryogenic coolers have been used to cool various objects to be cooled to a desired very low temperature. As cryogenic coolers, there are a cooler that directly cools an object to be cooled by a mechanical refrigerator, such as a GM refrigerator, a Stirling refrigerator, or a pulse tube refrigerator, a cooler that cools a refrigerant by such a mechanical refrigerator and cools an object to be cooled by a refrigerant, and the like.

[0004] An example of the related art includes Japanese Unexamined Patent Application Publication No. 2016-211795.

SUMMARY OF THE INVENTION

[0005] A plurality of individual refrigerant circulation paths between which a refrigerant cannot be circulated are formed in a refrigerant cooling type cryogenic cooler. The cryogenic cooler includes a plurality of mechanical refrigerators, and the refrigerator is installed on each refrigerant circulation path to cool a refrigerant that is circulated in each refrigerant circulation path. In a case in which a function to cool a certain refrigerant circulation path is lost due to the failure of any one of the refrigerators or other reasons, the cooling capacity of the refrigerant circulation path is lost. In addition, since the refrigerator is a structure that connects a high-temperature section (for example, a room-temperature section) to a low-temperature section (for example, an object to be cooled), a refrigerator, which is stopped due to a failure or the like, forms a heat transfer path to the low-temperature section from the high-temperature section. For this reason, the refrigerator causes an increase in the penetration of heat into the object to be cooled. In this case, the cryogenic cooler cannot continue to perform desired cryogenic cooling or it may be difficult for the cryogenic cooler to perform desired cryogenic cooling.

[0006] An exemplary object of an aspect of the invention is to improve the continuity of the cooling operation of a cryogenic system.

[0007] According to an aspect of the invention, a cryogenic system includes a cryogenic cooling unit, a plurality of refrigerant circulation loops which are adapted to cool the cryogenic cooling unit by heat exchange between the cryogenic cooling unit and a refrigerant and

each of which includes a circulation pump circulating the refrigerant and a mechanical refrigerator cooling the refrigerant, and a connection line that connects the plurality of refrigerant circulation loops to allow the refrigerant to be circulated. The connection line is adapted to be switchable to a connected state from an unconnected state, isolates the plurality of refrigerant circulation loops from each other in the unconnected state so that the circulation pump of each refrigerant circulation loop circulates the refrigerant in the refrigerant circulation loop, and connects the plurality of refrigerant circulation loops in the connected state so that the circulation pump of at least one refrigerant circulation loop circulates the refrigerant in at least one of the other refrigerant circulation loops as well.

[0008] Embodiments in which any combination of the above-mentioned components and the components or expressions of the invention are substituted between a method, a device, a system, and the like are also effective as aspects of the invention.

[0009] According to the invention, the continuity of the cooling operation of a cryogenic system can be improved.

BRIEF DESCRIPTION OF THE DRAWINGS

[0010]

FIG. 1 is a diagram schematically showing a cryogenic system according to an embodiment.

FIG. 2 is a table illustrating a relationship between failure modes of the cryogenic system according to the embodiment and the state of a connection line.

FIG. 3 is a diagram schematically showing the cryogenic system according to the embodiment.

FIG. 4 is a diagram schematically showing another example of the cryogenic system according to the embodiment.

FIG. 5 is a table illustrating a relationship between failure modes of the cryogenic system shown in FIG. 4 and the state of a connection line.

FIG. 6 is a diagram schematically showing another example of the cryogenic system according to the embodiment.

FIG. 7 is a table illustrating a relationship between failure modes of the cryogenic system shown in FIG. 6 and the state of a connection line.

DETAILED DESCRIPTION OF THE INVENTION

[0011] An embodiment of the invention will be described in detail below with reference to the drawings. The same or equivalent components, members, and processing in the description and the drawings are denoted by the same reference numerals and the repeated description thereof will be appropriately omitted. The scale and shape of each part to be shown are conveniently set to facilitate description, and is not interpreted in a limited way as long as not particularly mentioned.

The embodiment is exemplary, and does not limit the scope of the invention at all. All the characteristics to be described in the embodiment or combinations thereof are not necessarily essential in the invention.

[0012] FIG. 1 is a diagram schematically showing a cryogenic system 10 according to an embodiment. The cryogenic system 10 includes a plurality of refrigerant circulation loops 12, a connection line 14, a vacuum vessel 16, and a cryogenic cooling unit 20 that cools an object 18 to be cooled. A radiation shield, which is used to suppress the incidence of radiant heat on the object 18 to be cooled and the cryogenic cooling unit 20, is usually installed in the vacuum vessel 16, but is not shown for simplification.

[0013] The refrigerant circulation loops 12 are adapted to cool the cryogenic cooling unit 20 by heat exchange between the cryogenic cooling unit 20 and a refrigerant. The refrigerant is, for example, a refrigerant gas (for example, helium). Each of the plurality of refrigerant circulation loops 12 circulates the refrigerant. The connection line 14 connects the plurality of refrigerant circulation loops 12 so that the refrigerant can be circulated. The exemplary structures of the refrigerant circulation loops 12 and the connection line 14 will be described later.

[0014] The vacuum vessel 16 is a cryogenic vacuum vessel, such as a cryostat, and partitions the cryogenic system 10 into a normal-temperature section 22 and a low-temperature section 24. That is, the normal-temperature section 22 of the cryogenic system 10 is disposed outside the vacuum vessel 16, and the low-temperature section 24 of the cryogenic system 10 is disposed in the vacuum vessel 16. The normal-temperature section 22 takes, for example, a room temperature or a temperature of about 300K.

[0015] For example, the object 18 to be cooled is a detection element that detects infrared rays, submillimeter waves, X-rays, or other electromagnetic waves, and such a detection element is a component of an observation device that is used for astronomical observation. The object 18 to be cooled is in physical contact with the cryogenic cooling unit 20 and is thermally coupled to the cryogenic cooling unit 20, or is thermally coupled to the cryogenic cooling unit 20 through a heat transfer member.

[0016] The cryogenic cooling unit 20 is also called a cooling stage. As shown in FIG. 1, the cryogenic system 10 may include one common cooling stage as the cryogenic cooling unit 20. Alternatively, the cryogenic cooling unit 20 may include a plurality of cooling stages. In this case, each of the refrigerant circulation loops 12 may be provided with the cooling stage (for example, see FIG. 4).

[0017] The cryogenic system 10 is adapted to be capable of being mounted on, for example, a spacecraft, such as an artificial satellite, together with the object 18 to be cooled. The cryogenic system 10 may be mounted on a ground facility including the object 18 to be cooled. The cryogenic system 10 may be mounted on a spacecraft or a ground facility together with, for example, a

superconducting device or other objects 18 to be cooled for which a cryogenic environment is desirable.

[0018] The refrigerant circulation loops 12 include a first refrigerant circulation loop 12a and a second refrigerant circulation loop 12b. Since these refrigerant circulation loops 12 have the same configuration, the configuration of the first refrigerant circulation loop 12a will be mainly described below and the description of the second refrigerant circulation loop 12b will be appropriately omitted.

[0019] The first refrigerant circulation loop 12a includes a circulation pump 26 that circulates a refrigerant and a mechanical refrigerator (hereinafter, simply referred to as a refrigerator) 28 that cools the refrigerant.

[0020] The circulation pump 26 is adapted to increase the pressure of a refrigerant gas, which is collected from, for example, the low-temperature section 24, to, for example, about the atmospheric pressure or about several atmospheres. The circulation pump 26 can recover a pressure loss that occurs on the refrigerant in the refrigerant circulation loop 12. The circulation pump 26 may be a pump of which the output is lower than the output of a compressor 30 to be described later (for example, by about several W). The circulation pump 26 is disposed in the normal-temperature section 22 of the cryogenic system 10.

[0021] For example, the refrigerator 28 is a two-stage Stirling refrigerator. The refrigerator 28 includes a compressor 30, a two-stage cold head 32 as an expander, and a connecting pipe 34 that connects the compressor 30 to the two-stage cold head 32. The connecting pipe 34 provides a gas flow channel that circulates a refrigerant gas (for example, a helium gas) between the compressor 30 and the two-stage cold head 32. The two-stage cold head 32 includes a first-stage refrigerator stage 36 and a second-stage refrigerator stage 38. The normal-temperature section 22 of the cryogenic system 10 includes the compressor 30, a room-temperature portion of the two-stage cold head 32, and the connecting pipe 34, and the low-temperature section 24 of the cryogenic system 10 includes the first-stage refrigerator stage 36 and the second-stage refrigerator stage 38.

[0022] The compressor 30 is adapted to generate the pressure oscillation of a refrigerant gas. The generated pressure oscillation is transmitted to the two-stage cold head 32 through the connecting pipe 34. The two-stage cold head 32 is adapted to induce pressure oscillation where the pressure oscillation transmitted from the compressor 30 has a phase difference at the same frequency as the pressure oscillation in the two-stage cold head 32. Accordingly, a refrigeration cycle (specifically, reverse Stirling cycle) is formed between the compressor 30 and the two-stage cold head 32.

[0023] In this way, the first-stage refrigerator stage 36 of the refrigerator 28 is cooled to a first-stage cooling temperature and the second-stage refrigerator stage 38 is cooled to a second-stage cooling temperature. The first-stage cooling temperature of the refrigerator 28 is

selected from the temperature range of, for example, 50K to 150K. The first-stage cooling temperature maybe in the temperature range of, for example, 80K to 120K. The second-stage cooling temperature is lower than the first-stage cooling temperature. The second-stage cooling temperature is selected from the temperature range of, for example, 4K to 25K. The second-stage cooling temperature may be in the temperature range of, for example, 10K to 20K. The second-stage cooling temperature may be lower than 4K (for example, in the range of 1K to 4K).

[0024] The first refrigerant circulation loop 12a further includes a first heat exchanger 40, a first-stage cooling unit 42, a second heat exchanger 44, a second-stage cooling unit 46, and a cooling-stage heat exchanger 48. The first heat exchanger 40, the first-stage cooling unit 42, the second heat exchanger 44, the second-stage cooling unit 46, and the cooling-stage heat exchanger 48 are disposed in the vacuum vessel 16, that is, in the low-temperature section 24 of the cryogenic system 10.

[0025] Further, for the connection of these components, the first refrigerant circulation loop 12a further includes a refrigerant supply line 50 and a refrigerant collection line 52. The refrigerant supply line 50 connects the discharge side of the circulation pump 26 to the supply side of the cooling-stage heat exchanger 48, and the refrigerant collection line 52 connects the collection side of the cooling-stage heat exchanger 48 to the suction side of the circulation pump 26. Accordingly, a part of each of the refrigerant supply line 50 and the refrigerant collection line 52 is disposed in the normal-temperature section 22, and the remaining part thereof is disposed in the low-temperature section 24.

[0026] The refrigerant supply line 50 includes a supply-side refrigerant pipe 51 in the low-temperature section 24, and the refrigerant collection line 52 includes a collection-side refrigerant pipe 53 in the low-temperature section 24 (for example, pipes surrounded in FIG. 1 by a broken line). The supply-side refrigerant pipe 51 connects the second-stage cooling unit 46 to the cooling-stage heat exchanger 48, and the collection-side refrigerant pipe 53 connects the cooling-stage heat exchanger 48 to a collection-side flow channel of the second heat exchanger 44. A refrigerant is supplied to the cooling-stage heat exchanger 48 from the second-stage cooling unit 46 through the supply-side refrigerant pipe 51, and the refrigerant is collected to the second heat exchanger 44 from the cooling-stage heat exchanger 48 through the collection-side refrigerant pipe 53.

[0027] The first heat exchanger 40 cools a high-temperature (for example, a normal temperature, for example, about 300K) refrigerant gas that flows into the vacuum vessel 16 from the circulation pump 26. The second heat exchanger 44 further cools the refrigerant that is cooled by the first heat exchanger 40 and the first-stage cooling unit 42.

[0028] Each of the first and second heat exchangers 40 and 44 is a counterflow heat exchanger. The refrigerant supply line 50 includes a supply-side flow channel

of each of the first and second heat exchangers 40 and 44, and the refrigerant collection line 52 includes a collection-side flow channel of each of the first and second heat exchangers 40 and 44. A refrigerant, which flows through the supply-side flow channel, can be cooled in each heat exchanger by heat exchange between the supply-side flow channel and the collection-side flow channel.

[0029] The first-stage cooling unit 42 is thermally coupled to the first-stage refrigerator stage 36. A refrigerant, which flows through the first-stage cooling unit 42, is cooled by heat exchange with the first-stage refrigerator stage 36. The first-stage cooling unit 42 is disposed on the refrigerant supply line 50 between the first and second heat exchangers 40 and 44.

[0030] The second-stage cooling unit 46 is thermally coupled to the second-stage refrigerator stage 38. A refrigerant, which flows through the second-stage cooling unit 46, is cooled by the second-stage refrigerator stage 38. The second-stage cooling unit 46 is disposed on the refrigerant supply line 50 between the second heat exchanger 44 and the cooling-stage heat exchanger 48.

[0031] The cooling-stage heat exchanger 48 is thermally coupled to the cryogenic cooling unit 20. A refrigerant, which flows through the cooling-stage heat exchanger 48, cools the cryogenic cooling unit 20.

[0032] Likewise, the second refrigerant circulation loop 12b includes a circulation pump 26 and a refrigerator 28. The refrigerator 28 includes a compressor 30, a two-stage cold head 32, and a connecting pipe 34. The two-stage cold head 32 includes a first-stage refrigerator stage 36 and a second-stage refrigerator stage 38. Further, the second refrigerant circulation loop 12b includes a first heat exchanger 40, a first-stage cooling unit 42, a second heat exchanger 44, a second-stage cooling unit 46, a cooling-stage heat exchanger 48, a refrigerant supply line 50, and a refrigerant collection line 52.

[0033] The first refrigerant circulation loop 12a includes a backflow prevention unit 54. The backflow prevention unit 54 includes a pair of on-off valves (V1 and V2) for backflow prevention. One on-off valve V1 for backflow prevention is provided on the refrigerant collection line 52, and the other on-off valve V2 for backflow prevention is provided on the refrigerant supply line 50. The on-off valves (V1 and V2) for backflow prevention are opened in an unconnected state of the connection line 14. The on-off valves (V1 and V2) for backflow prevention are closed in a connected state of the connection line 14. The details of the unconnected state and the connected state of the connection line 14 will be described later.

[0034] In the example shown in FIG. 1, two on-off valves (V1 and V2) for backflow prevention are provided on the upstream side and the downstream side of the circulation pump 26, respectively. However, only one on-off valve for backflow prevention may be provided, and any one of the on-off valves (V1 and V2) for backflow prevention may be provided in this case.

[0035] Likewise, the second refrigerant circulation loop

12b also includes a backflow prevention unit 54. On-off valves for backflow prevention of the second refrigerant circulation loop 12b are denoted by V5 and V6 for convenience so as to be distinguished from the on-off valves (V1 and V2) for backflow prevention of the first refrigerant circulation loop 12a. Only one on-off valve for backflow prevention may be provided on the second refrigerant circulation loop 12b as well, and any one of the on-off valves (V5 and V6) for backflow prevention may be provided in this case.

[0036] The circulation of the backflow of a refrigerant in each refrigerant circulation loop 12 can be prevented by a relatively simple structure of closing the on-off valves (V1, V2, V5, and V6) for backflow prevention.

[0037] The backflow prevention units 54 are disposed in the normal-temperature section 22 of the cryogenic system 10. For this reason, a general-purpose component of which the operational reliability is ensured under a normal temperature can be employed as the backflow prevention unit 54. Such a general-purpose component can be available at a lower cost than a component of which the reliability in a cryogenic environment is ensured. The backflow prevention units 54 may be disposed in the low-temperature section 24 of the cryogenic system 10, if possible.

[0038] The connection line 14 is adapted to be switchable to the connected state from the unconnected state. The connection line 14 isolates the plurality of refrigerant circulation loops 12 from each other in the unconnected state so that the circulation pump 26 of each refrigerant circulation loop 12 circulates a refrigerant in the refrigerant circulation loop 12. On the other hand, the connection line 14 connects the plurality of refrigerant circulation loops 12 in the connected state so that the circulation pump 26 of at least one refrigerant circulation loop 12 circulates a refrigerant in at least one of the other refrigerant circulation loops 12 as well. The connection line 14 can also return to the unconnected state from the connected state.

[0039] The connection line 14 includes connection flow channels that connect the two refrigerant circulation loops 12 and on-off valves (V3 and V4) for connection that are provided on the connection flow channels, are closed in the unconnected state, and are opened in the connected state. The connected state and the unconnected state of the connection line 14 can be switched by a relatively simple structure of opening and closing the on-off valves (V3 and V4) for connection.

[0040] More specifically, the connection line 14 includes a supply-side connection flow channel 56 that connects the refrigerant supply lines 50 of the two refrigerant circulation loops 12 and a supply-side on-off valve V3 for connection that is provided on the supply-side connection flow channel 56. Further, the connection line 14 includes a collection-side connection flow channel 58 that connects the refrigerant collection lines 52 of the two refrigerant circulation loops 12 and a collection-side on-off valve V4 for connection that is provided on the collection-

side connection flow channel 58. Both the supply-side on-off valve V3 for connection and the collection-side on-off valve V4 for connection are closed in the unconnected state, and are opened in the connected state.

[0041] A supply-side junction 60 between the refrigerant supply line 50 and the supply-side connection flow channel 56 is disposed between the on-off valve V2 for backflow prevention and the supply-side flow channel of the first heat exchanger 40. Accordingly, the on-off valve V2 for backflow prevention is disposed between the discharge side of the circulation pump 26 and the supply-side junction 60. Further, a collection-side junction 62 between the refrigerant collection line 52 and the collection-side connection flow channel 58 is disposed between the on-off valve V1 for backflow prevention and the collection-side flow channel of the first heat exchanger 40. Accordingly, the on-off valve V1 for backflow prevention is disposed between the suction side of the circulation pump 26 and the collection-side junction 62.

[0042] The connection line 14 is disposed in the normal-temperature section 22 of the cryogenic system 10. Accordingly, general-purpose components of which the operational reliability is ensured under a normal temperature can be employed as the on-off valves (V3 and V4) for connection or the other components of the connection line 14. Such a general-purpose component can be available at a lower cost than a component of which the reliability in a cryogenic environment is ensured. The connection line 14 may be disposed in the low-temperature section 24 of the cryogenic system 10, if possible.

[0043] In a case in which the respective on-off valves (V1 to V6) provided on the refrigerant circulation loops 12 and the connection line 14 are opened, a refrigerant can flow through the on-off valves. However, in a case in which the respective on-off valves (V1 to V6) are closed, a refrigerant cannot flow through the on-off valves. The respective on-off valves (V1 to V6) may be electromagnetic on-off valves, mechanical on-off valves, manual on-off valves, or other driven-type on-off valves.

[0044] FIG. 2 is a table illustrating a relationship between failure modes of the cryogenic system 10 according to the embodiment and the state of the connection line 14. The open/closed states of the respective on-off valves (V1 to V6) of the connection line 14 are shown so as to correspond to some failure modes. In the table, "open" represents that the on-off valve is opened and "close" represents that the on-off valve is closed.

[0045] A normal operation and four failure modes of the cryogenic system 10 are exemplified in FIG. 2. "Normal operation" represents that all the circulation pumps 26 and the refrigerators 28 provided in the cryogenic system 10 are normally operated without a failure. "ST1 failure" represents that a failure occurs in the refrigerator 28 of the first refrigerant circulation loop 12a, and "ST2 failure" represents that a failure occurs in the refrigerator 28 of the second refrigerant circulation loop 12b. "P1 failure" represents that a failure occurs in the circulation pump 26 of the first refrigerant circulation loop 12a, and

"P2 failure" represents that a failure occurs in the circulation pump 26 of the second refrigerant circulation loop 12b.

[0046] Since a temperature sensor 64, which measures the temperature of the refrigerator stage, is usually installed on at least one of the first-stage refrigerator stage 36 and the second-stage refrigerator stage 38, it is possible to determine whether or not a failure occurs in the refrigerator 28 from the measurement result of the temperature sensor 64. Since a refrigerant sensor 66, such as a pressure sensor for measuring the pressure of a refrigerant (and/or a flow sensor for measuring the flow rate of a refrigerant), is usually installed on the refrigerant circulation loop 12, it is possible to determine whether or not a failure occurs in the circulation pump 26 from the measurement result of the refrigerant sensor 66.

[0047] As shown in the column of "normal operation" in FIG. 2, in a case in which the cryogenic system 10 is normally operated without a failure or abnormality, all the on-off valves (V1, V2, V5, and V6) for backflow prevention are opened and the both the supply-side on-off valve V3 for connection and the collection-side on-off valve V4 for connection are closed. This state is the unconnected state of the connection line 14. The supply-side on-off valve V3 for connection and the collection-side on-off valve V4 for connection are closed in the unconnected state.

[0048] Accordingly, in the unconnected state of the connection line 14, as shown in FIG. 1 by arrows, the circulation pump 26 of the first refrigerant circulation loop 12a circulates a refrigerant in the first refrigerant circulation loop 12a and the circulation pump 26 of the second refrigerant circulation loop 12b circulates a refrigerant in the second refrigerant circulation loop 12b. A refrigerant does not flow in the connection line 14, and is not circulated between the first refrigerant circulation loop 12a and the second refrigerant circulation loop 12b. In this way, the plurality of refrigerant circulation loops 12 are operated independently of each other.

[0049] In the normal operation of the cryogenic system 10, a refrigerant, which is sent to the refrigerant supply line 50 from the circulation pump 26 of each refrigerant circulation loop 12, flows into the vacuum vessel 16 and is supplied to the supply-side flow channel of the first heat exchanger 40 for the first time. The refrigerant, which flows through the supply-side flow channel of the first heat exchanger 40, is cooled by exchanging heat with a return refrigerant that flows through the collection-side flow channel of the first heat exchanger 40. The refrigerant, which is cooled by the first heat exchanger 40, flows into the first-stage cooling unit 42 through the refrigerant supply line 50.

[0050] The refrigerant is cooled in the first-stage cooling unit 42 by the first-stage refrigerator stage 36, and is sent to the supply-side flow channel of the second heat exchanger 44. The refrigerant, which flows through the supply-side flow channel of the second heat exchanger 44, is cooled by exchanging heat with a return refrigerant

that flows through the collection-side flow channel of the second heat exchanger 44. The refrigerant, which is cooled by the second heat exchanger 44, flows into the second-stage cooling unit 46 through the refrigerant supply line 50.

[0051] The refrigerant is cooled in the second-stage cooling unit 46 by the second-stage refrigerator stage 38, and is supplied to the cooling-stage heat exchanger 48. The cryogenic cooling unit 20 is cooled by heat exchange between the refrigerant, which flows through the cooling-stage heat exchanger 48, and the cryogenic cooling unit 20. The cryogenic cooling unit 20 is cooled to, for example, the second-stage cooling temperature of the refrigerator 28. Accordingly, the cryogenic cooling unit 20 can cool the object 18 to be cooled to the temperature range of the second-stage cooling temperature.

[0052] The refrigerant flows to the refrigerant collection line 52 from the cooling-stage heat exchanger 48. The refrigerant flows through the refrigerant collection line 52 in the order of the second heat exchanger 44 and the first heat exchanger 40. The temperature of the return refrigerant rises while the return refrigerant cools the refrigerant, which flows through the refrigerant supply line 50, at each of the heat exchangers (44 and 40) as described above. The refrigerant, which returns to the normal temperature in this way, gets out of the vacuum vessel 16, is collected to the circulation pump 26, and is sent again. In this way, the respective refrigerant circulation loops 12 are operated individually at the time of the normal operation and the cryogenic system 10 can cool the cryogenic cooling unit 20 and the object 18 to be cooled.

[0053] As shown in FIG. 2, the connection line 14 is in the unconnected state in the cases of the ST1 failure and the ST2 failure as well. However, in these cases, unlike in the case of the normal operation, a refrigerant does not need to be circulated in the refrigerant circulation loop 12 to which the refrigerator 28 in which a failure occurs belongs. Accordingly, the operation of the circulation pump 26 of the first refrigerant circulation loop 12a is stopped in the case of the ST1 failure, and the circulation pump 26 of the second refrigerant circulation loop 12b is stopped in the case of the ST2 failure. In this way, the circulation pump 26 of the refrigerant circulation loop 12 to which the refrigerator 28 in which a failure occurs belongs is stopped, and the circulation pump 26 of the other refrigerant circulation loop 12 continues to be operated.

[0054] In the cases of the ST1 failure and the ST2 failure, the refrigerator 28 cannot be already cooled. The refrigerator 28 becomes a heat transfer path for heat to be transferred to the refrigerator stage from the normal-temperature section 22. The refrigerator 28 in which a failure occurs can also be said a heat penetration source. Heat penetrates due to the conduction of heat to the first-stage refrigerator stage 36 and the second-stage refrigerator stage 38 from the normal-temperature section 22 through structural members (for example, a cylinder, a displacer, and the like) of the refrigerator 28. As a result, the temperature of each of the first-stage refrigerator

stage 36 and the second-stage refrigerator stage 38 gradually rises to a normal temperature. If the cryogenic cooling unit 20 is directly mounted on the refrigerator stage, the temperature of the cryogenic cooling unit 20 also rises together with the temperature of the refrigerator stage due to the failure of the refrigerator 28. Since the cooling capacity of the cryogenic system 10 is reduced, it may be also difficult to maintain the cooling of the object 18 to be cooled.

[0055] However, in this embodiment, a heat transfer path for heat to be transferred to the cryogenic cooling unit 20 from the refrigerator stage in the cases of the ST1 failure and the ST2 failure is limited to the supply-side refrigerant pipe 51 and the collection-side refrigerant pipe 53. Each of the supply-side refrigerant pipe 51 and the collection-side refrigerant pipe 53 is a thin pipe which is relatively long and of which the thickness of a wall is small. The amount of heat, which is transferred to the cryogenic cooling unit 20 from the first-stage refrigerator stage 36 and the second-stage refrigerator stage 38 through the supply-side refrigerant pipe 51 and the collection-side refrigerant pipe 53 by the conduction of heat, is limited. For this reason, since the temperature rise of the cryogenic cooling unit 20 is delayed even though a failure occurs in the refrigerator 28, the cooling of the object 18 to be cooled can be continued to some extent.

[0056] Preferably, the supply-side refrigerant pipe 51 and the collection-side refrigerant pipe 53 are designed to limit penetration heat that is generated due to the conduction of heat to the cryogenic cooling unit 20 from the refrigerator stage (for example, the second-stage refrigerator stage 38) caused by the failure of the refrigerator 28, or are designed so that the penetration heat can be substantially ignored. Thermal connection between the refrigerator 28 and the cryogenic cooling unit 20 is limited by a combination of such a design of a low-temperature-section refrigerant pipe and the stop of the operation of the circulation pump 26. Further, since a refrigerant, which is cooled by the refrigerator 28, is supplied to the cryogenic cooling unit 20 by the operation of the circulation pump 26 in the normal state of the refrigerator 28, the thermal connection between the refrigerator 28 and the cryogenic cooling unit 20 is maintained. In this way, the low-temperature-section refrigerant pipe and the circulation pump 26 function as a so-called thermal switch.

[0057] There are various problems in a case in which a generally-known mechanical thermal switch is applied to the cryogenic system 10. In a case in which the mechanical thermal switch is disposed in a cryogenic environment, operational reliability at a very low temperature or the generation of heat from a drive unit may become a problem. In a case in which the drive unit of the mechanical thermal switch is disposed under a normal temperature, the drive of a switch is transmitted from the drive unit through a transmission member but this transmission member becomes a heat transfer path. Accordingly, the mechanical thermal switch is not used in this embodiment. Further, a gas-gap type thermal switch suit-

able for a cryogenic environment is also already known. However, since this thermal switch can be operated only in a cryogenic range equal to or lower than 4K, the thermal switch cannot be used in a cryogenic range higher than 4K.

[0058] In contrast, the above-mentioned combination of the low-temperature-section refrigerant pipe and the circulation pump 26 does not have disadvantages, which are caused by an existing thermal switch, at all or hardly has the disadvantages. A refrigerator 28 in which a failure occurs can be easily thermally isolated from the cryogenic system 10 by the use of this combination.

[0059] At least one refrigerant circulation loop 12 includes the low-temperature-section refrigerant pipe (the supply-side refrigerant pipe 51 and/or the collection-side refrigerant pipe 53) that is disposed in the low-temperature section 24 of the cryogenic system 10. The amount of heat per unit time to be transferred due to the conduction of heat to the refrigerator stage of the refrigerator 28 from the normal-temperature section 22 of the cryogenic system 10, which is supposed in a case in which the refrigerator 28 does not function, may be in the range of 1/100 to 1/1000 (for example, 1/400 to 1/500) of the amount of heat per unit time that is transferred due to the conduction of heat to the cryogenic cooling unit 20 from the refrigerator stage through the low-temperature-section refrigerant pipe. Here, the case in which the refrigerator 28 does not function means a state in which the operation of the refrigerator 28 is stopped due to a failure or the like and the refrigerator 28 does not perform cooling work. In this case, penetration heat, which is generated due to the conduction of heat to the cryogenic cooling unit 20 from the refrigerator stage caused by the failure of the refrigerator 28, can be substantially ignored.

[0060] As an example of the design of the low-temperature-section refrigerant pipe, the material, the length, and the cross-sectional area of the low-temperature-section refrigerant pipe may be designed so that the amount of heat per unit time to be transferred due to the conduction of heat to the refrigerator stage of the refrigerator 28 from the normal-temperature section 22, which is supposed in a case in which the refrigerator does not function, is in the range of 1/100 to 1/1000 (for example, 1/400 to 1/500) of the amount of heat per unit time to be transferred due to the conduction of heat to the cryogenic cooling unit 20 from the refrigerator stage through the low-temperature-section refrigerant pipe. In this case, penetration heat, which is generated due to the conduction of heat to the cryogenic cooling unit 20 from the refrigerator stage caused by the failure of the refrigerator 28, can be substantially ignored.

[0061] The supply-side refrigerant pipe 51 and the collection-side refrigerant pipe 53 are made of, for example, a material that has a thermal conductivity lower than the thermal conductivity of the material of the refrigerator stage. Since the refrigerator stage is usually made of copper, each of the supply-side refrigerant pipe 51 and the collection-side refrigerant pipe 53 may be a pipe

made of, for example, stainless steel. Each of the supply-side refrigerant pipe 51 and the collection-side refrigerant pipe 53 may be a flexible pipe. In this case, the transmission of vibration to the cryogenic cooling unit 20 from the refrigerator 28 can be suppressed.

[0062] Each of the supply-side refrigerant pipe 51 and the collection-side refrigerant pipe 53 is relatively long and is longer than, for example, the length of the refrigerator 28 in an axial direction. The length of each of the supply-side refrigerant pipe 51 and the collection-side refrigerant pipe 53 may be 2 times or more, 5 times or more, or 10 times or more the length of the refrigerator 28 in the axial direction. Here, the length of the refrigerator 28 in the axial direction may be a distance between the surface of a wall of the vacuum vessel 16 on which the refrigerator 28 is mounted and the refrigerator stage (for example, the second-stage refrigerator stage 38) (in other words, a distance between the normal-temperature section 22 and the refrigerator stage). In a case in which the cold head (for example, the two-stage cold head 32) includes a reciprocating member, such as a displacer, the axial direction of the refrigerator 28 corresponds to the reciprocating direction of the reciprocating member. The length of each of the supply-side refrigerant pipe 51 and the collection-side refrigerant pipe 53 may be 100 times or less the length of the refrigerator 28 in the axial direction.

[0063] Further, the cross-sectional area of each of the supply-side refrigerant pipe 51 and the collection-side refrigerant pipe 53 is relatively small and is smaller than, for example, the cross-sectional area of the refrigerator 28. The cross-sectional area of each of the supply-side refrigerant pipe 51 and the collection-side refrigerant pipe 53 may be 1/2 or less, 1/5 or less, or 1/10 or less of the cross-sectional area of the refrigerator 28. Here, the cross-sectional area of the refrigerant pipe means a cross-sectional area perpendicular to the axial direction of the pipe, and is obtained from the inner diameter and the outer diameter of the refrigerant pipe. The cross-sectional area of the refrigerator 28 means a cross-sectional area perpendicular to the axial direction of the refrigerator 28. For example, the cross-sectional area of the refrigerator 28 may be the cross-sectional area of a cylinder member of the cold head (for example, the two-stage cold head 32). The cross-sectional area of the cylinder member is obtained from the inner diameter and the outer diameter of the cylinder member. Each of the supply-side refrigerant pipe 51 and the collection-side refrigerant pipe 53 may be a pipe of which the thickness of a wall is smaller than that of the cylinder member. The cross-sectional area of each of the supply-side refrigerant pipe 51 and the collection-side refrigerant pipe 53 may be 1/100 or more of the cross-sectional area of the refrigerator 28.

[0064] As shown in FIG. 2, in the case of the P1 failure, the on-off valves (V1 and V2) for backflow prevention of the first refrigerant circulation loop 12a to which the circulation pump 26 in which a failure occurs belongs are closed and the supply-side on-off valve V3 for connection

and the collection-side on-off valve V4 for connection are opened together. The on-off valves (V5 and V6) for backflow prevention of the second refrigerant circulation loop 12b to which a normal circulation pump 26 belongs are opened. Further, in the case of the P2 failure, the on-off valves (V5 and V6) for backflow prevention of the second refrigerant circulation loop 12b to which the circulation pump 26 in which a failure occurs belongs are closed and the supply-side on-off valve V3 for connection and the collection-side on-off valve V4 for connection are opened together. The on-off valves (V1 and V2) for backflow prevention of the first refrigerant circulation loop 12a to which a normal circulation pump 26 belongs are opened. These states correspond to the connected state of the connection line 14. In the connected state, the supply-side on-off valve V3 for connection and the collection-side on-off valve V4 for connection are opened.

[0065] The flow of a refrigerant in the connected state of the connection line 14 is shown in FIG. 3 by arrows. The P2 failure, that is, a case in which a failure occurs in the circulation pump 26 of the second refrigerant circulation loop 12b is shown as an example. Accordingly, the circulation pump 26 of the first refrigerant circulation loop 12a is normally operated but the circulation pump 26 of the second refrigerant circulation loop 12b is not operated. As shown in FIG. 3, the circulation pump 26 of the first refrigerant circulation loop 12a circulates a refrigerant in both the first refrigerant circulation loop 12a and the second refrigerant circulation loop 12b. A refrigerant is circulated in the first refrigerant circulation loop 12a as in the normal state.

[0066] In regard to the second refrigerant circulation loop 12b, a refrigerant is supplied to the refrigerant supply line 50 of the second refrigerant circulation loop 12b from the refrigerant supply line 50 of the first refrigerant circulation loop 12a through the supply-side connection flow channel 56. The refrigerant is cooled by the heat exchangers (40 and 44) and the refrigerator stages (36 and 38), is supplied to the cooling-stage heat exchanger 48, and flows out to the refrigerant collection line 52. The refrigerant returns to the refrigerant collection line 52 of the first refrigerant circulation loop 12a from the refrigerant collection line 52 of the second refrigerant circulation loop 12b through the collection-side connection flow channel 58, and is collected to the circulation pump 26 of the first refrigerant circulation loop 12a. Since the on-off valves (V5 and V6) for backflow prevention of the second refrigerant circulation loop 12b are closed, the circulation of the backflow of a refrigerant in the second refrigerant circulation loop 12b in the connected state of the connection line 14 is prevented.

[0067] In the case of the P1 failure, the circulation pump 26 of the second refrigerant circulation loop 12b can circulate a refrigerant in both the first refrigerant circulation loop 12a and the second refrigerant circulation loop 12b.

[0068] In this way, in a case in which a failure occurs in the circulation pump 26 of a certain refrigerant circulation loop 12, the cryogenic system 10 can cool the cry-

ogenic cooling unit 20 by operating the plurality of refrigerant circulation loops 12 using the normal circulation pump 26 of the other refrigerant circulation loop 12. Even though a failure occurs in any circulation pump 26, the cooling operation of the cryogenic system 10 can be continued.

[0069] As described above, the cryogenic system 10 according to this embodiment includes the first refrigerant circulation loop 12a, the second refrigerant circulation loop 12b, and the connection line 14 that connects these two refrigerant circulation loops 12. The connection line 14 is adapted to be switchable to the connected state from the unconnected state.

[0070] In the unconnected state, the first refrigerant circulation loop 12a and the second refrigerant circulation loop 12b are isolated from each other, the circulation pump 26 of the first refrigerant circulation loop 12a circulates a refrigerant in the first refrigerant circulation loop 12a, and the circulation pump 26 of the second refrigerant circulation loop 12b circulates a refrigerant in the second refrigerant circulation loop 12b. In the connected state, the first refrigerant circulation loop 12a and the second refrigerant circulation loop 12b are connected to each other through the connection line 14 and a refrigerant can be supplied to the second refrigerant circulation loop 12b from the first refrigerant circulation loop 12a or to the second refrigerant circulation loop 12b from the first refrigerant circulation loop 12a.

[0071] The connected state of the connection line 14 is selected in a case in which a failure occurs in any circulation pump 26, so that the cooling of the cryogenic system 10 can be continued by the other normal circulation pump 26. The cryogenic system 10, which has stable cooling performance for a longer time and uses a plurality of refrigerators 28, can be realized in this way.

[0072] The refrigerator 28 is not limited to a two-stage Stirling refrigerator, and may be another two-stage mechanical refrigerator, such as a two-stage GM refrigerator or a two-stage pulse tube refrigerator. Further, the refrigerator 28 may be a single-stage mechanical refrigerator, such as a single-stage Stirling refrigerator, a single-stage GM refrigerator, or a single-stage pulse tube refrigerator.

[0073] The cryogenic system 10 can be expanded for various applications. The cryogenic system 10 includes two refrigerators 28 in the above-mentioned embodiment, but the cryogenic system 10 may include three or more refrigerators 28.

[0074] Further, each refrigerant circulation loop 12 is provided with one circulation pump 26 and one refrigerator 28 in the above-mentioned embodiment, but the invention is not limited thereto. At least one refrigerant circulation loop may include a plurality of refrigerant circulation sub-loops, each of which includes a mechanical refrigerator. The refrigerant circulation loop is provided with at least one circulation pump that is shared by the plurality of refrigerant circulation sub-loops. The plurality of refrigerant circulation sub-loops may be adapted to be capable of being individually isolated from the circulation

pump.

[0075] FIG. 4 is a diagram schematically showing another example of the cryogenic system 10 according to the embodiment. FIG. 5 is a table illustrating a relationship between failure modes of the cryogenic system 10 shown in FIG. 4 and the state of a connection line 14.

[0076] The cryogenic system 10 according to the embodiment exemplified in FIGS. 4 and 5 is common to the cryogenic system 10 exemplified in FIGS. 1 to 3 except that each of the refrigerant circulation loops 12 includes a plurality of refrigerant circulation sub-loops 70. Hereinafter, differences between the cryogenic systems 10 according to the embodiments will be mainly described and common configuration will be briefly described or the description thereof will be omitted.

[0077] The cryogenic system 10 includes a first refrigerant circulation loop 12a and a second refrigerant circulation loop 12b. A connection line 14 connects the first refrigerant circulation loop 12a to the second refrigerant circulation loop 12b. Each of the refrigerant circulation loops 12 includes a plurality of refrigerant circulation sub-loops 70, that is, a first refrigerant circulation sub-loop 70a and a second refrigerant circulation sub-loop 70b. A circulation pump 26 of each refrigerant circulation loop 12 is shared by the plurality of refrigerant circulation sub-loops 70, and a refrigerant is supplied to both the first refrigerant circulation sub-loop 70a and the second refrigerant circulation sub-loop 70b from the common circulation pump 26. Further, the common circulation pump 26 collects a refrigerant from both the first refrigerant circulation sub-loop 70a and the second refrigerant circulation sub-loop 70b.

[0078] The cryogenic system 10 includes a total of four refrigerators 28. Each of the refrigerators 28 is a single-stage Stirling refrigerator. Cryogenic cooling units 20 include a plurality of cooling stages, and each of the cooling stages is cooled by the corresponding refrigerant circulation sub-loop 70. Each refrigerator 28 includes a first-stage refrigerator stage 36. Each of the refrigerant circulation sub-loops 70 includes a first heat exchanger 40, a first-stage cooling unit 42, a cooling-stage heat exchanger 48, a refrigerant supply line 50, and a refrigerant collection line 52.

[0079] The cryogenic system 10 includes eight on-off valves (V11 to V18). The open/closed states of the on-off valves (V11 to V18) in each failure mode are shown in FIG. 5. The on-off valves (V14 and V15) are on-off valves for connection, and the on-off valves (V11 and V16) are on-off valves for backflow prevention.

[0080] The remaining on-off valves (V12, V13, V17, and V18) are provided to individually isolate the refrigerant circulation sub-loops 70 from the refrigerant circulation loops 12. The on-off valves (V12 and V13) are disposed between the circulation pump 26 and the supply-side flow channel of the first heat exchanger 40, and the on-off valves (V17 and V18) are disposed between the circulation pump 26 and the supply-side flow channel of the first heat exchanger 40.

[0081] The on-off valve V12 is provided on the first refrigerant circulation sub-loop 70a of the first refrigerant circulation loop 12a, and is closed in a case in which a failure occurs in the refrigerator 28 of the first refrigerant circulation sub-loop 70a ("ST1 failure" of FIG. 5). In this case, since the other on-off valves (V11 and V13) of the first refrigerant circulation loop 12a are opened, the circulation pump 26 of the first refrigerant circulation loop 12a can circulate a refrigerant in the second refrigerant circulation sub-loop 70b of the first refrigerant circulation loop 12a.

[0082] Likewise, the on-off valve V13 is provided on the second refrigerant circulation sub-loop 70b of the first refrigerant circulation loop 12a, and is closed in a case in which a failure occurs in the refrigerator 28 of the second refrigerant circulation sub-loop 70b ("ST2 failure" of FIG. 5). The on-off valve V17 is provided on the first refrigerant circulation sub-loop 70a of the second refrigerant circulation loop 12b, and is closed in a case in which a failure occurs in the refrigerator 28 of the first refrigerant circulation sub-loop 70a ("ST3 failure" of FIG. 5). The on-off valve V18 is provided on the second refrigerant circulation sub-loop 70b of the second refrigerant circulation loop 12b, and is closed in a case in which a failure occurs in the refrigerator 28 of the second refrigerant circulation sub-loop 70b ("ST4 failure" of FIG. 5).

[0083] The connected state of the connection line 14 is selected by the cryogenic system 10 shown in FIGS. 4 and 5 as well in a case in which a failure occurs in any circulation pump 26, so that the cooling of the cryogenic system 10 can be continued by the other normal circulation pump 26.

[0084] Further, the corresponding on-off valve (V12, V13, V17, or V18) is closed in a case in which a failure occurs in any refrigerator 28, so that the refrigerant circulation sub-loop 70 to which the refrigerator 28 belongs can be isolated from the cryogenic system 10.

[0085] The supply-side refrigerant pipe 51 and the collection-side refrigerant pipe 53 are designed so that penetration heat generated due to the conduction of heat to the cryogenic cooling unit 20 from the refrigerator stage (for example, the first-stage refrigerator stage 36) caused by the failure of the refrigerator 28 can be substantially ignored. Thermal connection between the refrigerator 28 in which a failure occurs and the cryogenic cooling unit 20 is limited by a combination of such a design of a low-temperature-section refrigerant pipe and the on-off valves (V12, V13, V17, and V18). The penetration of heat into the cryogenic cooling unit 20 from the refrigerator 28 in which a failure occurs can be suppressed.

[0086] FIG. 6 is a diagram schematically showing another example of the cryogenic system 10 according to the embodiment. FIG. 7 is a table illustrating a relationship between failure modes of the cryogenic system 10 shown in FIG. 6 and the state of a connection line 14. The states of circulation pumps 26 (P1 to P4) of the respective refrigerant circulation loops 12 are also shown in FIG. 7.

[0087] The cryogenic system 10 according to the embodiment exemplified in FIGS. 6 and 7 is common to the cryogenic system 10 exemplified in FIGS. 1 to 3 except that the cryogenic system 10 includes four refrigerant circulation loops 12. Hereinafter, differences between the cryogenic systems 10 according to the embodiments will be mainly described and common configuration will be briefly described or the description thereof will be omitted.

[0088] The cryogenic system 10 includes a first refrigerant circulation loop 12a, a second refrigerant circulation loop 12b, a third refrigerant circulation loop 12c, and a fourth refrigerant circulation loop 12d. Each refrigerant circulation loop 12 is provided with one circulation pump 26 and one refrigerator 28. The refrigerator 28 is a single-stage Stirling refrigerator. The cryogenic system 10 includes a first connection line 14a that connects the first refrigerant circulation loop 12a to the second refrigerant circulation loop 12b, a second connection line 14b that connects the second refrigerant circulation loop 12b to the third refrigerant circulation loop 12c, and a third connection line 14c that connects the third refrigerant circulation loop 12c to the fourth refrigerant circulation loop 12d.

[0089] The cryogenic system 10 includes ten on-off valves (V21 to V30). The on-off valves (V22 and V23) for connection are provided on the first connection line 14a, the on-off valves (V25 and V26) for connection are provided on the second connection line 14b, and the on-off valves (V28 and V29) for connection are provided on the third connection line 14c. The remaining four on-off valves (V21, V24, V27, and V30) are on-off valves for backflow prevention of the first refrigerant circulation loop 12a, the second refrigerant circulation loop 12b, the third refrigerant circulation loop 12c, and the fourth refrigerant circulation loop 12d, respectively. The open/closed states of the on-off valves (V21 to V30) in each failure mode are shown in FIG. 7.

[0090] The connected state of the connection line 14 is selected by the cryogenic system 10 shown in FIGS. 6 and 7 as well in a case in which a failure occurs in any circulation pump 26, so that the cooling of the cryogenic system 10 can be continued by the other normal circulation pumps 26. For example, in a case in which a P1 failure occurs, the first connection line 14a is in a connected state (that is, the on-off valves (V22 and V23) for connection are opened) and a refrigerant can be circulated to the first refrigerant circulation loop 12a from the second refrigerant circulation loop 12b. In a case in which a P2 failure occurs, the first connection line 14a is in a connected state (that is, the on-off valves (V22 and V23) for connection are opened) and a refrigerant can be circulated to the second refrigerant circulation loop 12b from the first refrigerant circulation loop 12a. Alternatively, in a case in which a P2 failure occurs, the second connection line 14b is in a connected state (that is, the on-off valves (V25 and V26) for connection are opened) and a refrigerant can also be circulated to the second refrigerant circulation loop 12b from the third refrigerant circulation loop 12c.

tion loop 12c.

[0091] The connected state of the connection line 14 is selected by the cryogenic system 10 shown in FIGS. 6 and 7 as well in a case in which a failure occurs in any circulation pump 26, so that the cooling of the cryogenic system 10 can be continued by the other normal circulation pumps 26. Further, a refrigerator 28 in which a failure occurs can be thermally isolated from the cryogenic system 10 and the penetration of heat into the cryogenic cooling unit 20 from the refrigerator 28 in which a failure occurs can be suppressed by a combination of a low-temperature-section refrigerant pipe and the circulation pumps 26.

[0092] The invention has been described above on the basis of the embodiments. Since the invention can include various design changes without being limited to the above-mentioned embodiments, it is understood by those skilled in the art that the invention can have various modification examples and the modification examples are also included in the scope of the invention.

Brief Description of the Reference Symbols

[0093]

10: cryogenic system
 12: refrigerant circulation loop
 12a: first refrigerant circulation loop
 12b: second refrigerant circulation loop
 14: connection line
 20: cryogenic cooling unit
 22: normal-temperature section
 24: low-temperature section
 26: circulation pump
 28: refrigerator
 54: backflow prevention unit
 56: supply-side connection flow channel
 58: collection-side connection flow channel
 70: refrigerant circulation sub-loop
 70a: first refrigerant circulation sub-loop
 70b: second refrigerant circulation sub-loop

Claims

1. A cryogenic system comprising:

a cryogenic cooling unit;
 a plurality of refrigerant circulation loops which are adapted to cool the cryogenic cooling unit by heat exchange between the cryogenic cooling unit and a refrigerator and each of which includes a circulation pump circulating the refrigerant and a mechanical refrigerator cooling the refrigerant; and
 a connection line that connects the plurality of refrigerant circulation loops to allow the refrigerant to be circulated,

wherein the connection line is adapted to be switchable to a connected state from an unconnected state, isolates the plurality of refrigerant circulation loops from each other in the unconnected state so that the circulation pump of each refrigerant circulation loop circulates the refrigerant in the refrigerant circulation loop, and connects the plurality of refrigerant circulation loops in the connected state so that the circulation pump of at least one refrigerant circulation loop circulates the refrigerant in at least one of the other refrigerant circulation loops as well.

2. The cryogenic system according to claim 1,

wherein the connection line includes a connection flow channel that connects two refrigerant circulation loops and an on-off valve for connection that is provided on the connection flow channel, is closed in the unconnected state, and is opened in the connected state.

3. The cryogenic system according to claim 1 or 2,

wherein the connection line is disposed in a normal-temperature section of the cryogenic system.

4. The cryogenic system according to any one of claims 1 to 3,

wherein each refrigerant circulation loop includes a backflow prevention unit.

5. The cryogenic system according to claim 4,

wherein the backflow prevention unit includes an on-off valve for backflow prevention that is opened in the unconnected state and is closed in the connected state.

6. The cryogenic system according to claim 4 or 5,

wherein the backflow prevention unit is disposed in a normal-temperature section of the cryogenic system.

7. The cryogenic system according to any one of claims 1 to 6,

wherein at least one refrigerant circulation loop includes a plurality of refrigerant circulation sub-loops each of which includes the mechanical refrigerator, and the plurality of refrigerant circulation sub-loops are capable of being individually isolated from the circulation pumps.

8. The cryogenic system according to any one of claims 1 to 7,

wherein at least one refrigerant circulation loop includes a low-temperature-section refrigerant pipe that is disposed in a low-temperature section of the cryogenic system, and the amount of heat per unit time to be transferred due to conduction of heat to a refrigerator stage of the mechanical refrigerator from the normal-temperature section of the cryogenic system, which is supposed in a case in which the mechanical refrigerator does not function, is in a range of 1/100 to 1/1000 of the amount of heat per unit time to be transferred due to conduction of heat to the cryogenic cooling unit from the refrigerator stage through the low-temperature-section refrigerant pipe.

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FIG. 1

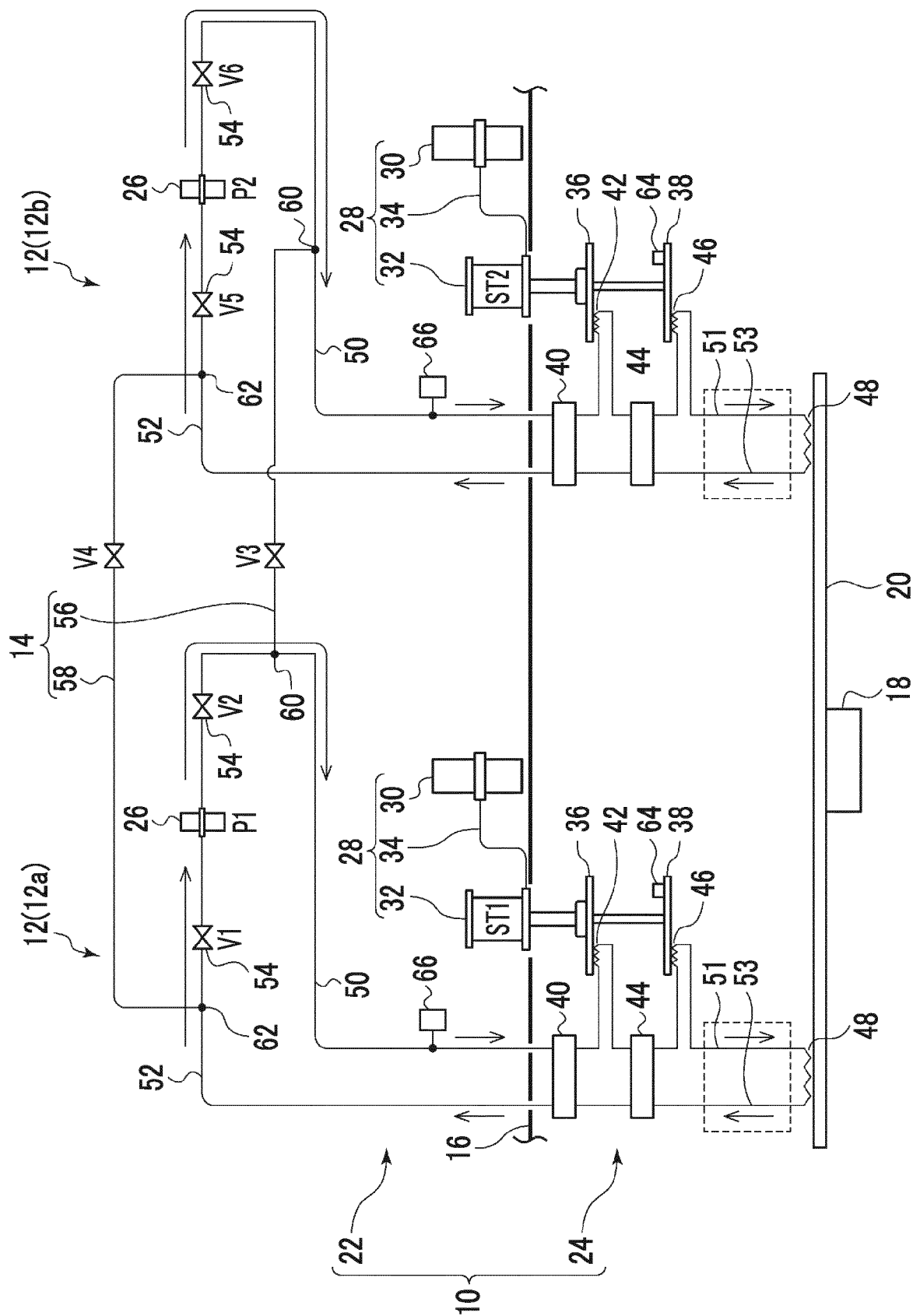
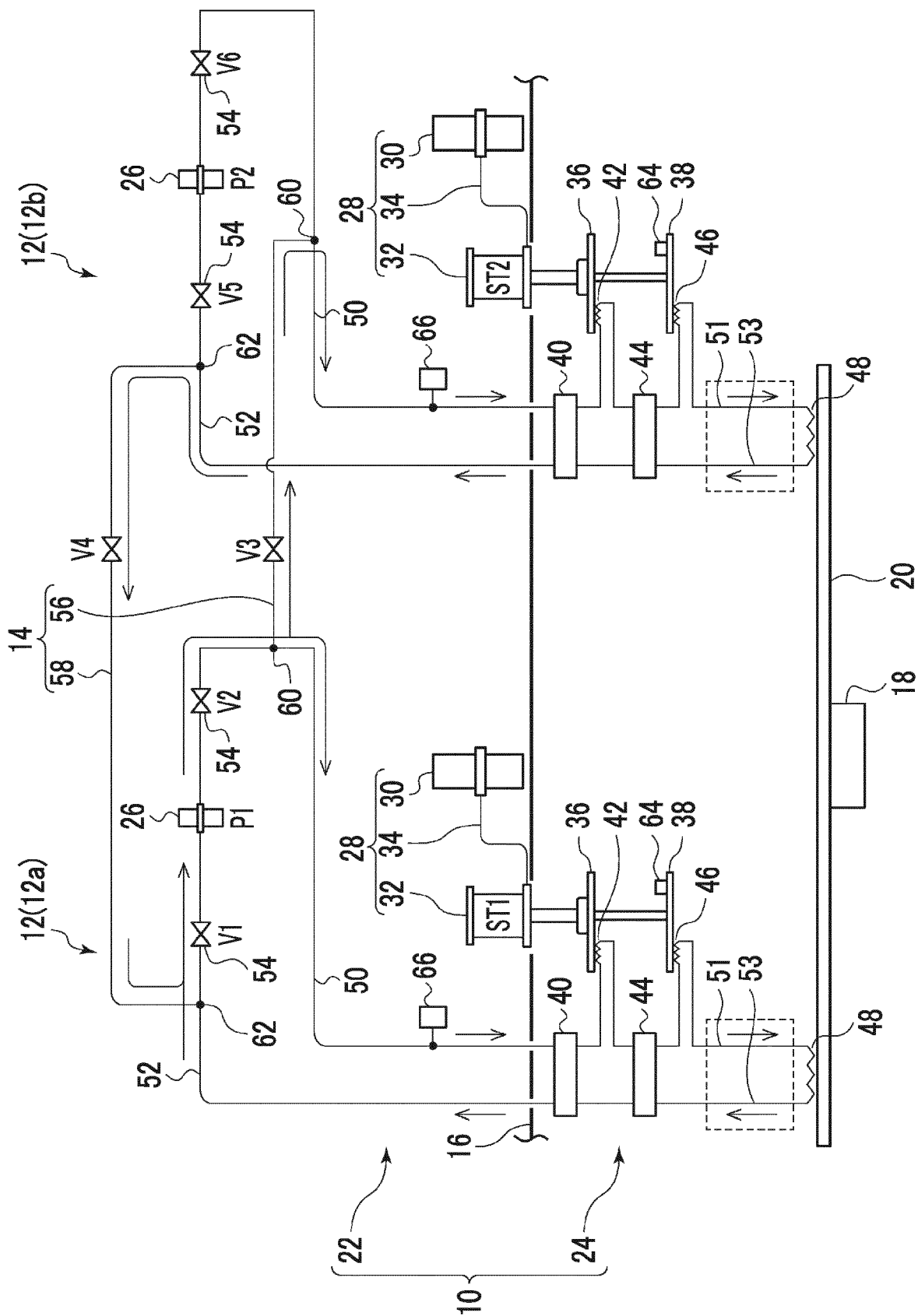


FIG. 2

FAILURE MODE	V1	V2	V3	V4	V5	V6
NORMAL OPERATION	Open	Open	Close	Close	Open	Open
ST1 FAILURE	Open	Open	Close	Close	Open	Open
ST2 FAILURE	Open	Open	Close	Close	Open	Open
P1 FAILURE	Close	Close	Open	Open	Open	Open
P2 FAILURE	Open	Open	Open	Open	Close	Close

3G+



E.G. 4

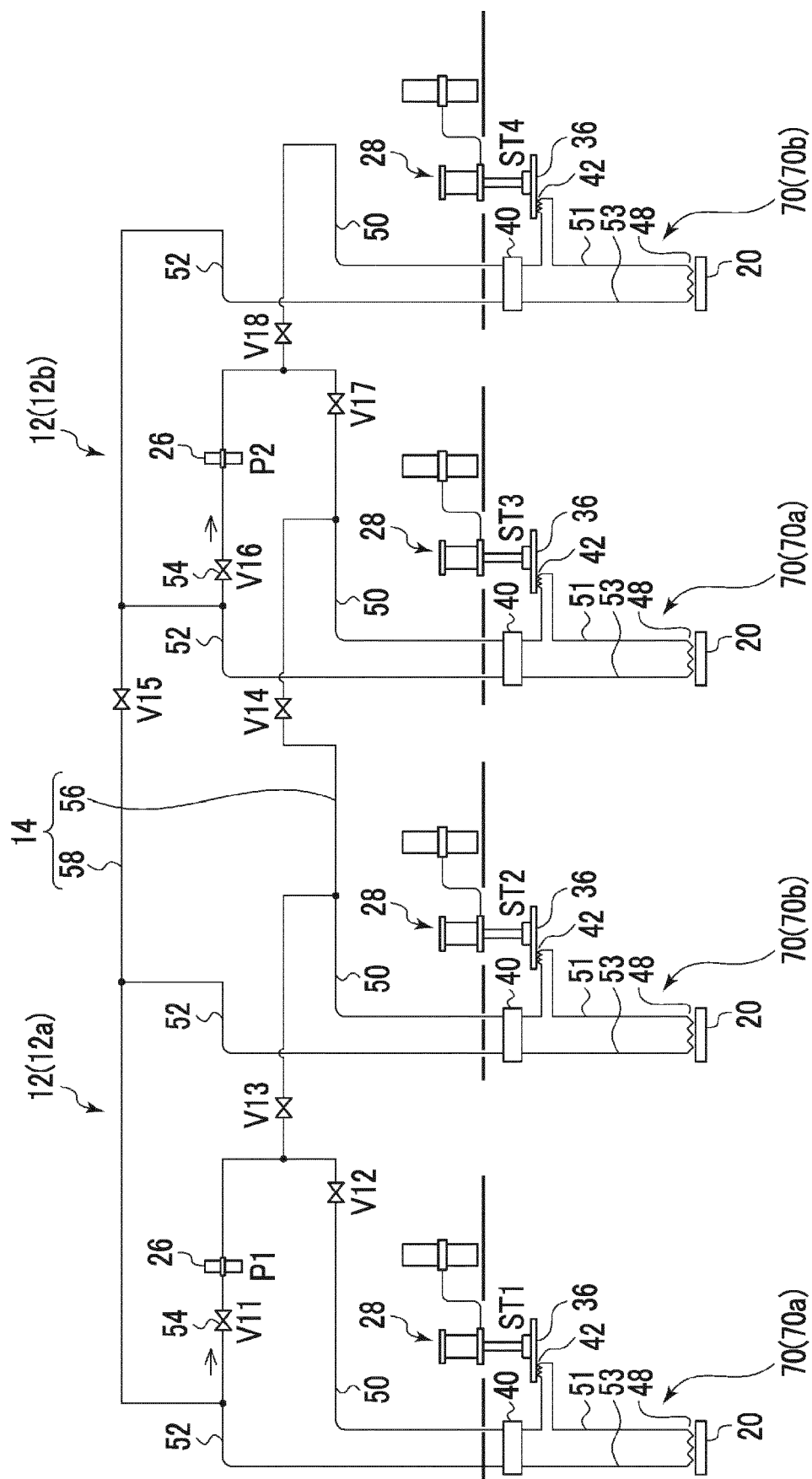


FIG. 5

	V11	V12	V13	V14	V15	V16	V17	V18
NORMAL OPERATION	Open	Open	Open	Close	Close	Open	Open	Open
ST1 FAILURE	Open	Close	Open	Close	Close	Open	Open	Open
ST2 FAILURE	Open	Open	Close	Close	Close	Open	Open	Open
ST3 FAILURE	Open	Open	Open	Close	Close	Open	Close	Open
ST4 FAILURE	Open	Open	Open	Close	Close	Open	Open	Close
P1 FAILURE	Close	Open	Open	Open	Open	Open	Open	Open
P2 FAILURE	Open	Open	Open	Open	Open	Close	Open	Open

FIG. 6

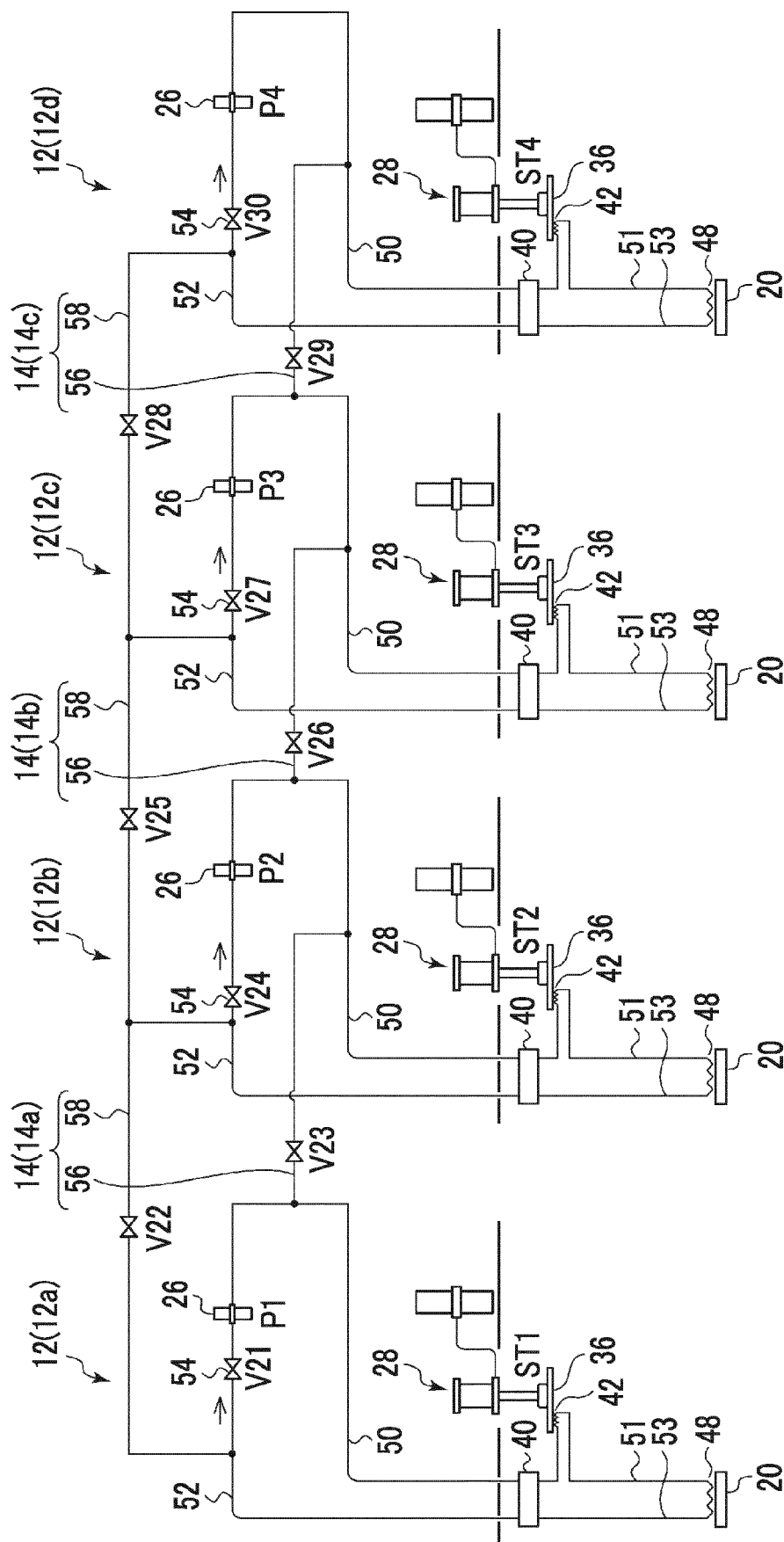


FIG. 7

	V21	V22	V23	V24	V25	V26	V27	V28	V29	V30	P1	P2	P3	P4
NORMAL OPERATION	Open	Close	Close	Open	Close	Close	Open	Close	Close	Open	DRIVE	DRIVE	DRIVE	DRIVE
ST1 FAILURE	Close	Close	Close	Open	Close	Close	Open	Close	Close	Open	STOP	DRIVE	DRIVE	DRIVE
ST2 FAILURE	Open	Close	Close	Close	Close	Close	Open	Close	Close	Open	DRIVE	STOP	DRIVE	DRIVE
ST3 FAILURE	Open	Close	Close	Open	Close	Close	Close	Close	Close	Open	DRIVE	DRIVE	STOP	DRIVE
ST4 FAILURE	Open	Close	Close	Open	Close	Close	Open	Close	Close	Close	DRIVE	DRIVE	DRIVE	STOP
P1 FAILURE	Close	Open	Open	Open	Close	Close	Open	Close	Close	Open	STOP	DRIVE	DRIVE	DRIVE
P2 FAILURE	Open	Open	Open	Close	Close	Close	Open	Close	Close	Open	DRIVE	STOP	DRIVE	DRIVE
P3 FAILURE	Open	Close	Close	Open	Close	Close	Close	Open	Open	Open	DRIVE	DRIVE	STOP	DRIVE
P4 FAILURE	Open	Close	Close	Open	Close	Close	Open	Open	Open	Close	DRIVE	DRIVE	DRIVE	STOP
OR														
P2 FAILURE	Open	Close	Close	Close	Open	Open	Open	Close	Close	Open	DRIVE	STOP	DRIVE	DRIVE
P3 FAILURE	Open	Close	Close	Open	Open	Open	Close	Close	Close	Open	DRIVE	DRIVE	STOP	DRIVE



EUROPEAN SEARCH REPORT

 Application Number
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Place of search Munich		Date of completion of the search 13 March 2019	Examiner Lucic, Anita
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