SLAC-PUB-898

PROPOSED HIGH PERFORMANCE REFRIGERATION CYCLES TO OBTAIN SUPERCONDUCTING OPERATION OF A TWO-MILE LINEAR ACCELERATOR AT 1.85K, 1.425K, OR 1.0K

*F. F. Hall
Senior Staff Member
Stanford Linear Accelerator Center
Stanford University, Stanford, California

Summary

The existing two-mile linear electron accelerator at SLAC has a duty cycle of less than 0.1% and is limited to 20 GeV.

If it were converted to superconducting operation, the duty cycles might be 100% at 20 GeV and 6% at 100 GeV.

This paper discusses high performance refrigeration cycles as necessary to make superconducting operation of a two-mile linear accelerator most reliable and least costly.

General Arrangement

The existing SLAC linac is divided into 30 sectors, each 333'-4" long. Electrical power is distributed from 15 substations to each pair of sectors. Likewise, waste heat is rejected to cooling tower water from each pair of sectors. The electrical substation at the injector end is duplex to provide adequate reliability.

Studies to date indicate 16 refrigerators to be optimum with 15 serving each pair of sectors and one providing standby capacity for the injector end or refrigeration for a positron source.

The use of 16 refrigerators appears quite feasible and consideration of using more smaller units is unnessary. By using 16 refrigerators, maximum use of existing electrical distribution and cooling tower water facilities could be made for economy.

The use of fewer refrigerators would require extensive use of liquid helium transfer lines, helium vapor pumps far larger than any in existence or even contemplated, and gargantuan vacuum tanks and heat exchangers.

Using 16 refrigerators, for instance, will require 8-foot diameter by 12 foot high vacuum tanks and may require the use of the largest vacuum pumps presently available or planned. The existing 10^{-8} torr sputter-ion pumped vacuum system would be used to evacuate the tanks.

Refrigeration Requirements

The operating temperature of a two mile linac designed for superconducting service has not been established. Table 1 shows some of the parameters.

Cycle Investigation

At the start, 1.85K operation seemed reasonable and an all-helium four solution the only one possible. It is still evident that for 1.85K operation, an all-helium four cycle is optimum, not because of lowest capital cost, but due to less pumping power. In a hybrid helium three-helium four refrigerator, the specific power for pumping helium three is 4.0026 ÷ 3.016 times that of pumping helium four.

We also looked at 1.85K ± cycles, both existing and planned. The largest of these provide 300W of refrigeration and we would need 15,120W. It soon was evident we could not extrapolate with either economic or functional justification. Cycles built or postulated earlier for 1.85K operation have Wc/Q values of from about 900 to 1,800W/W and, if used at the SLAC scale, would be very cumbersome and expensive.

Accordingly, we began to look for ways to cut costs starting with the vacuum pumps and the compressors because of their high initial cost, sealing problems and low compression ratios. Perhaps, because this phase of the cycle is "best known" it has suffered from the search for an "absolutely dry" machine and the "perfect mechanical seals" to seal against air leaking in or helium leaking out. Fortunately, neither of these two ideals is either very practical or necessary.

Reciprocating compressors are inefficient and very difficult to seal. On the other hand, there are available hermetically sealed, oil mist cooled, helical lobed, rotary units having 100% load modulation through use of piston-actuated slide gate controllers and integral oil separators. The oil mist removes 95% of the heat of compression, thus holding the temperature of discharged helium gas under 218°F which is not detrimental to high grade lubrication oils. Although oil separation is said to be excellent with carryover at less than one ppm, we would plan to use a duplex activated charcoal after stripper to insure only clean gas enters the refrigerator. The feature of critical interest is compression ratios of eight as opposed to little more than two for equipment which is not internally oil mist cooled. Thus, we would hope to use either three or four stages of compression rather than six to ten as has been done.

Next, we looked at ways to reduce the flows of helium both through the evaporator, the expanders, and thus through the vacuum pumps and compressors. It appeared that the yield of liquid helium within evaporators is limited to close to 80% when helium gas is cooled to the point of final expansion. On the other hand, if we liquefy helium at an intermediate pressure and then subcool the liquid we can more closely approach the lambda point and obtain yields of better than 90%. This is about all we can hope for at the cold end. After considerable study, we found that for cycles having large flows of gas, the use of three expansion machines with the discharge of the cold end expansion machine at close to 4°K results in excellent ΔTs across the cold end heat exchangers, least flow through all expanders and fairly small flows through each individual expander. We would plan to use reciprocating expanders because they are efficient and can be one stage irrespective of selection of high and intermediate pressures. We also would hope to obtain isentropic efficiencies of 86% for the cold end expander, 84% for the middle expander, and 80% for the upper expander.

All heat exchanger applications studied so far are readily resolved should we use the compact, economical platefin type, arranged for either two or three stream

*Work supported by U. S. Atomic Energy Commission

(Published in IEEE Trans. on Nucl. Sci., Vol. NS-18, No. 3, 711-715 (1971))

service and to limit maximum Reynolds numbers of any stream to 2000 or less. This will allow us to accurately predict heat exchange data while holding pressure drops of the low pressure cold return stream within reasonable limits. Most of these exchangers would be of braised all-aluminum construction. Exceptions are the use of copper for "stagnant" liquid He4II to boiling liquid He3 heat exchangers where T would be constant and longitudinal conduction impossible and stainless steel for warm end heat exchangers where longitudinal heat conduction could be a very real problem. If long cores were necessary, the low pressure ΔP could become excessive.

As to gas purity, we plan an ambient full-flow filter to remove particulates, some oil and water vapor, an intermediate temperature filter to remove all water vapor, oil, CO_2, O_2, N_2, etc. and a cold end filter to remove A, Ne, H_2, etc.

Finally we looked at heat shields. For an all-He4 cycle, the best bet is a full flow heat shield discharging at the inlet temperature of the third, warm end expander. For a hybrid He3-He4 refrigerator, the use of a separate He4 heat shield refrigerator is a must. We cannot use He3 either within accelerator dewars as a liquid or even in a heat shield as a gas due to its 5000 barn cross section for absorption of thermalized neutrons. Also, liquid He3 is not a superfluid and might not adequately remove heat from accelerator components.

Operation at 1.85 K, 1.42 K, and 1.0 K

The remainder of this paper will quickly outline our proposed solutions for operation of a superconducting accelerator at these temperatures. Reasons for selecting these cycles and for rejecting alternate possible methods will not be discussed because they are part of another paper scheduled for delivery later, elsewhere. In addition, only one conclusion will be reached herein.

Operation at 1.85 K

Economics dictate the use of an all He4 system. Over a wide selection of high and intermediate pressures, the indicated Wc/Q values are less than 500W/W. The selected pressures of interest are 6.0 atmospheres high pressure, 0.8 atmosphere and 0.1 atmosphere pressures, and 0.01316 atmosphere (10.0 torr) low pressure.

The Temperature-Entropy Diagram is shown in Figure 1. The total indicated power for pumping He4 gas, lubricating oil, cooling tower water and ventilating air and electrical system losses is 6,938 kW. The brake Wc/Q value is 399 W/W.

The Schematic One-Line Diagram is shown in Figure 2. Note that while only three stages of compression are needed, some five separate pump casings are required, including three units to operate in parallel for the first stage.

Operation at 1.45 °K and at 1.0 °K

At 1.45°K, the pumping power for an all He4 cycle and a hybrid He3-He4 cycle is about equal. The capital cost of a hybrid system is less. Below 1.425°K down to 1.0°K, reasonableness ends and also, at the moment, scientific justification for steady state, large scale refrigeration of accelerators.

The Temperature-Entropy Diagram for a separate low temperature He4 heat shield refrigerator is shown in Figure 3. The 1300W requirement is 200W greater than for a higher temperature shield but that leakage from the shield to the cold end is only 8W per refrigerator. The 9.04°K heat shield would be used at 1.425°K down to 1.0°K for shielding He3 low watt refrigerators.

The Temperature-Entropy Diagram for a separate He3 refrigerator to remove 75W at 1.325°K is shown in Figure 4. The gross electrical demand is 3,413 kW which is far less than that for all He4 refrigeration at 1.85°K, although the Wc/Q is 2,528 W/W which is much higher.

A Rough Schematic One-Line Diagram for Operation from 1.0°K to 1.425°K is shown in Figure 5. For low watt He3 refrigerators, one stage of vacuum pumping plus two stages compression will be needed but one casing per stage should suffice.

Conclusion

Assuming rf losses fall off as predicted as temperature falls below 1.85°K, the use of a hybrid He3-He4 refrigeration system having liquid superfluid He4-II within accelerator dewars chilled by a boiling liquid He3 refrigerator protected by a He4 gas heat shield refrigerator should be the logical and economical solution.

References

1. "Proposed Solutions of Four Refrigention Problems Relating to Superconducting Accelerators and Cryogenic Experimental Equipment" - Fred F. Hall, March 1, 1971 - submitted for presentation at the XIII International Congress of Refrigeration.

2. Helium four data is taken or interpolated from "Provisional Thermodynamic Functions for Helium 4 for Temperatures from 2 to 1500K with pressures to 100 MN/m² (1000 Atmospheres)" by R. D. McCarty of NBS, Boulder Laboratories, Boulder, Colorado except the value of 3.99 J/Mol lquid enthalpy of He_4 at 185°K was given verbally by R. D. McCarty and the value of 96.484 J/Mol gas enthalpy at 1.85° K and 0.0195 atmosphere was derived by the author. The resultant value of the latent heat of evaporation at 1.85° K of 92.494 J/Mol may be unique but is also defendable.

3. Helium three data is taken from AFML Report TR-87-175 "Thermodynamic Date of Helium - 3" by R. M. Gibbons and D. I. Nathan or interpolated and extrapolated by the author. While specific points of state are subject to doubt it is not likely that the general conclusions reached are totally in error.

Acknowledgement

The indefatigueable efforts of K. G. Carney, Jr. in reducing the refrigeration cycle studies to computer programs is highly appreciated. On the eve of March, 1971 these confirm that the cycles described are subject to minor refinement and only through new approaches could further ramp improvements be made.

Cost Estimates

During the past year, emphasis was placed on what we might do as opposed to what would it cost. Accordingly, we have no firm cost estimates. The \$ K (W refrigeration)$^{0.6}$ quickie estimating approach as a serious flaw in that the problem establishes the estimate irrespective of approach and K can only be refined by making a complete takeoff of hardware. The 6000 (input KW)$^{0.7}$ approach published by T. R. Strobridge in the Proceedings of the AIEEE 1969 Particle Accelerator Conference is much better since cycle improvements generally result in reduced input KW and this is recognized directly. If one had 2 variations using 2 expanders in one and 3 in the other and input KW were the same one could directly approximate the cost difference. Usually it isn't this easy and the count of nuts and bolts must be made eventually.

The original SLAC estimate for 31 installed 500W refrigerators for 185°K, 2856 MH$_z$ service was \$14,100,000. The value of K was estimated to be 12,000. Thus 31x12000 $(500)^{0.6}$ = \$15,485,000 and 31x6000 $(473)^{0.7}$ = \$13,872,000.

Since then we have made considerable progress in cycle refinement. However, 16x12000 $(967)^{0.6}$ = \$11,873,000 does not reflect this. On the other hand 16 x 6000 $(422)^{0.7}$ = \$6,738,000 does reflect this progress. Despite the lack of definitive cost estimates our current thinking is that 16 installed 967W refrigerators for 1.85°K service would cost close to \$6,738,000 and 16 installed 75W refrigerators for 1.425°K service would cost close to \$4,094,000.

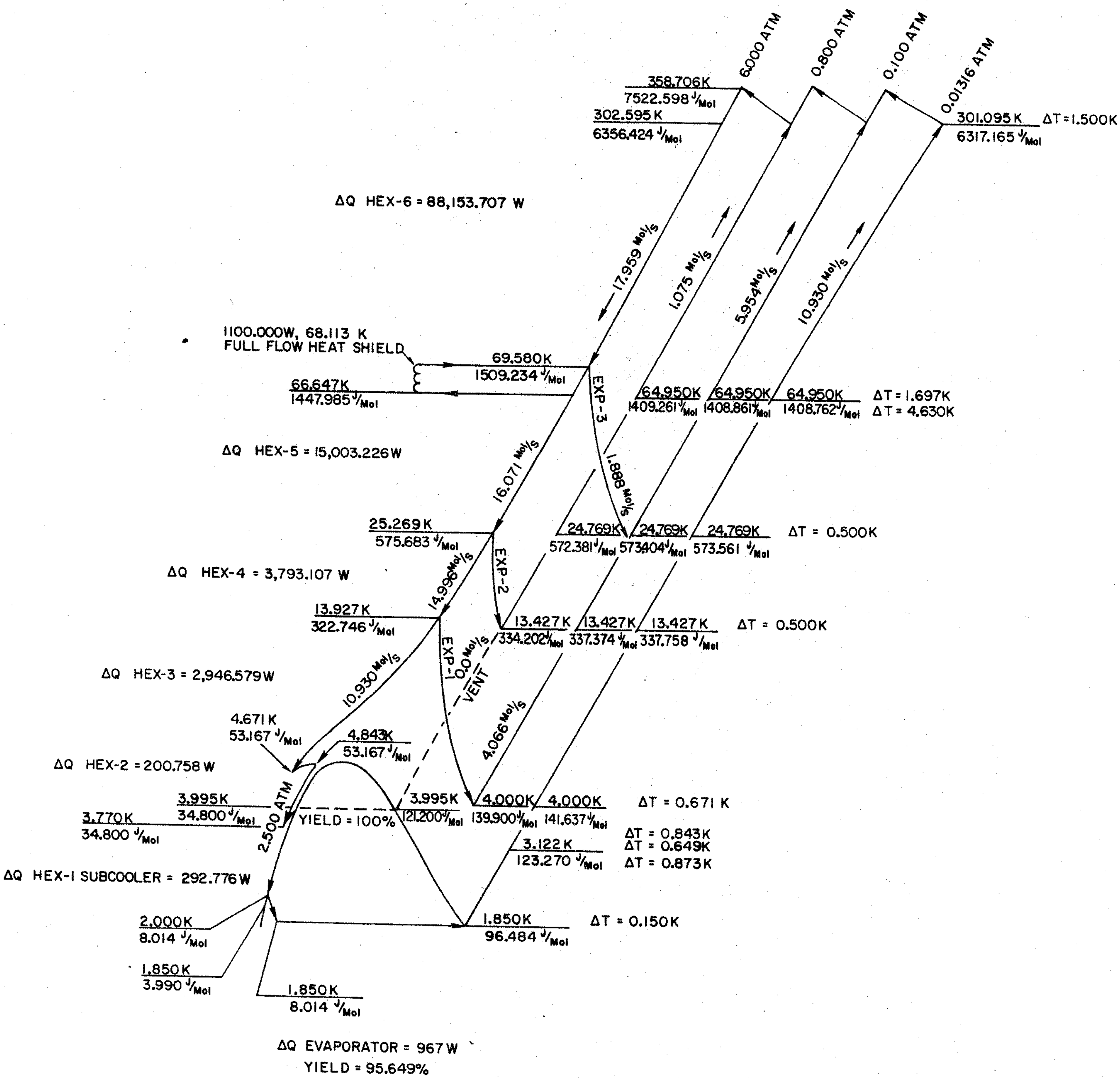

Fig. I T-S DIAGRAM FOR A 967W He_4 REFRIGERATOR FOR 1.85°K SERVICE.

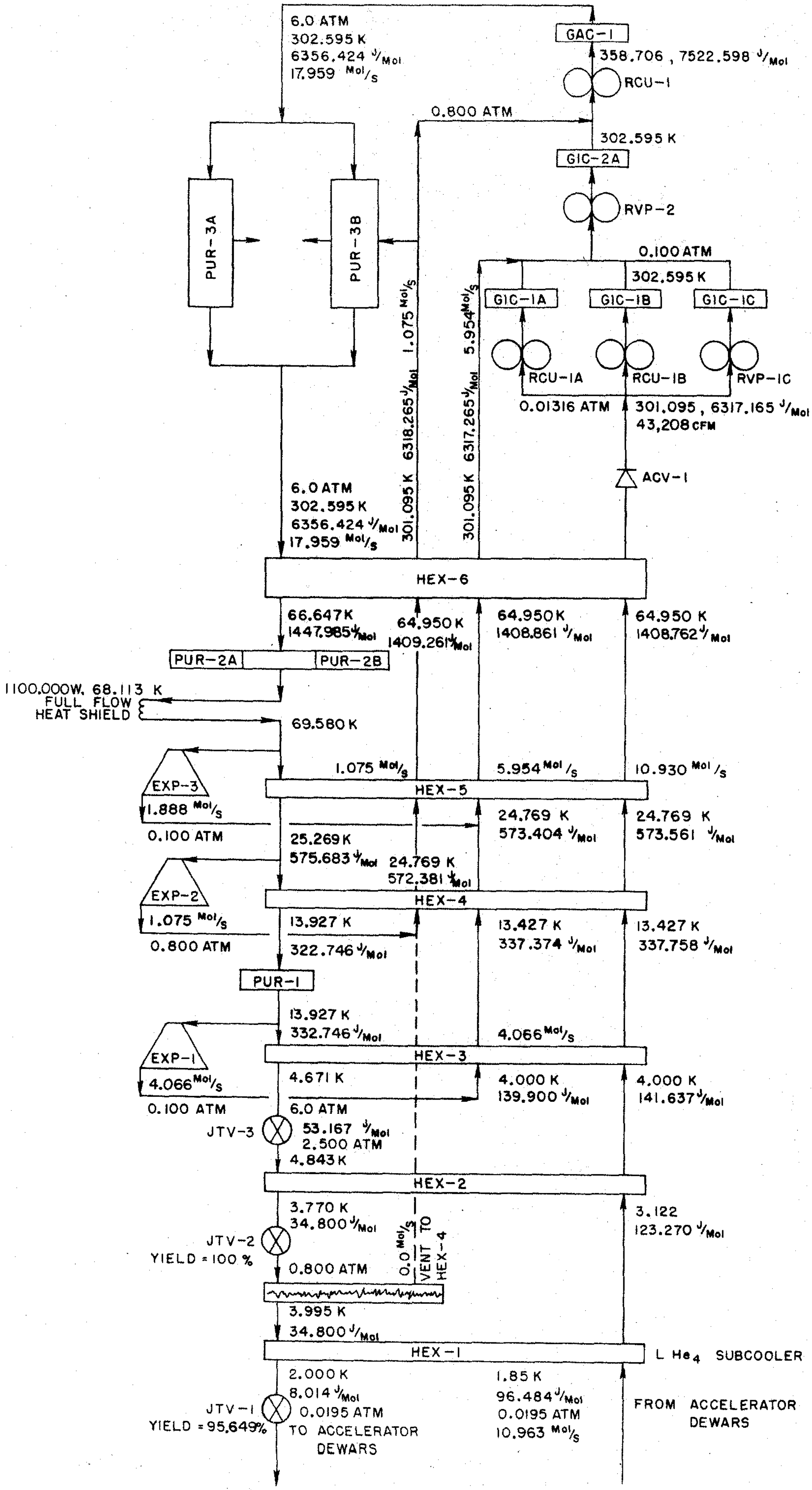

Fig. 2 SCHEMATIC DIAGRAM FOR A 967 W He_4 REFRIGERATOR FOR 1.85°K SERVICE.

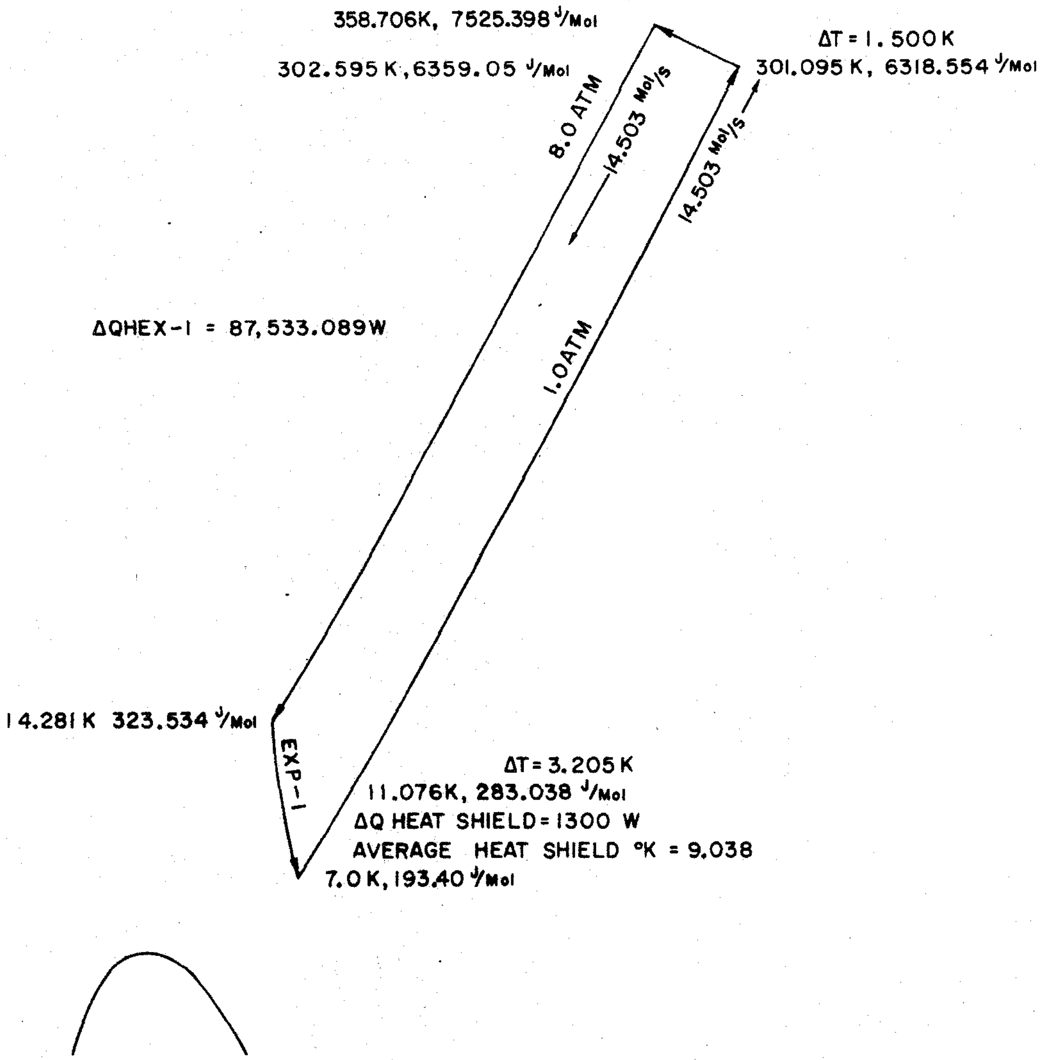

Fig. 3 T-S DIAGRAM OF A 1300W
He 4 REFRIGERATOR FOR 9.038 °K SERVICE

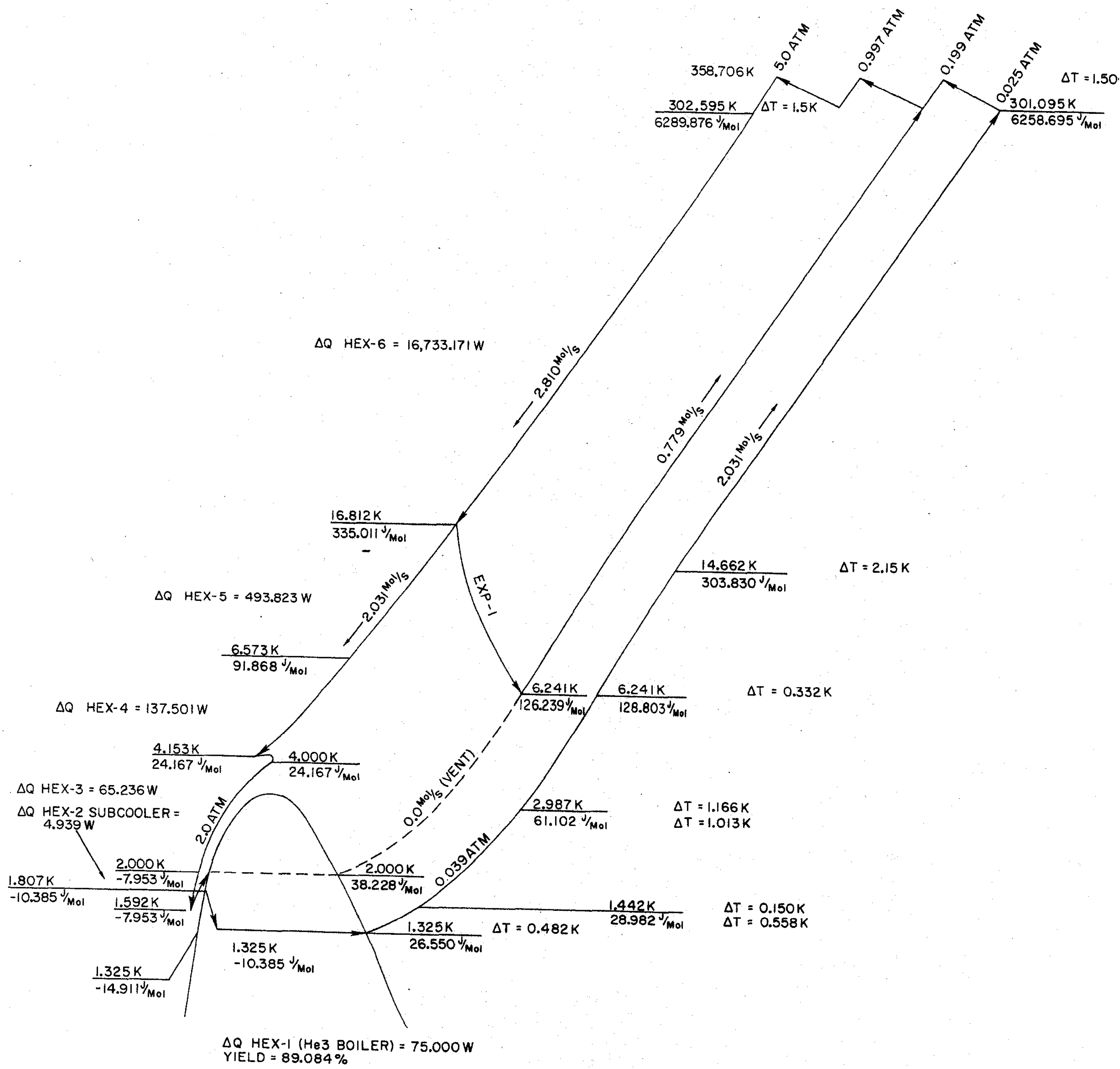

Fig. 4 T-S DIAGRAM FOR A 75.0 W He3 REFRIGERATOR TO OPERATE AT 1.325°K AND MAINTAIN SUPERFLUID He4-II AT 1.425°K. SEPARATE HEAT SHIELD IS SHOWN IN Fig. 3.

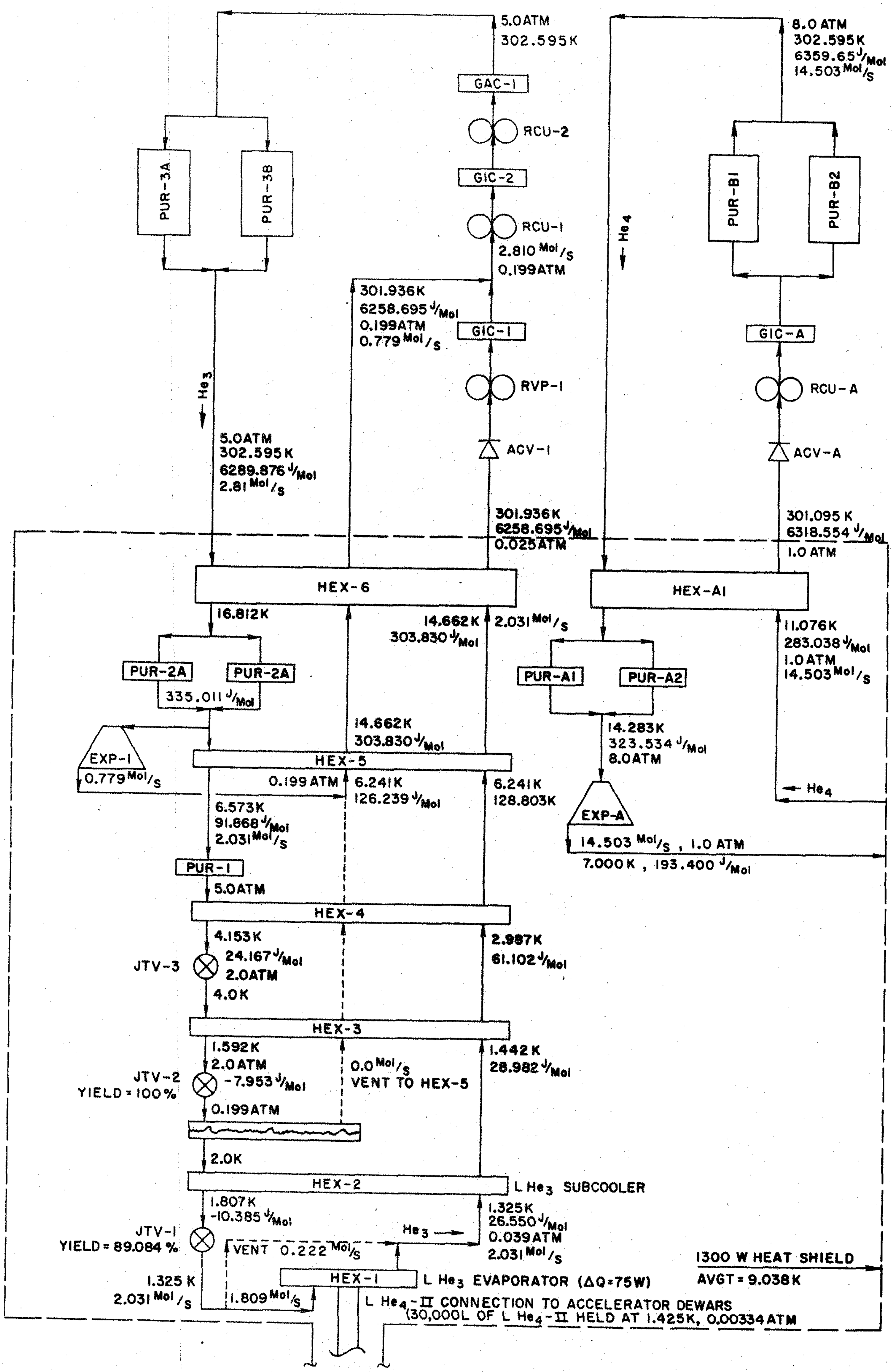

Fig. 5 SCHEMATIC DIAGRAM FOR A 75W He_3 REFRIGERATOR TOGETHER WITH A SEPARATE 1300W He_4 HEAT SHIELD REFRIGERATOR