THERMAL ANALYSIS OF CRYOGENICALLY COOLED LINEAR ACCELERATORS

S. Fixler, J. Healey, T. Schultheiss, J. Szot
Grumman Space Systems Division

Abstract

This paper presents the evolution of a cryogenic cooling system design for a linear accelerator. Critical design issues were identified and resolved based on optimization and trade studies that considered cooling performance, initial and life-cycle costs, operational hazards, and program delays.

The results presented compare cooling fluids for cryogenic and RF conditioning (room temperature) operation for continuous wave (CW) loads. An in-depth thermal analysis for the radio frequency quadrupole (RFQ) also is presented.

Introduction & Summary

Heat dissipation of RF-powered linear accelerators can be reduced significantly by maintaining them at cryogenic temperatures. Tests have shown that copper losses can be reduced by factors of between 3 and 5 at cryogenic temperatures. This paper presents the evolution of a cryogenic cooling system for a linear accelerator. Design issues included optimization, system performance, initial and life-cycle costs, and safety.

Supercritical neon was used as the cryogenic coolant. Analyses were performed to validate the principle of accelerator performance simulation by referee fluids. Optimization studies were conducted on the selection of a cryogen referee fluid, the cooling mode (supercritical), the RF conditioning fluid, accelerator operating temperature, and coolant pressure.

Thermal response and temperature distributions were obtained and are presented for the radio frequency quadrupole (RFQ) for cryogenic and RF conditioning (room temperature) operation under continuous wave (CW) loads.

Selection of a Cryogen

Two options were considered: direct use of hydrogen as a coolant and the use of a referee fluid that would maintain the same accelerator temperature as would hydrogen. The advantage of using hydrogen is its efficiency; the primary disadvantages are safety and cost.

A mixed-mode (partly open loop and partly closed loop) cooling method was adopted for the cryo cooling system. In the closed loop, either hydrogen or a referee fluid could be used. In the open-loop, hydrogen is boiled off in the referee fluid/hydrogen heat exchanger, thereby absorbing the accelerator heat load; the hydrogen boil-off is vented to the stack. The referee fluid option was selected.

Performance simulation of a referee fluid was proven by analysis. Reference [1] shows that cooling with a referee fluid produces the same accelerator metal temperature as cooling with hydrogen, provided a prescribed ratio of heat transfer coefficients, Hr/Hh (referee fluid to hydrogen), is maintained. Reference [2] shows that the referee fluid simulation principle is valid at each point of an accelerator segment, provided that there are no significant changes in fluid properties within that segment. Reference [2] also shows that for a given accelerator design, hydrogen performance can be duplicated with a referee fluid by monitoring only flow rate or pressure.

Selection of a Referee Fluid

To reduce RF power dissipation to reasonable levels, accelerator operation below 50K is required. Most cryogens have freezing points (important in supercritical flow) and boiling points (important in 2-phase flow) in excess of 50K. Notable exceptions include neon, hydrogen, and helium. The referee fluid choice thus reduced to only two candidates: neon and helium.

A trade study was conducted to evaluate the drift tube cooling performance of neon and helium in order to arrive at the optimum referee fluid. The drift tube coolant flow pattern through the coaxial stem and double-channel body was selected. Inlet parameters representative of accelerator operation were used for the study.

The results, Fig. 1, show that neon performs better than helium in all categories. Note that the required pumping power is rather large for helium (larger than neon by a factor of about 13). Since cost in consumable LH_2 is directly proportional to the pumping power, the same ratio applies to cost.

Cryogen Cooling Mode Selection

Three cooling mode options were investigated.

- Two-phase flow (boiling)
- Subcooled liquid flow
- Supercritical flow.

Two-phase flow is limited by critical heat flux, and its analysis is complex. Tests have shown large pressure and temperature fluctuations, Reference [3], which could lead to unforseen problems. A comparison of power densities of various components with predicted critical heat flux for neon indicates that there is too little margin. Subcooled flow for neon was shown to be thermodynamically less efficient than for supercritical conditions. In the subcooled region, below 9 atm, cooling performance starts to deteriorate. Another disadvantage of subcritical flow is the possibility of entering the 2-phase flow regime if there is a rise in fluid temperature. This possibility is precluded under supercritical conditions. Neon thermodynamic and transfer properties used in these analyses were taken from References [4] and [5] .

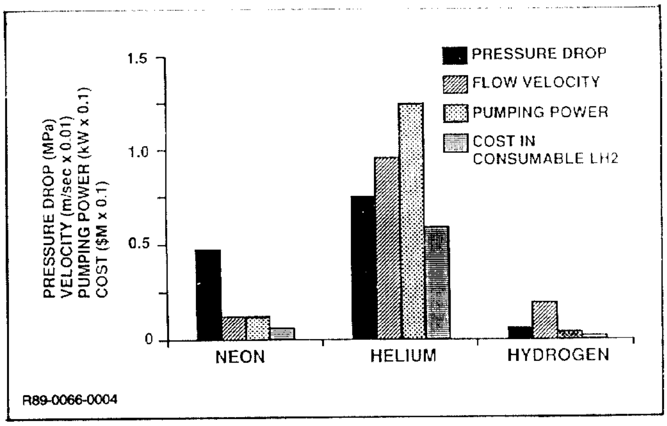

Fig. 1 Comparison of Drift Tube Cryogen Cooling Performance

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Selection of RF Conditioning Fluid

Trade studies were performed to determine an optimum fluid for room temperature RF cavity conditioning. Water, water/glycol, and two Freons (R-113 and R-114) were considered as the conditioning fluid. Though Freon residues can be removed more effectively than water residues, water performs better than the two Freons in the vital categories shown on Fig. 2. In addition to the Freons, a 50/50 water/glycol mixture was eliminated. In view of the superior cooling performance of water and the preclusion of having to introduce another cooling system (Freon), water was chosen as the room temperature conditioning fluid.

Selection of Accelerator Operating Temperature Regime

Although low metal temperatures are desirable to reduce power dissipation, studies show that severe penalties in cooling performance are incurred by using low metal temperatures. Conversely, low metal temperatures ensure a more dimensionally predictable structure since distortion is minimized. The temperature regime was selected as a compromise between cooling performance and distortion.

The analysis results of Fig. 3 show pertinent cooling performance parameters plotted against accelerator maximum metal temperature. Below 35K, the penalties incurred increase at a steep rate. Program cost in consumable LH_2 is directly proportional to the pumping power required to circulate the neon. Figure 3 also shows that temperatures higher than 35K yield little gain in performance. Moreover, the higher temperatures might place the operating regime within the temperature inversion curve. Based on the results of these trade studies, the accelerator operating temperature was chosen as 35K.

Selection of Accelerator Operating Pressure Regime

Pressure was varied to determine the possible performance advantages of going to high pressure, as in the case of helium. Figure 4 shows the results of neon at elevated pressures.

Unlike helium, neon performance does not improve as pressure is increased above the critical point. Since no performance gains can be made for neon by going to high pressures, the optimum pressure regime would be sufficiently above the critical pressure (26.87 atm) to compensate for the total system pressure drop. An inlet neon pressure of 30 atm thus was selected.

Performance Simulation of Referee Fluid

For reasons of safety, economy, and hydrogen cooling efficiency, the coolant selected for actual application is hydrogen. Neon, however, has been chosen as the referee fluid. For neon to be acceptable as the referee fluid, the temperature response and distribution of a neon-cooled accelerator must be equivalent to the temperature response and distribution of a hydrogen-cooled accelerator. The radio frequency quadrupole (RFQ) was selected to show the neon/hydrogen equivalence.

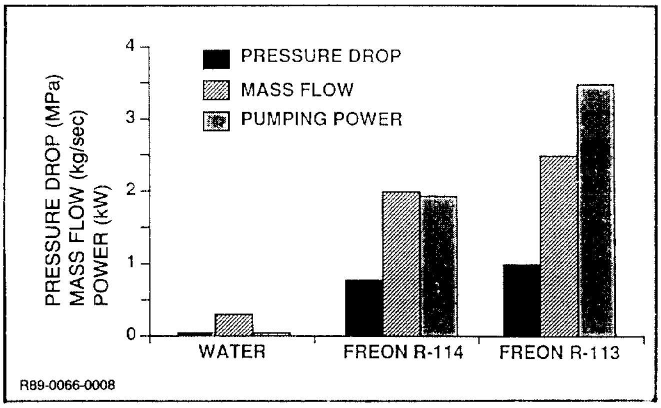

Fig. 2 RF Cavity Room Temperature Conditioning Coolant Comparison

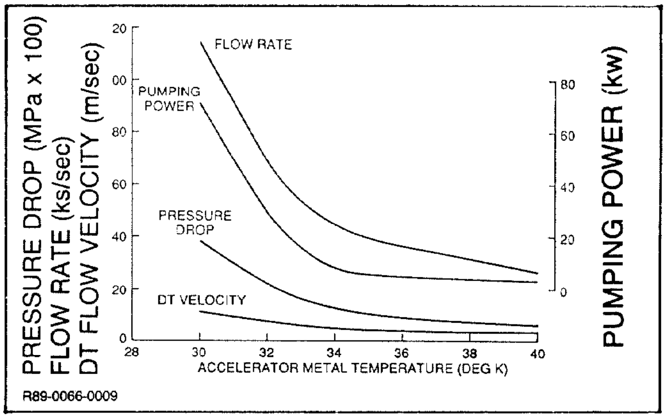

Fig. 3 Effect of Accelerator Metal Temperature on Cooling Performance

RFQ Thermal Response

A thermal hydraulic analysis determined the coolant flow rate and pressure drop that a 1 meter section of the RFQ requires to maintain a metal temperature below 35K. A detailed 2-d finite element model of the RFQ cross section was built. The exit temperatures and film coefficients for each channel were input in the finite element model to predict the temperature distribution.

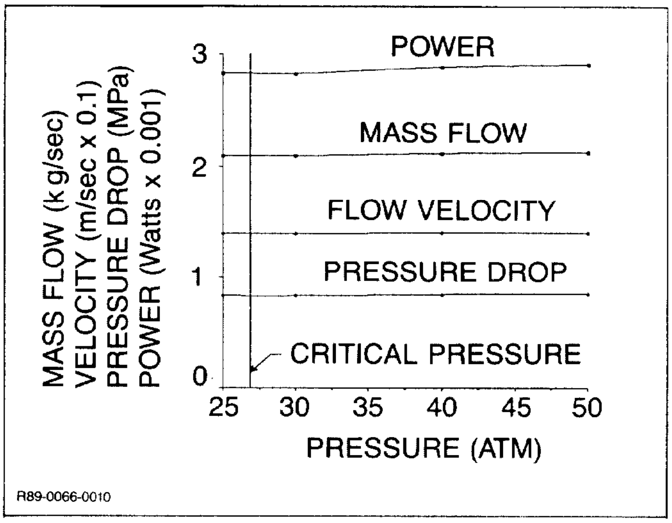

Fig. 4 Effect of Operating Pressure on Cooling Performance of Neon

The curves in Fig. 5 show the thermal response for both hydrogen and neon coolant at four discrete locations. Both coolants have nearly the same thermal response over the required time period of 20 seconds (5 time constants within 20 seconds was a requirement).

RFQ Temperature Distribution

Isothermal plots for hydrogen and neon are shown in Fig. 6. The plots show two identical cross sections of the RFQ where steady-state temperatures have been reached. A comparison of the two temperature distributions shows the nearly identical thermal performance of the two coolants. Each isotherm on the plot of the hydrogen-cooled RFQ is matched in location and temperature by an isotherm in the neon-cooled RFQ plot. The agreement between the two plots supports the principle of simulating hydrogen with a referee fluid.

Conclusion

Supercritical neon has been chosen and optimized by analysis for a cryogenically cooled linear accelerator. It has also been shown to be an effective referee fluid for hydrogen, thereby eliminating many operational hazards. Water was chosen as the coolant for RF conditioning, which is performed at room temperature.

References

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[3] S.J. Black, ''Cryogenic Cooling Tests of a Neutral Particle Beam Accelerator Component'', *18th Intersociety Conference on Environmental Systems*, 881110, July 11-13, 1986.

[4] V.A. Rabinovich, et al, *Thermophysical Properties of Neon, Argon etc*, Hemisphere Publ, 1986.

[5] R.D. McCarty and R.B. Stewart, 'NBS Report 8726'', 1965.

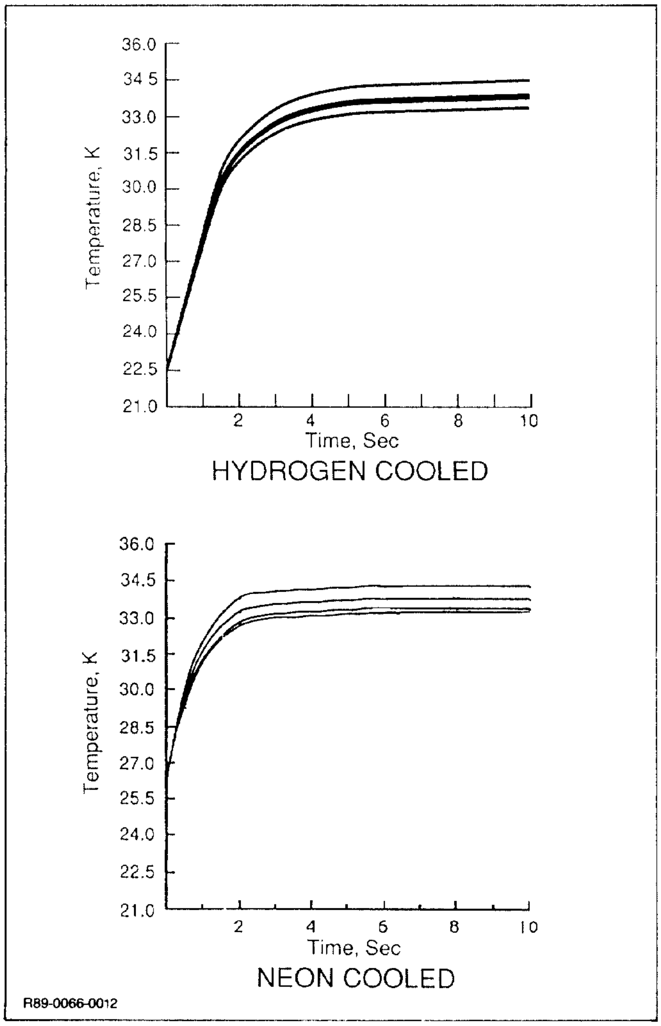

Fig. 5 Performance Simulation Results, RFQ Thermal Responses

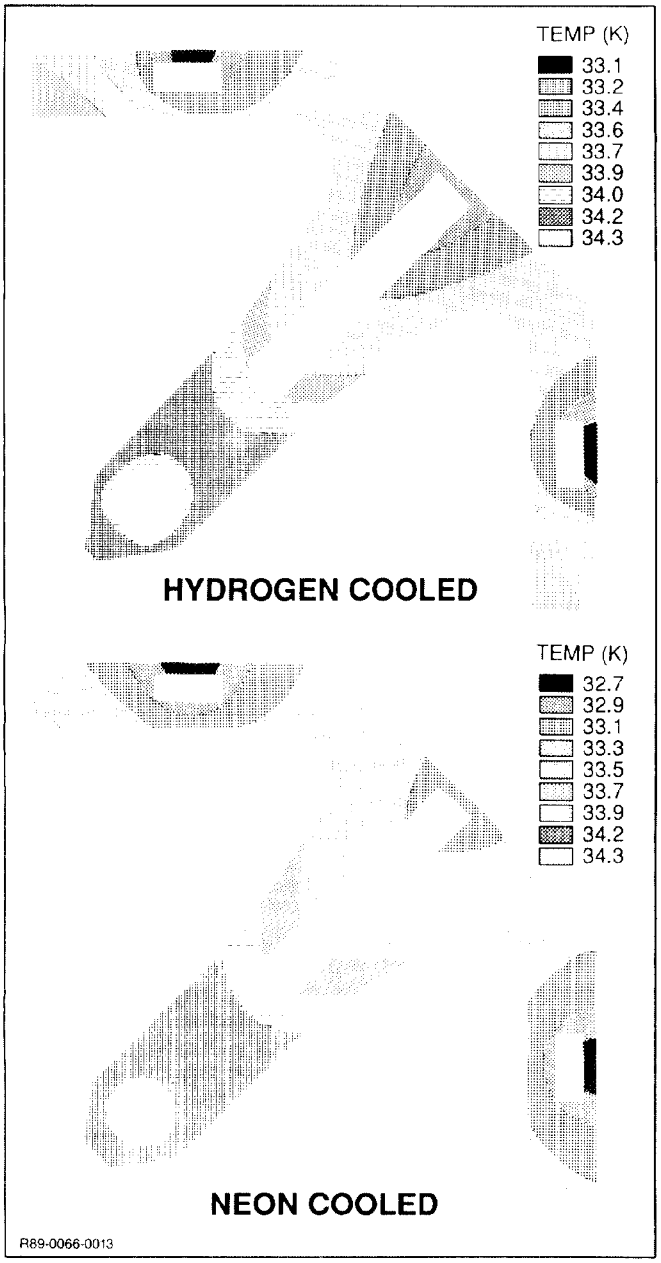

Fig. 6 Performance Simulation Results, RFQ Isotherms