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THERMAL MANAGEMENT OF AN ACCELERATOR SYSTEM IN SPACE

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I. INTRODUCTION

For the past several years the Accelerator Technology Division at Los Alamos National Laboratory has been working under Strategic Defense Initiative sponsorship to develop a Neutral Particle Beam (NPB) weapon system. An artist's concept of such a system is shown in Fig. 1.

The NPB weapon system consists of an injector subsystem whose function it is to generate the H^- particle beam and the accelerator subsystem that accelerates the particle beam. The particle beam then goes through a 180° bend and is expanded in a telescope subsystem prior to entering the neutralizer where the extra electron is stripped from the hydrogen particle creating the neutral beam. This system is shown in block diagram form in Fig. 2

The power subsystem, cryogen storage and other support functions are typically placed in the U created by the accelerator and expanding telescope as shown in Fig. 3.

A weapon grade NPB system generates 10s of MWs of waste energy which must be dissipated in some fashion. There are only three ways that heat may be dissipated in space. The first is to expel a hot gas or liquid from the spacecraft. The second method is to directly radiate the generated heat to deep space. The third method is to dissipate the heat in some type of thermal mass storage. Regardless of the method chosen, the name of the game is how much will the thermal management system weigh?

The present objective of the program is to put the entire space platform on one launch vehicle. The payload weight of the Advanced Launch System, ALS, is approximately 125,000 lbs or a little more than twice the payload weight of the Shuttle. The consensus opinion is that the power system for the NPB weapon will comprise about 40% of the total weight of the platform. If one talks about a generic 50 MW power system with a specific weight of 0.5 kg/kW the power system then weighs 55,000 lbs. This will take up 44% of the ALS lift capacity! This specific weight is at least a factor of 4 less than what could be built today. The name of the game is truly weight! The objective of this workshop is to try to determine the best way to dissipate MWs in space.

II. ACCELERATOR STRUCTURES

One of the critical issues that the accelerator scheme chosen for the NPB

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must address is beam quality. Because of the engagement ranges that are anticipated the emittance or quality of the beam must be extremely good. The beam quality, of course, can never improve as it passes through the accelerator unless scraping devices or beam collimators are used. Because of the high current and energy of the proposed NPB beam, beam collimation and its associated cooling problems are undesirable. Thus the quality of the beam at the beam generation point is controlled as tightly as possible.

To control beam emittance at the injector the concept of funneling has been introduced. High current beams such as that which will be used in the NPB accelerator are difficult to control at their generation point because their velocity is low hence the self-magnetic field generated by the beam is almost non-existent and the space charge forces tend to blow the beam up. If the current can be reduced then the emittance is also reduced.

Figure 4 is a block diagram showing the funneling concept. Two injectors are used each of which inject a continuous beam of H^- particles into the Radio Frequency Quadrupoles (RFQ). Each RFQ accelerates and bunches the beam. The bunches are shown as a's and o's in the block diagram. The bunches depicted by the a's are 180° out of phase with the bunches depicted by the o's. When the two beams are brought together in the funnel the bunches, represented by the a's and o's, are interlaced together and the bunched beam, now with twice the current of an individual injected beam, enters the Ramp Gradient Drift Tube Linac (RGDTL). The rf drive frequency for the RGDTL, Drift Tube Linac (DTL), and Coupled-Cavity Linac (CCL), now must be twice the frequency of the RFQ. The chosen frequency for the RFQ is 425 MHz which means that the rest of the accelerating structure must operate at 850 MHz. Greater than 90% of the total rf power will be generated at 850 MHz.

Figure 5 shows an artist's concept of how the beam enters the RFQ (from the left), is bunched, and then accelerated. The typical RFQ which is built today has an exit beam velocity of about 2.5 MeV rather than the 640 KeV shown in the diagram. Figure 6 is a picture from the output end of an actual RFQ showing the 4 vanes and the ripples in the vane tips. These geometrical ripples are necessary to properly bunch and accelerate the beam.

Figure 7 is a block diagram of a DTL. Geometrically, a DTL is a large circular tank on whose axis is placed a series of smaller cylinders with holes in the middle through which the beam passes. Each cylinder also contains a quadrupole magnet. The small cylinders are suspended from a post which is connected to the large circular tank wall. A half rf cavity consists of the distance from the center of the suspension post to the center of the gap between the small cylinders. The distance from cylinder to cylinder is spaced longitudinally so that the bunch of particles sees an accelerating field as it passes through each gap. When the rf field reverses the bunch is hidden by the small cylinder. The RGDTL is a special type of DTL in which the field strength in each gap gradually increases as the beam velocity increases.

Figure 8 is a picture of a DTL section showing the cylinders with their support posts attached to the tank wall.

The metal rods on either side of the small cylinders are tuning rods.

Figure 9 is a cross section view of a CCL. The CCL derives its name from the coupling cavity that is used to couple rf energy from beam-line cavity to beam-line cavity. These are shown in the cross section as appendages to the beam-line cavities. Again, the distance from gap center to gap center is geometrically fixed so that the bunches of the particle beam are accelerated as they pass through each gap.

Figure 10 shows an actual cavity half-section. Please note the iris to the coupling cavity on the left. Figure 11 shows a CCL accelerating structure. In this case the beam line cavities are not machined concentrically which provides for the coupling cavity to occur on alternate sides of the structure.

III. THERMAL MANAGEMENT

By far the biggest heat producers on the platform are the power system and the accelerator structure. The equations shown below gives the power that must be dissipated in terms of the power that is stored in the chemical fuels. If PG is the electrical power generated from the fuel (PF) then

$$PG = PF(\eta_C) \qquad (1)$$

where η_c is the efficiency of the chemical to electrical power conversion system and is about 0.73. The electrical power that must be dissipated is given by Eq. 2. The efficiency terms $(\eta_{RF}, \eta_{ACC}, \eta_{PC})$,

$$PD = PG\text{-}PG\,(\eta_{RF}, \eta_{ACC}, \eta_{PC}) \qquad (2)$$

are those for the rf amplifiers, the accelerator structure, and the power conditioning respectively. The rf amplifier efficiency will run about 55%, the cryogenically cooled accelerator structure 80%, and the power conditioning 95%. The total power to be dissipated is composed of two terms, the electrical power, PD, given by Eq. 2, and a second term which represents the heat generated in the fuel to electrical conversion. Thus, if PT is the total power to be dissipated then

$$PT = PF(\eta_C)[1\text{-}\eta_{rf}\eta_{ACC}\eta_{PC}] + PF(1\text{-}\eta_c) \ (3)$$

Substituting the numbers yields

$$PT = .695\ RF \qquad (4)$$

This exercise clearly shows that the efficiency of the various subsystems is very important.

One of the ways that the efficiency of the overall system has been substantially improved is to run the accelerator structure at cryogenic temperatures using hydrogen as coolant. Figure 12 is a curve showing the cryogenic properties of copper, the typical material that is used in accelerator structures. The electrical resistivity of the copper can be reduced 2 to 3 orders of magnitude by operating in the temperature range of 20° to 30° K. Cooling the copper to cryogenic temperatures enables the accelerator structure to operate at an electrical efficiency of 80% as opposed to the typical value of 40% to 50% when operated at room temperature.

At the present time the input temperature of the hydrogen to the accelerator is 20° K at a pressure of about 30 bars. The pressure is this high to assure that the hydrogen will remain supercritical. The hydrogen will exit the accelerator structure at about 35° K and close to 30 bars pressure. The hydrogen flow under these conditions will be 18 kg/sec.

Figure 13 is a curve showing the dependence of radiator area on the fourth power of temperature. This curve is for an emissivity of 0.8 and a dissipation of 410 kW. Obviously, there will be a reduction in the area required if the emissivity can be increased to 0.9 but the big factor is temperature. Previous calculations, which will not be repeated here,

indicate that a typical rf amplifier tube operating at 1 MW of cw output power and 65% beam efficiency will require 1 m^2 of radiator area operating at 1600° K for proper dissipation.

Since a relatively large volume of hydrogen will be on the space craft anyway, it is logical to use that hydrogen as both a fuel and a coolant. The following table compares the properties of supercritical hydrogen and gaseous hydrogen as a coolant.

PARAMETER	SUPERCRITICAL HYDROGEN	GASEOUS HYDROGEN
Temp in °K	50	50
Pressure in Atmos	30	1
Entrophy, kJ/(kg·K)	19	34 5
Density kg/M³	10	082
Flow for 1 MW/sec ΔT = 65°K	0 81 kg/sec	0 45 kg/sec
Volume Flow	81 l/sec	5 5x10³ l/sec

Obviously the 30 bars of pressure in the case of supercritical hydrogen is to keep the hydrogen in that state. It is clear from the last line of the table, the flow rate require to dissipate 1 MW of power, that the hydrogen must be kept supercritical to be an effective coolant.

Figure 14 is a state diagram for a prime power system using fuel cells. In this representative case, each rf amplifier has its own prime power source, a fuel cell. As shown, the hydrogen would flow through the accelerator, then into the rf amplifiers for cooling purposes and thence to the fuel cells as a fuel. The hydrogen flows to the fuel cells last because the fuel cells like the hydrogen temperature to be about 550° K.

Another way to provide prime power is to use a turboalternator. The state diagram for this system is shown, in Fig. 15.

As can be seen it is substantially more complicated as far as hydrogen flow is concerned but may be somewhat lighter than the fuel cell system. As in the fuel cell case the liquid hydrogen is fed first to the accelerator structure and then, as a supercritical coolant, to the rf amplifiers and then to other items that need to be cooled. A portion of the hydrogen then flows to the combuster, then to the condenser and then to the turbine. From the turbine it flows to a recuperator and then is exhausted. A portion of the hydrogen flows directly to the recuperator.

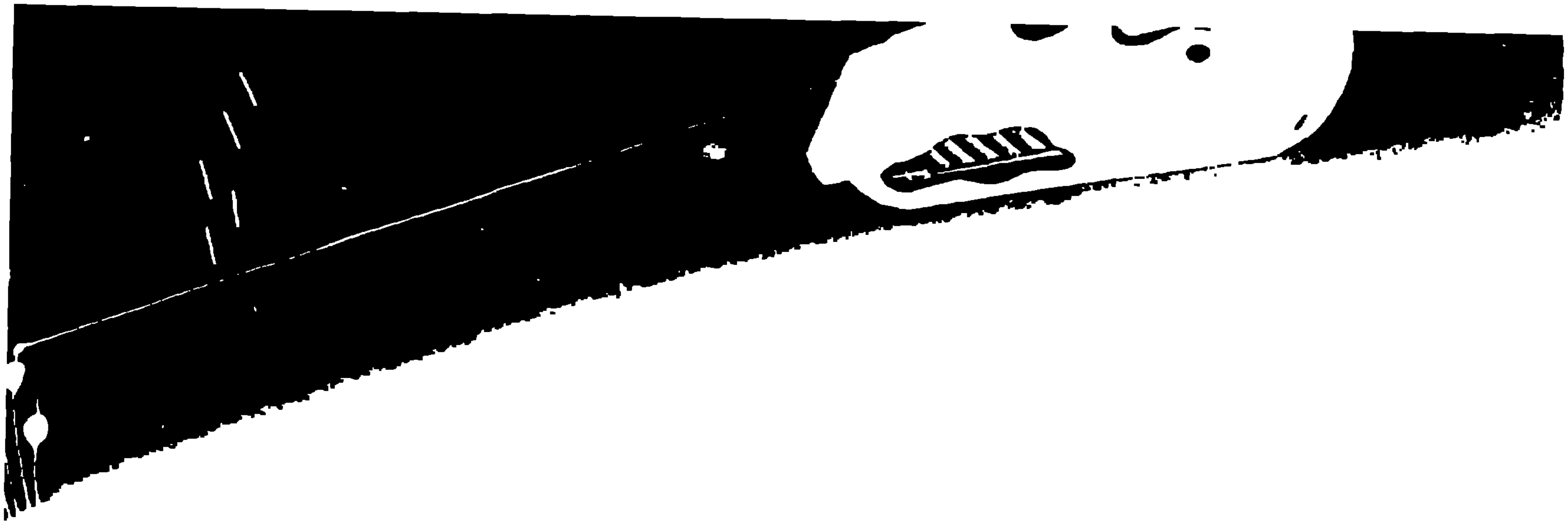
In both systems it is necessary to "dry" the hydrogen before expelling it from the space craft. The fuel cell does this naturally. In the turboalternator case a separator of some type must be used. In both cases the water is stored.

There are three things that are missing from these state diagrams.

First, the flow volumes in each of the lines has not been calculated. Second, entrance and exit temperatures in each subsystem block need to be calculated. Finally, these are only simple block diagrams of the prime power portion of the overall system. Many other subsystems on the platform are dependent on hydrogen for cooling. These all must be added in one diagram to make sure that various subsystems have the appropriate volume of cooling at the appropriate temperature and pressure.

IV. SUMMARY

Simply stated, the thermal management problem on an NPB platform is how to dissipate 10's of MW of electrical power in space over a time period of 100's of seconds. Most of the power that must be dissipated is generated in the power system and the power subsystem with the worst efficiency is the rf amplifier. The heat sources, i.e., rf amplifiers, will be distributed along the platform. Hydrogen is available for cooling at a flow rate of 15 kg/s, a temperature of approximately 35° K, and a pressure of 30 bars. It is not necessary to use the hydrogen as a coolant. The heat may be radiated to space or stored aboard the spacecraft in thermal mass storage. The basic question for this workshop to answer is what is the most promising approach and why?



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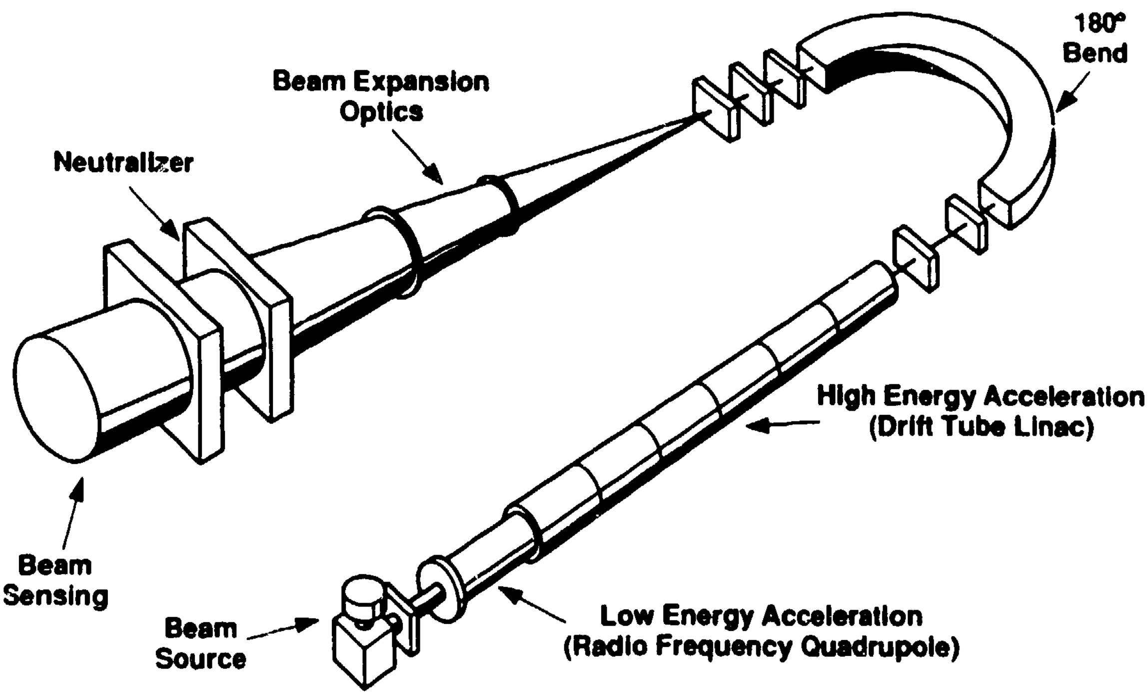


Fig. 2 Block diagram of a NPB device without a power system or cryogen/storage

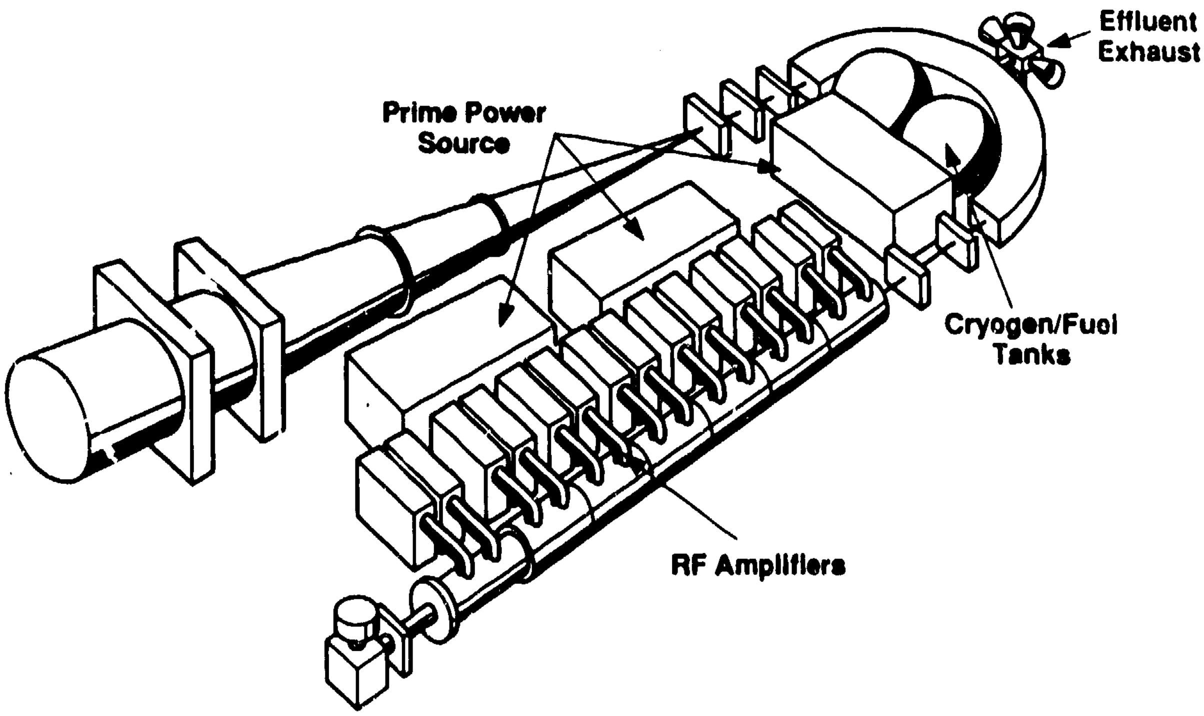


Fig. 3 Block diagram of a NPB device with power and cryogen fuel source

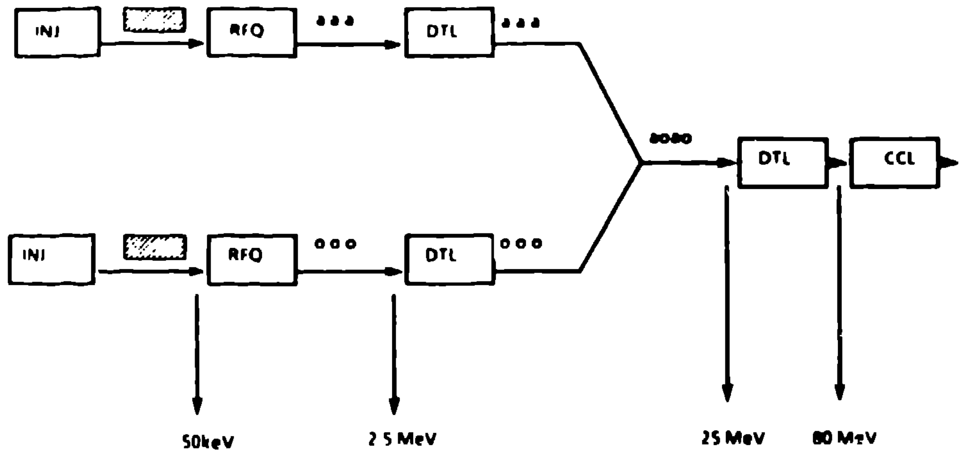


Fig. 4 Block diagram of a two beam funnel

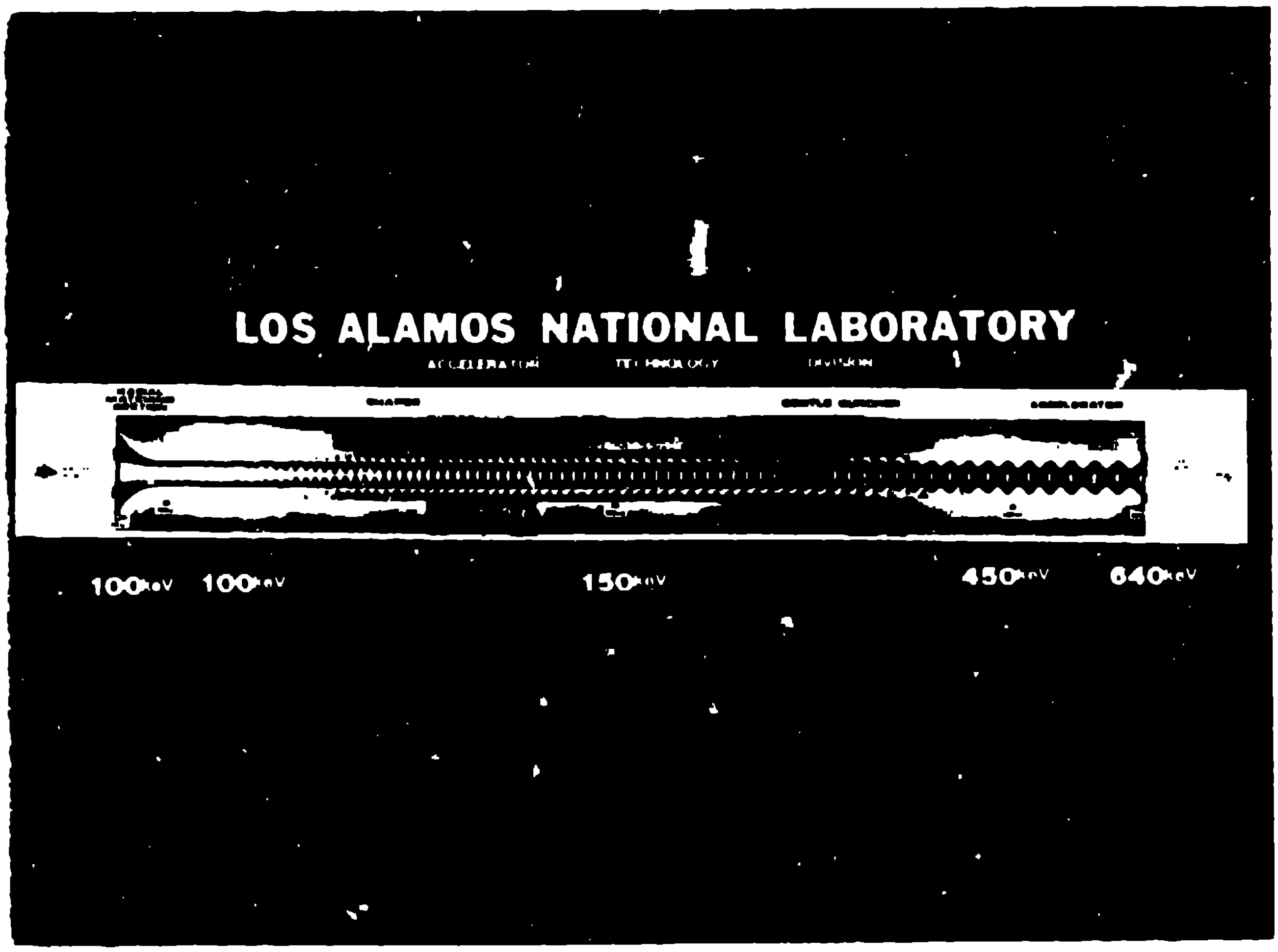
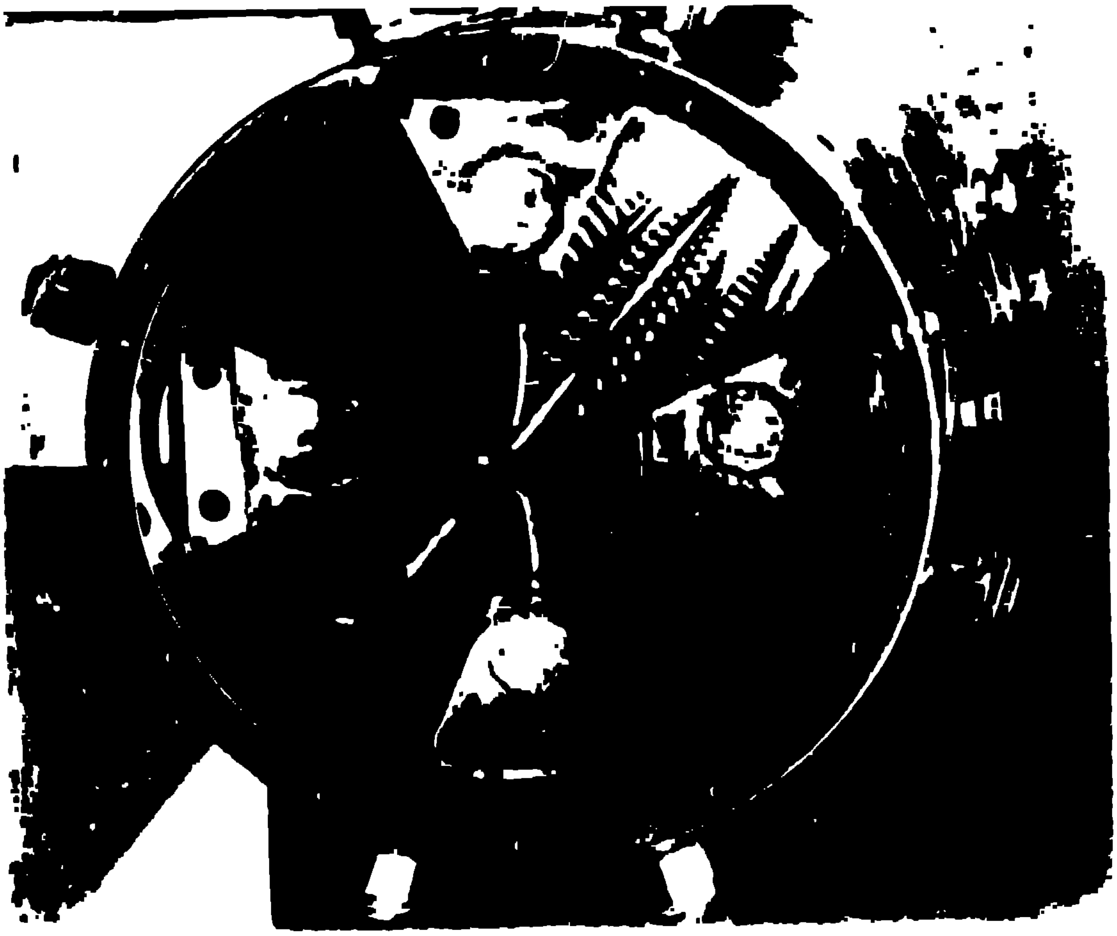
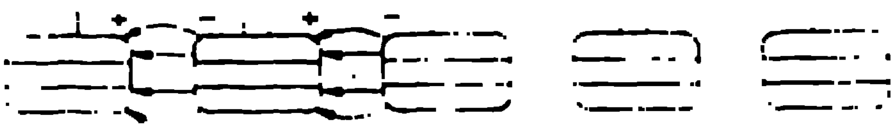


Fig. 5 Crossection of a Radio Frequency Quadrupole





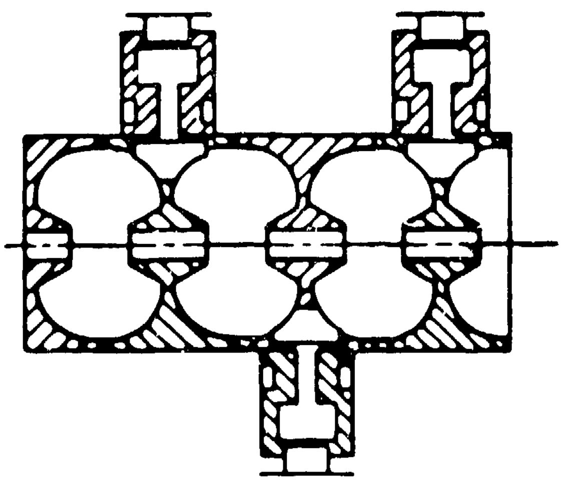
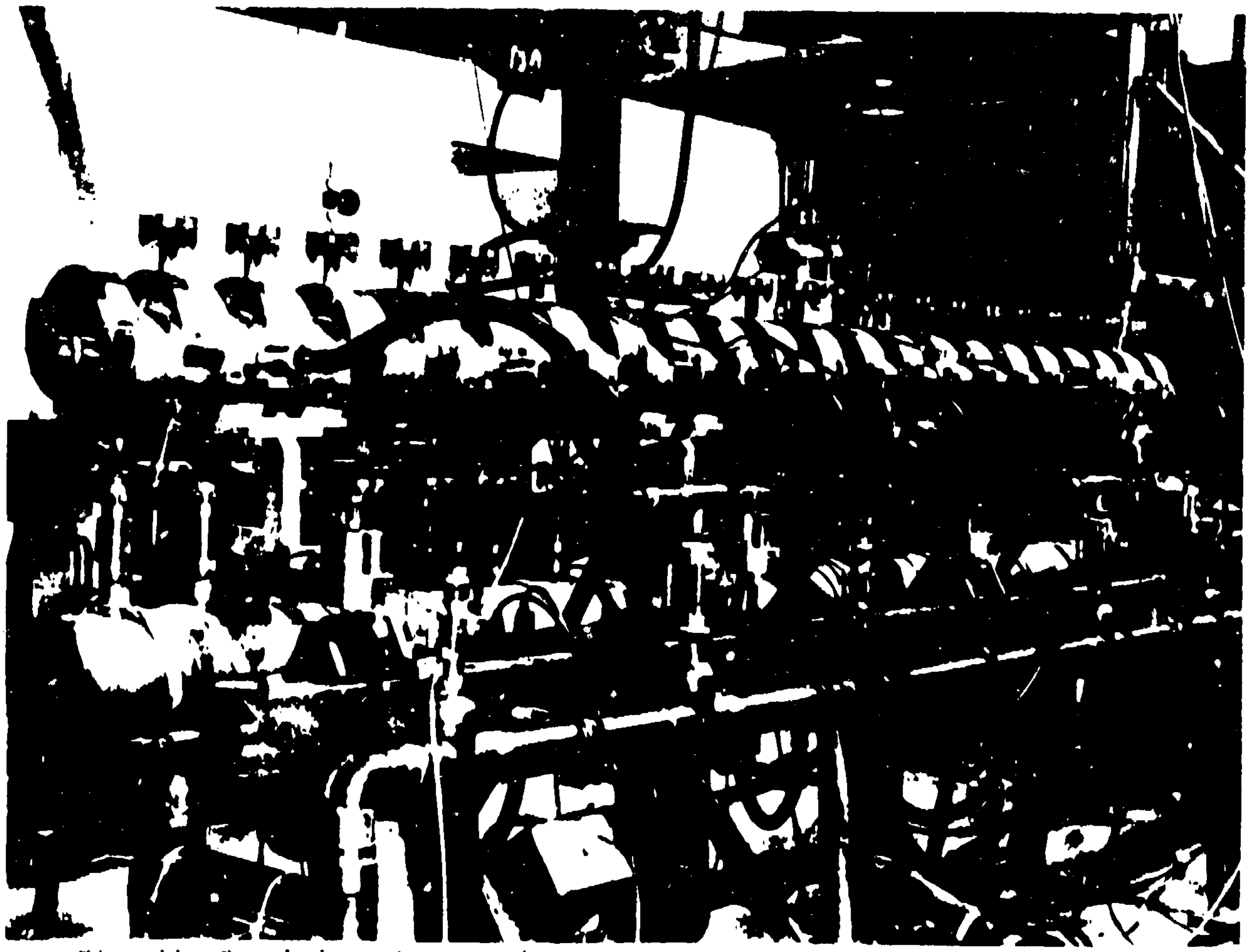


Fig. 10 Cavity half-section from a coupled-cavity acceleratcr structure



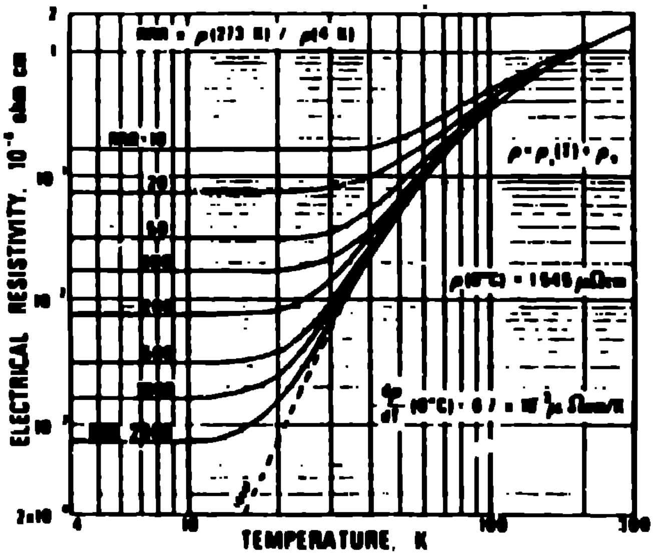


Fig. 12 Curve of cryogenic properties of copper as a function of normalized resistivity

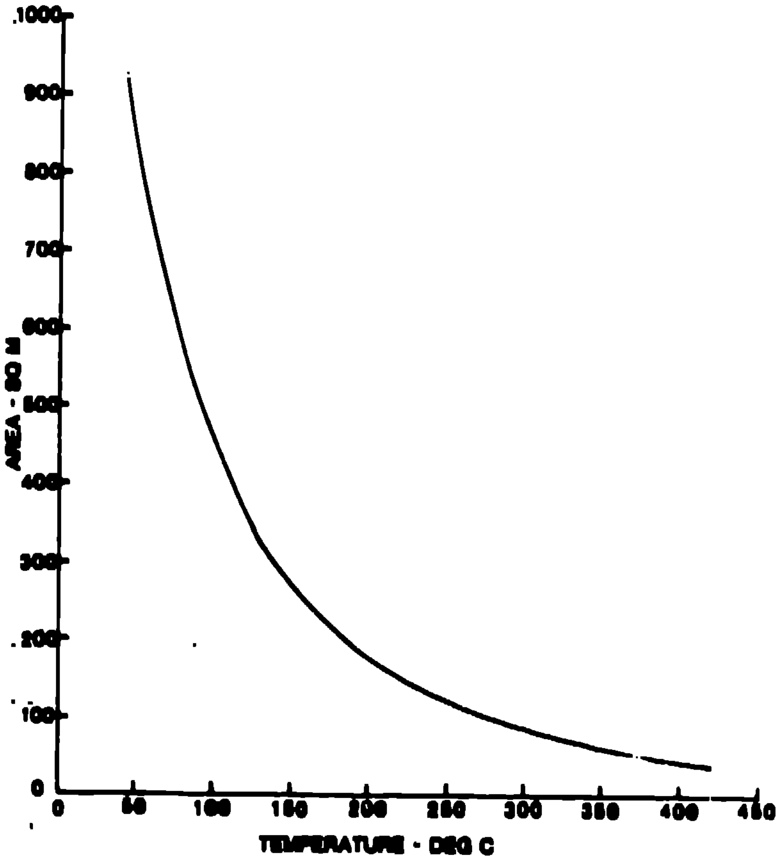


Fig. 13 Curve of radiator area vs. radiator temperature for a space radiator. Emissivity is 0.8 and power radiated is 410 kW

REPRESENTATIVE POWER/COOLING SCHEMATIC (FC)

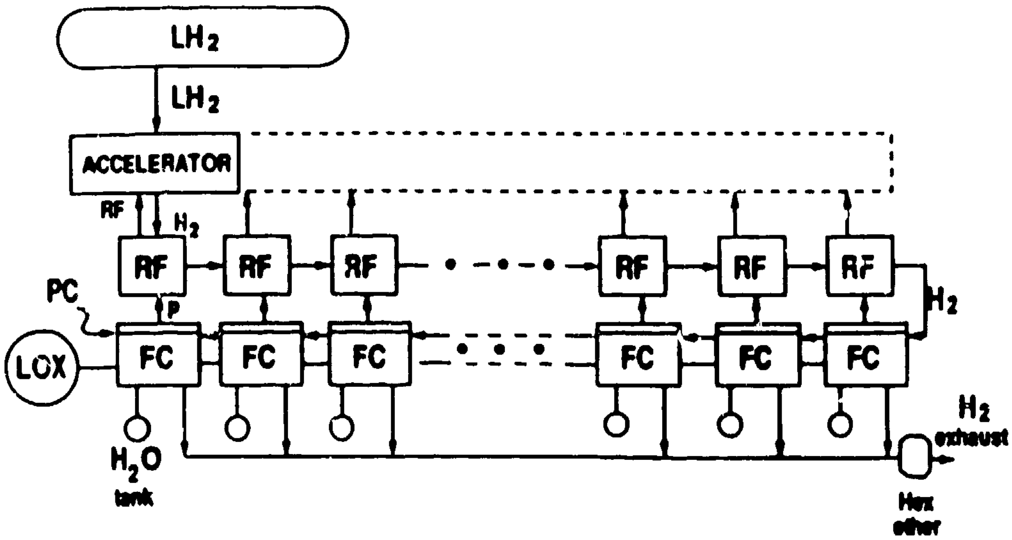


Fig. 14 State diagram for a fuel cell power system

REPRESENTATIVE POWER/COOLING SCHEMATIC (TA)

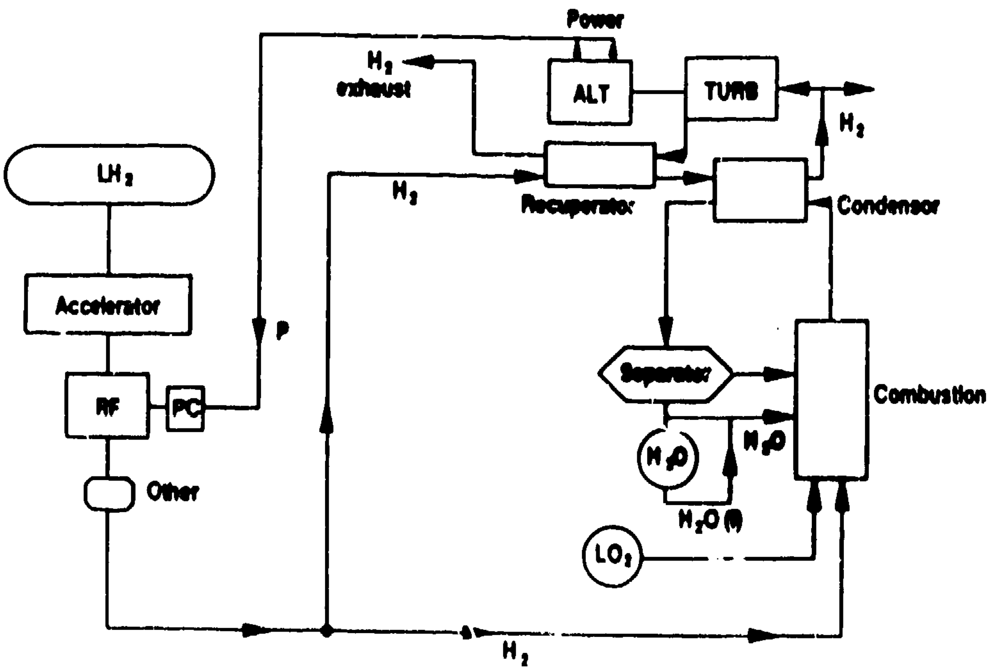


Fig. 15 State diagram for a turboalternator power system