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WATER COOLED BEAM DUMPS AND COLLIMATORS FOR THE STANFORD LINEAR ACCELERATOR*

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Summary

This paper deals with recent developments of power absorbing devices such as beam dumps, slits, and collimators. A brief discussion is given of the heat transfer experiments that have been conducted at the Stanford Linear Accelerator Center to establish design heat flux conditions for the various materials to be used for the power absorbing devices. Design concepts of a 2.2 MW, 11 to 25 GeV beam dump, as presently being built at SLAC, are also discussed. Finally, there is a typical analysis which leads to the design of a collimator, with emphasis on beam definition, heat transfer, thermal stress development and material selection.

Introduction

The extremely high power density in the electron beam of the Stanford two-mile linac poses interesting problems in the design of variable aperture collimators and slits, as well as beam dumps.

Collimators are used to define the spatial extent of the beam, to form aperture stops for beam transport systems, and to protect magnets and other equipment from physical damage by the beam.

Slits are similarly used to provide stops which define energy transmission in a beam transport system containing dispersive elements.

Beam dumps are required to absorb the residual electron beam after bremsstrahlung production and to dissipate all its power into heat.

Since the linac is expected to operate on a 24 hour a day schedule it is important that in nearly all applications these power absorbing devices must be capable of continuously absorbing and dissipating the full beam power for an extended period.

High Heat Flux Tests

General

Heat transfer experiments were performed because no data could be found in the literature for the permissable heat flux from a local hot spot. The latter is characteristic for conditions arising from impingment of high density particle beams into solids. Usual average values for burnout heat fluxes with moderate water velocities are in the neighborhood of 1.0 kW/cm^2. Use of these values as the design basis for dumps, slits and collimators would have made the size and cost of the equipment prohibitive. Reports of high local heat fluxes for water cooled targets were found.[1,2]

Test Apparatus

The test apparatus is shown in Fig. 1. The test section consisted of a thin rectangular water passage, formed by a six-inch-square by 1/8-inch test plate on one side and a lucite window on the other side. Water was circulated through this test section, a heat exchanger, a flowmeter, and a deionizing cartridge. Approximately one square centimeter of surface area of the test plate was heated by electron bombardment from a tungsten filament which was wound into a 7/16-inch-diameter flat spiral. The filament was located 1/8-inch away from the test plate which formed one wall of a vacuum chamber. The electrons were accelerated by a 60 kV, 500 mamp power supply. Thermocouples were used to read the water and test plate temperatures.

Test Results

Tests were made on 1/8-inch-thick plates made of OFHC copper, 1100 and 6061 aluminum, and stainless steel; a 2-inch-diameter by 0.050-inch-thick gold insert and a 2-inch-diameter by 1/8-inch tungsten (Kennametal) insert each brazed into a copper plate; and a 0.050-inch-thick copper plate. The water flow rate was varied from 1 to 10 fps, the inlet water temperature was varied from 20° to 60°C. The filament potential was maintained at 15 kV and the current was varied from 50 to 500 mamps. It is estimated that 75% of the power input was dissipated from the one square centimeter area associated with the heated filament.

Burnout, that is, actual destruction of the test plate, occured only with the tungsten and stainless steel plates. There was some evidence of damage to the heated side of the aluminum plates. The heated side of the copper plates showed no damage at all. Burnout of copper plates had been achieved during tests with the same test section using a heliarc welding torch as a heat source. The tungsten, aluminum, and copper plates showed varying degrees of severe erosion on the water side.

Failure of tungsten plate occurred at a heat flux less than 2.5 kW/cm^2; failure of the stainless steel plates occurred at fluxes less than 1.5 kW/cm^2.

Discussion of Tests and Hot Spot Fluxes

As shown above, the tests confirmed that due to the effects of conductivity, the undeveloped temperature profile, and possibly other local effects on the character of boiling, relatively high values could be used for the design heat flux. The pressure of other work has not yet permitted the

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generalization of these test results for the purpose of extrapolation to other materials and geometries.

The tests did serve to expose two additional deleterious effects of operation at high heat fluxes. The erosion effects due to the subcooled boiling, i.e., cavitation effects, can be very severe. The observed erosion rate at 1.5 to 2.0 kW/cm^2 was 8 mils per hundred hours for the 1100 aluminum plate, 0.5 mils per hundred hours for the 6061 aluminum plate, and 2.5 mils per hundred hours for the tungsten plate. Comparable damage was observed for the copper plates although 1000 hours of operation with a hard chrome-plated copper plate at 2.0 kW/cm^2 showed no appreciable damage.

The rapid build up of scale deposits on the hot spot was also observed. A 1.25-inch diameter by 0.027-inch thick layer of copper oxide was deposited on the chrome-plated test specimen during the 1000 hour test. The subsequent installation of a deionizing cartridge eliminated this scaling effect.

High Power Beam Dump

Description

The final beam dump design is shown in Fig. 2. It consists of a 58-inch-diameter by 14-ft 9-inch long stainless steel shell mounted on a mobile frame. The front section is 12-ft 6-inches long (10 radiation lengths of water) and contains headers designed to induce vortex flow of the water. The rear section contains 19 hard chrome-plated, water-cooled, copper plates of graduated thickness to provide 20 radiation lengths of material. Cooling water enters the rear section and flows into the front section through a tangential header which imparts a swirling motion and is discharged through a central pipe. The inlet window for the beam (not shown on the figure) is located on the vertical centerline of the front head of the tank, 12 inches above the horizontal centerline. Jets insure a high water velocity at the window. Provision is made for continuous venting of gas produced by radiolytic decomposition of the water, for remote draining and removal of the entire dump.

The window consists of an 0.050-inch thick hemisphereically shaped hard chrome-plated sheet of copper. The window can be replaced remotely.

Design Parameters and Criteria

The dump is designed to dissipate an average power of 2.2 MW for the range of 11 to 25 GeV from an incident electron beam which is 0.2 to 0.6 cm in diameter. The water flow is 550 gpm and the inlet temperature is 100°F. The maximum design value for the heat flux at the beam was 2.0 kW/cm^2 (6.3×10^6 Btu hr^{-1} ft^{-2}). The water velocity is 3 fps across the beam centerline in the vortex section and 7 fps in the water cooled copper plate section.

Due to the high level of induced radioactivity, the dump will be inaccessible after a relatively short time. Therefore, conservative design values were used for stress calculations and corrosion allowances to insure maximum useful life.

Slit and Collimator Analysis

General

As indicated above, collimators are used to physically define the particle beam, to form aperture stops for beam transport systems, and to protect magnets and other equipment from physical damage by the beam. Under normal operating conditions the heat load on such collimators should be relatively low compared to the total beam power. However, mis-steering of the beam or misalignment of these devices can cause abnormally high power densities which must be absorbed by the collimators without suffering physical damage, for an extended period of time, i.e., as long as the beam deviates far from its proper centerline.

In the case of a slit, a relatively high power absorption may occur when a narrow energy spectrum of electrons is desired and significant momentum components must be removed, or when the output of the machine is unstable or the energy spread is large.

Since one of the prime objectives of slits and collimators is to remove dispersive elements from beam transport systems, it is of utmost importance to select a proper geometry and/or suitable materials. A poor choice of the latter could result in excessive multiplicity along the beam defining edges and introduction of a new, significant momentum spread into the beam. This could minimize or destroy the value of the momentum separation in the beam transport system.

It would seem that optimum results can be obtained by using a high-Z material and a short physical length. This statement contains some element of speculation and more experimental work is needed to determine the effect of physical length on slit scattering.

Until recently, accelerator power and density was low enough to permit the use of devices following the criteria set forth above. A collimator was simply a block of medium-Z or high-Z material through which a hole was drilled to fix the desired aperture. Similarly, the jaws of a slit consisted of two opposing blocks of such material. The blocks formed a variable gap and were operated in a vice-like manner. As will be shown later, such ideal devices have a very limited power absorption capacity. A compromise and more sophisticated designs are necessary to provide useful units for the SLAC linac.

Power Deposition and Material Choice

The values for power deposition in various materials were obtained from the results of Monte Carlo calculations[3,4] of the longitudinal and radial development of the electromagnetic cascade shower in an infinite homogeneous medium due to 20 GeV incident electrons. Operating conditions for heterogeneous systems such as slits and collimators were estimated using these homogeneous values. Leakage of particles across the system boundaries into the vacuum is not taken into consideration and the treatments are conservative.

Because of their high thermal-conductivity and relatively good corrosion resistance, copper and aluminum were the two most likely candidates for materials of construction. Aluminum was finally chosen because the instantaneous temperature rise per pulse at the shower maximum is 158°C for copper and 18°C for aluminum, based on 2.2 MW and 20 GeV. Since there are up to 360 pulses/sec it is obvious that copper is not a suitable choice. The thickness of power absorbing walls must be extremely small to prevent burnout within less than one second.

The following material criteria thus becomes apparent: only low-Z materials can be used successfully to build the slits and collimators. In order to minimize temperature gradients materials should possess high thermal conductivity. Wall thickness between vacuum and coolant should be kept small.

Walls cannot be made infinitely thin since they separate the vacuum system from the coolant under pressure. The optimum geometry is a hollow circular cylinder, i.e., a tube. Therefore, it should be possible to build a collimator using an array of tubes [5,6] or what might be called a "tube-forest" or a modification thereof. A suggested design is shown in Fig. 3.

Heat Transfer and Thermal Stress Development

For wall thicknesses small in comparison to the beam size, one can assume uniform heat source distribution as a result of the beam power deposition. The temperature distribution is given by Fourier's law of conduction which for steady state and in polar coordinates is:

$$\frac{d^2T}{dr^2} + \frac{1}{r}\frac{dT}{dr} + \frac{s}{k} = Q \qquad (1)$$

where s = heat source.

Boundary conditions:

at $r = r_i \quad T = T_i$

$$r = r_i \quad q' = 2\pi k r_i \left(\frac{dT}{dr}\right)_{r_i} = \pi\left(r_o^2 - r_i^2\right) s \qquad (2)$$

The general solution is:

$$T = T_i + \frac{1}{2k} s r_o^2 \ln\left(\frac{r}{r_i}\right) - \frac{s}{4k}\left(r^2 - r_i^2\right) \qquad (3)$$

and the maximum temperature drop across the wall is

$$\Delta T = \frac{1}{2k} s r_o^2 \ln\left(\frac{r_o}{r_i}\right) - \frac{s}{4k}\left(r_o^2 - r_i^2\right) \qquad (4)$$

The heat transfer rate at the metal-water interface is readily obtained as:

$$q'' = \frac{q'}{2\pi r_o} = \frac{s}{2r_i}\left(r_o^2 - r_i^2\right) \qquad (5)$$

The maximum possible principle thermal stress due to such a temperature gradient is for a fully restrained system

$$\sigma_{th} = -E\beta\Delta T_{tot} \qquad (6)$$

where the effective temperature for the thermal stress development consists of two components

$$\Delta T_{tot} = \Delta T_{film} + \Delta T_{metal}$$

and

$E \equiv$ Young's Modulus

$\beta \equiv$ coefficient of linear thermal expansion

A typical value for the heat source at the shower maximum would be $s = 15\ kW/cm^3$ for aluminum with the given power and energy levels.

Material Selection

Aluminum alloy 6061-T6 was selected as material. It has good corrosion resistance, strength, and thermal conductivity and has been successfully used for uranium fuel element claddings in nuclear reactors under similar operating conditions.

The wall thickness for 2.2 MW and other stated criteria is 0.035 inches for a 0.75-inch tube O.D. (This is a commercially available tube size.) Efforts to manufacture such collimator units from tube stock have not been fully successful. The multitude of water-to-vacuum joints presented certain problems. Therefore, a modification of this design has been developed, using a solid aluminum block which has been perforated with 5/8-inch diameter holes running transverse to the beam direction and carrying cooling water, Fig. 4. The water-vacuum wall thickness for the shower maximum was initially limited to 0.050 inch to guarantee integrity of the material.

A total of 30 radiation lengths of material is needed to absorb and fully attenuate the beam. It proved to be advantageous to assemble this length from small modular sections. An assembly of modules tied to two rigid beams forms the slit, Fig. 5, and two slits rotated by 90° around the beam axis, form a collimator. Such units can safely dissipate up to 1 MW of power.

Since space is at a premium, it is desirable to build these devices as short as possible. The length can be optimized if the governing wall thickness between adjacent holes as well as at the vacuum interface is tailored according to shower development and attenuation. This means that the ratio of aluminum to water, downstream from the shower maximum, is increased in favor of aluminum according to the exponential attenuation of the beam power. Thus it has been possible to design a slit having an overall length of 16 feet corresponding to 30 radiation lengths.

The question of radiation damage to the atomic lattice, i.e., formation of dislocations, vacancies and interstitial atoms, is not yet well known for aluminum at 20 GeV. This might well be the limiting factor in the life of these modules, rather than corrosion or thermal stress fatigue. Therefore, the modules are large enough to allow for various beam exposure locations and distribution of the expected radiation damage over a larger volume.

Finally, the convoluted front face allows "nesting" of opposing modules. Thus, in fully closed position a slit or collimator can also be used as a beam stopper.

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Acknowledgments

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FIGURE CAPTIONS

1. Heat transfer test setup.
2. 2.2 MW beam dump.
3. "Tube forest" slit.
4. Collimator module.
5. High power slit.

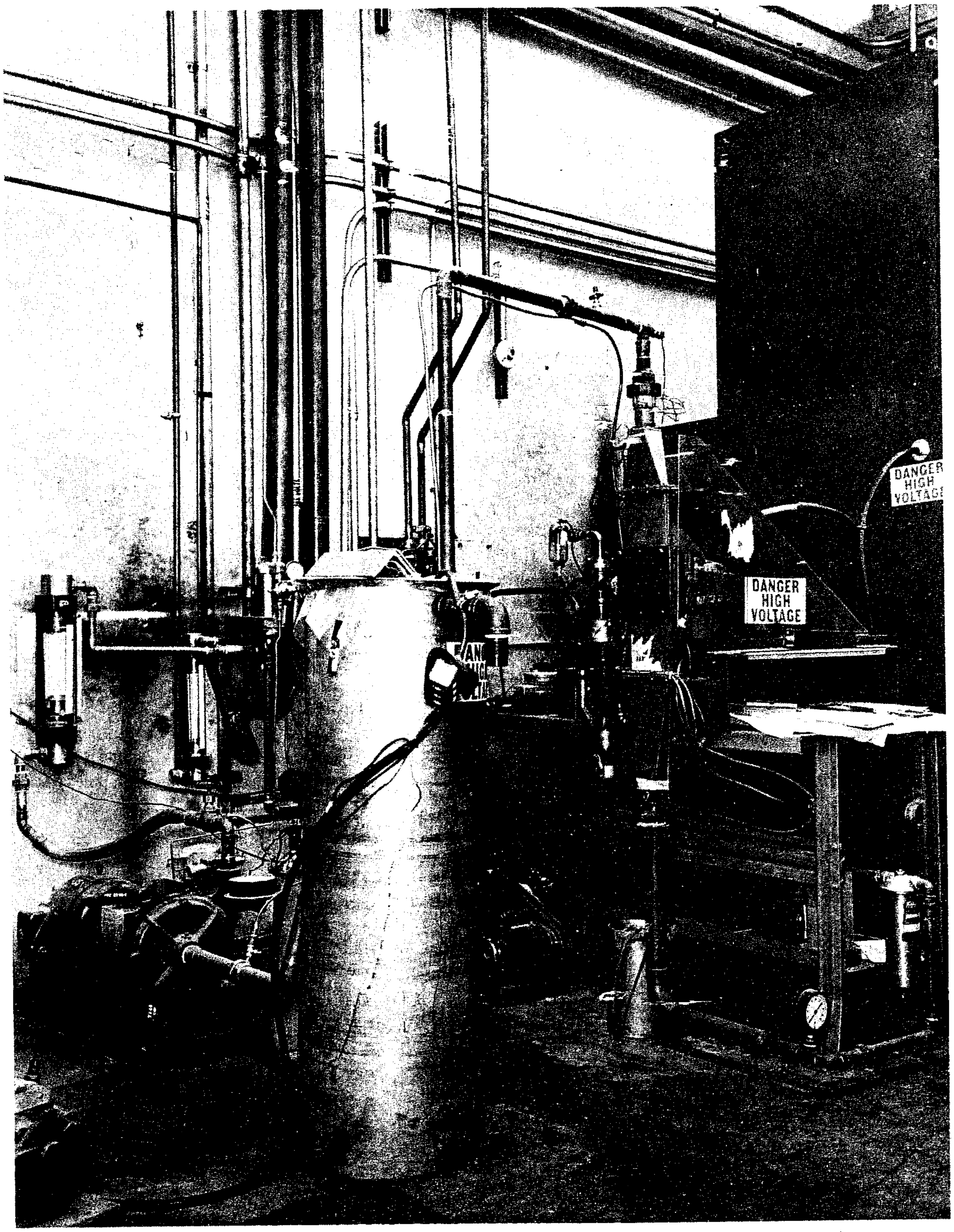

Figure 1

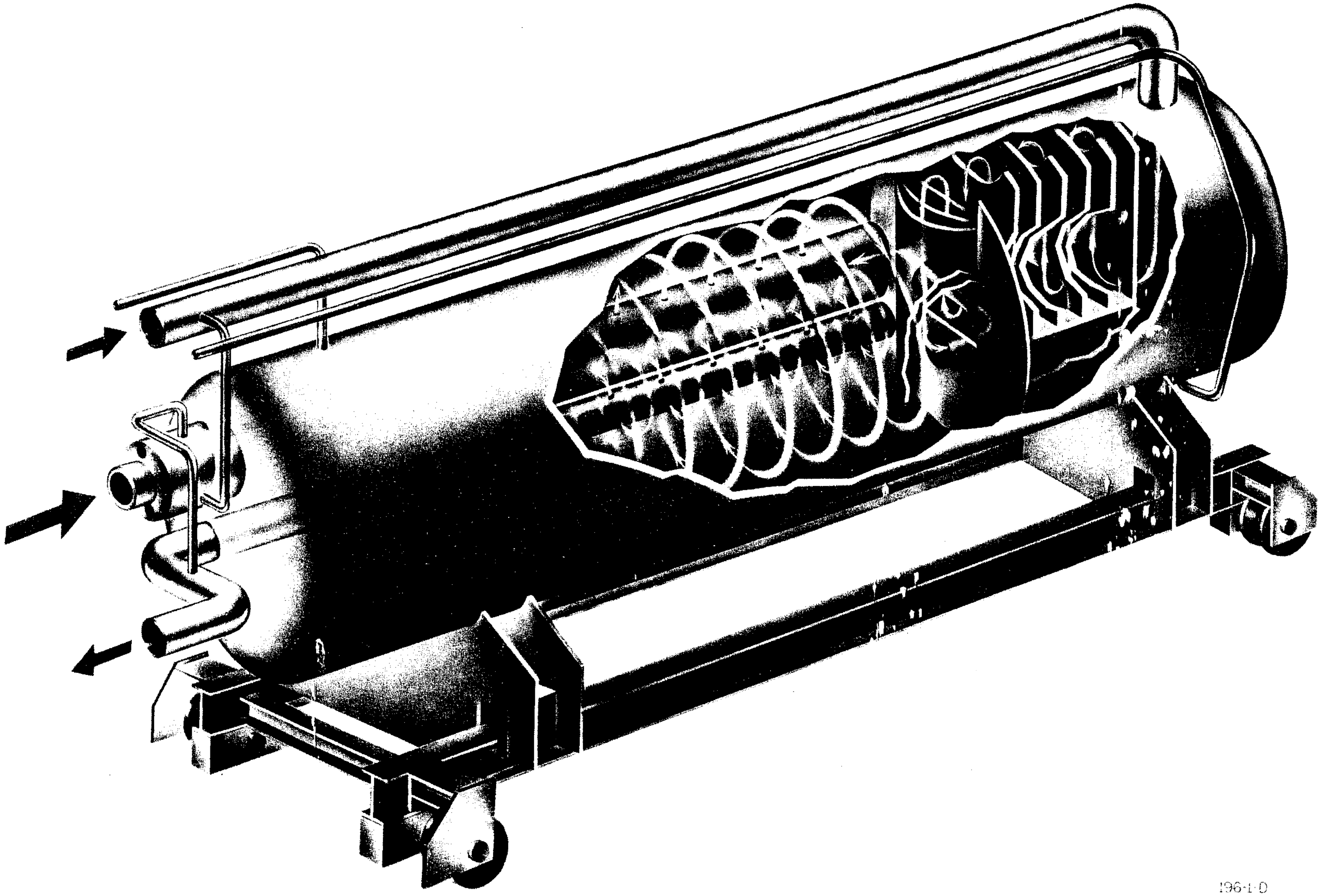

Figure 2

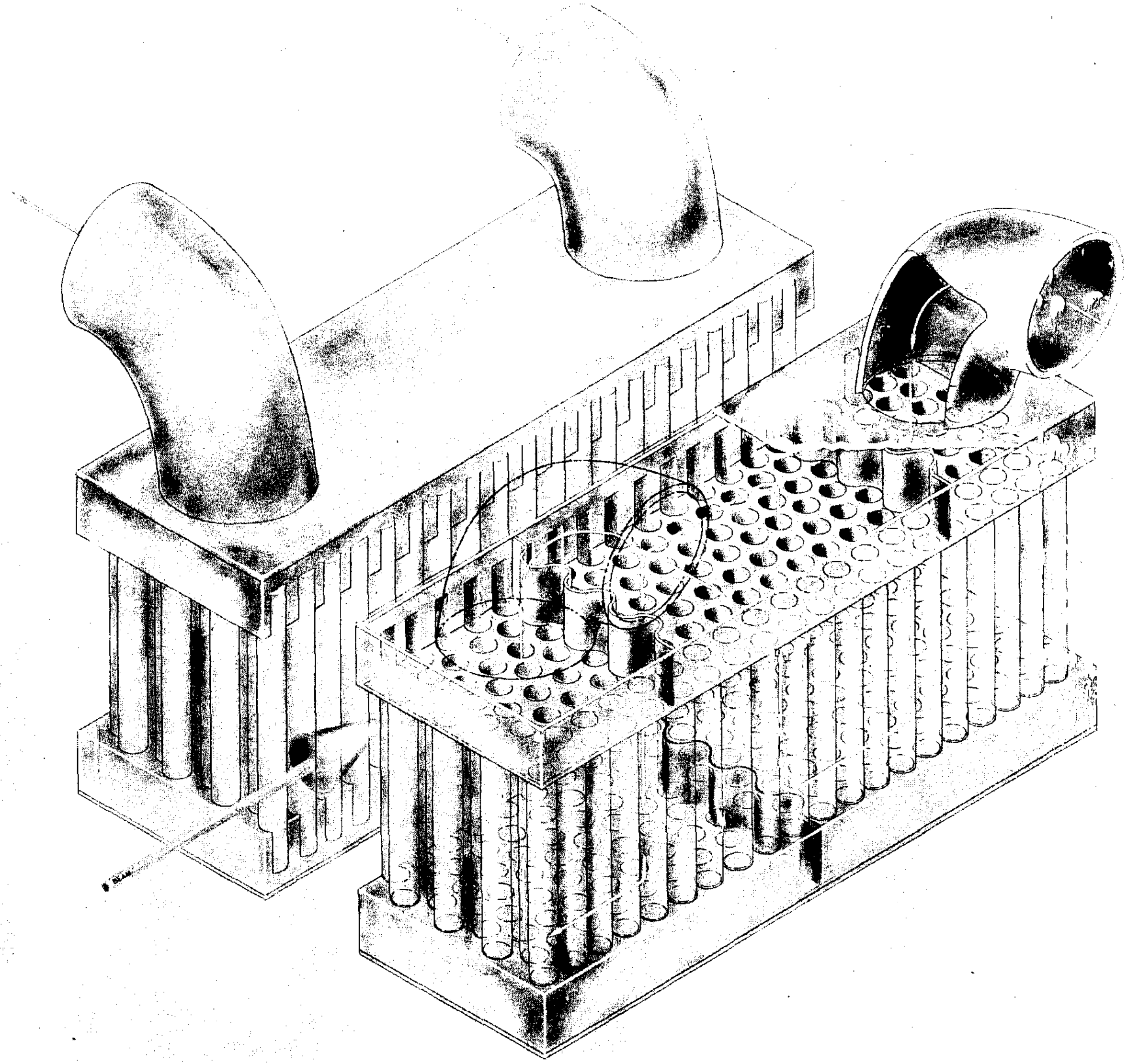

Figure 3

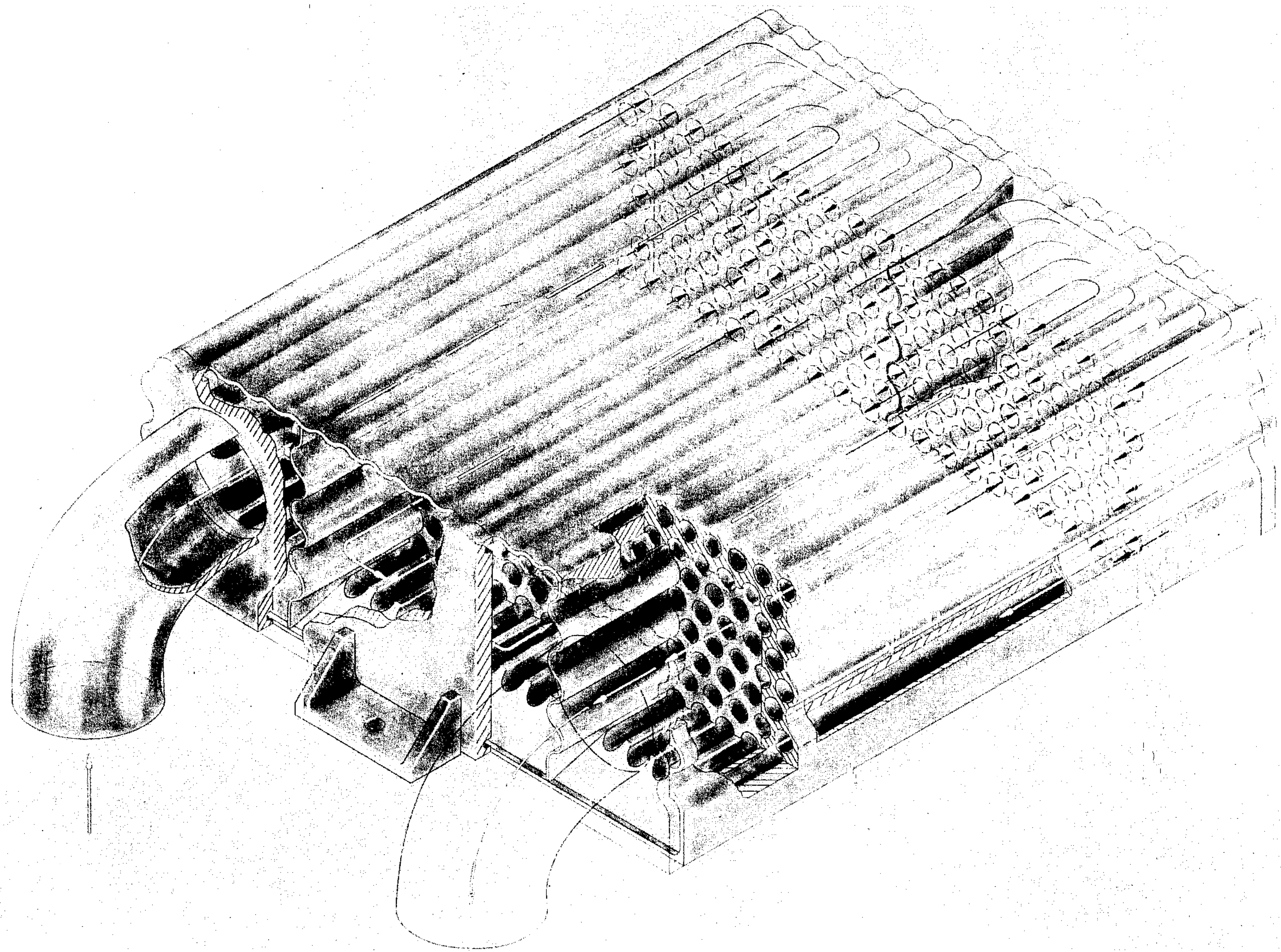

Figure 4

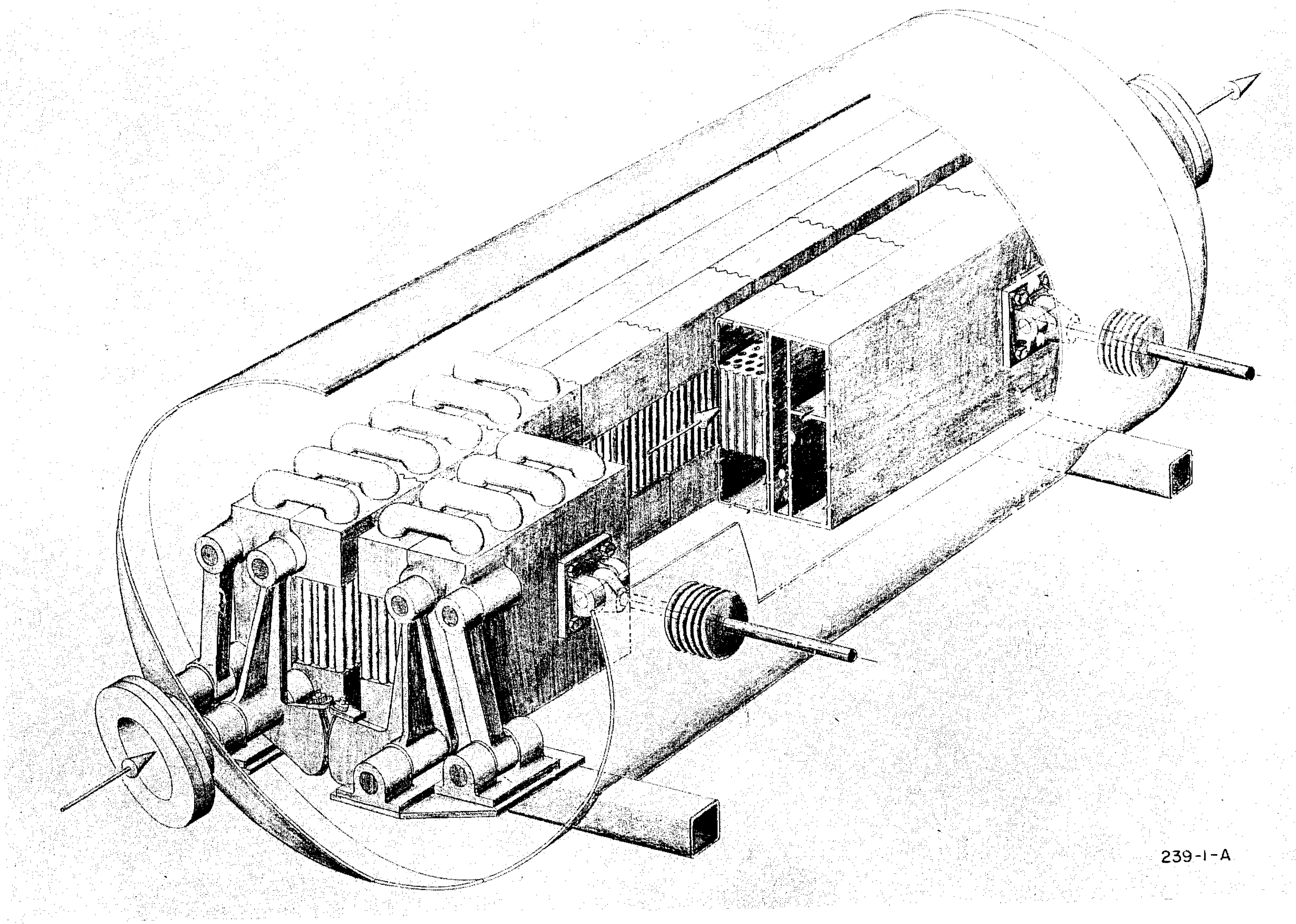

Figure 5