SLAC-TN-68-7
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April 1968

400-KW SPHERE BEAM DUMP

SUMMARY

Efforts to reduce production costs, simplify assembly procedures, and achieve compactness while at the same time retaining power absorption capacity led to the development of a new beam dump concept. The main power absorption and dissipation medium is a water-cooled bed of 1 cm diameter aluminum spheres. The bed of spheres replaces water-cooled plate assemblies of earlier versions of medium power beam dumps. The spheres are contained in a 25 cm diameter tube, which dimension is in accordance with radial shower attenuation in the aluminum-water mixture. The bed of spheres is terminated after a depth of 13.8 radiation lengths (r. l.) and followed by a peripherally-cooled solid aluminum cylinder of 4.2 r.l. The latter has a 23 r.l. long solid copper cylinder attached to it to make the total length of the dump equivalent to 41 r.l. For a flow rate of 100 gpm, the dump should have an average beam power absorption capacity of 400 kW for incident beam energies $E_0 \leq 25$ GeV. A prototype of this beam dump concept was built and fabrication costs were significantly below those for previously built water-cooled plate dumps.

I. INTRODUCTION

Low to medium power beam dumps capable of continuously absorbing and dissipating up to 120 kW average beam power are already in existence. Two such devices are presently installed in the B-Beam target room. These dumps were designed according to longitudinal and radial shower calculations[1] for 20-GeV incident electron beams. In addition, high-power beam dumps for average powers[2,3] of up to 500 kW and up to 2.2 MW are in operation. An increasing need for beam dumps at an intermediate power level ($500 \geq P_{av} \geq 100$ kW) appears to be developing.

Unfortunately, application of the high-power beam dumps, as mentioned above, is economically feasible only if the experiments are carried out in a permanent beam transport system containing such dumps. These units are bulky and require elaborate radioactive water systems. In the case of temporary beam transport systems, space is usually limited and individual components must be quickly adaptable to various experimental situations. This requires a beam dump that is light and compact, that will be inexpensive, and that can easily accomodate to varying beam configurations. The basic physical requirement for such a dump is adequate shower attenuation in the radial and axial directions. It must allow for certain deviations of the particle beam from its nominal trajectory as might occur from either sudden momentum changes or accidental mis-steering of the beam.

Since the beam dump should be as compact as possible, only medium or high-Z materials should be employed. Power deposition varies strongly as a function of Z and may result in total destruction of a high-Z material by either melting or evaporation. It can be shown that for average incident beam powers significantly in excess of 100 kW, only aluminum or materials with even lower Z are suitable.

Production of a dump using water-cooled aluminum plates is feasible for the desired power range up to 500 kW. However, production of such a device is expensive, primarily due to high labor costs resulting from the large number of precision-machined plates required for the assembly. Furthermore, these devices have the disadvantage that they are bulky.

Efforts were made to arrive at a design which would significantly reduce production labor costs and would have a simple assembly procedure while at the same time retaining high power absorption capacity.

II. THE POWER ABSORPTION MEDIUM

To optimize power absorption and preserve compactness, it is desirable to have a high volume-to-surface area ratio of the power absorption medium. The geometry of a sphere is unique in that it has the largest such ratio of any geometry. On the other hand, from a heat transfer point of view, a high surface area-to-volume ratio is most suitable. The optimum simple geometry for this requirement would be a cube and there exists an obvious conflict in the selection of an optimal geometry.

In order to achieve small temperature differences and for fabrication reasons, either body should be relatively small compared to the over-all dimensions of the beam dump. Thus, an array or bed of water-cooled spheres or cubes in a suitable container would form the main power absorption and dissipation medium. It would replace the plate assemblies mentioned earlier.

In such an arrangement the spherical geometry has obvious advantages. Each sphere is only in point-contact with neighboring spheres, whereas a full side of a cube can directly face and be in contact with another cube. The latter would significantly decrease the effective heat transfer surface area and result in excessive heat fluxes and temperature gradients. Thus, the total effective heat transfer surface area in a bed of spheres is maximum (for simple geometries) and water flow conditions are uniform throughout the medium.

Another unique feature of the spherical geometry is that the heat flux paths are all essentially radial; and as the heat flux increases as a function of radius from the center to the surface of the sphere (assuming uniformly distributed heat sources), the heat flow area increases also. This keeps temperature gradients, and, therefore, thermal stresses in the material, low. Moreover, a sphere cooled on the outside surface has its highest temperature and stress in the center. The hot center is fully restrained by colder material close to the surface. The sphere can therefore tolerate (without sustaining damage) thermal stresses which are in excess of the material yield strength or fatigue strength.

The maximum sphere diameter is determined by the maximum heat flux that can be safely transferred by forced convection and nucleate boiling from the sphere surface. Since each sphere is in point-contact with other spheres, the effective heat transfer area is less than the actual sphere surface area. This results in an increase of the effective heat transfer rate off the surface compared to that of a sphere which is uniformly submersed in the cooling fluid.

The minimum sphere diameter is determined by the maximum allowable pressure drop of the cooling fluid through the bed, i.e., by the characteristics of the available pump. The pressure drop varies inversely with the sphere diameter. The cooling fluid mass velocity should be high enough to result only in a modest bulk temperature rise and therefore preserve a large subcooling. The latter helps to prevent burnout at relatively low velocities.

III. IMPORTANT DESIGN FEATURES

1. Dump Size and Materials Selection

The diameter of the dump, 25 cm ($\sim$10 inch), was selected to be in accordance with radial shower attenuation in the bed of spheres with an allowance for radial excursions of the beam. The bed of spheres is housed in an aluminum tube (see Fig. 1). The beam enters the dump through a 0.475 cm thick, dished, aluminum head which acts as a window. It is cooled by the inlet manifold, which discharges part of the water directly onto it.

The bed of spheres is approximately 160 cm long. The spheres are fabricated from aluminum alloy. Assuming a packing factor of 70%, the 160 cm long mixture of spheres and water is equivalent to approximately 13.8 r.l. This is adequate to develop the shower maximum and partially attenuate the shower of a 25 GeV, 400 kW beam.

The spheres are followed by a solid aluminum cylinder which is also contained in the 25 cm diameter tube. The aluminum block is peripherally cooled by the water which exits from the bed of spheres. Its length is 38 cm or about 4.2 r.l. The dump is finally terminated with a copper cylinder, which has a length of 33 cm or approximately 23 r.l.

The total length of the vessel is then equivalent to 41 r.l. or 231 cm($\sim$90 inch).

2. The Window

For $P_{av} = 400$ kW and $E_0 = 20$ GeV the average current becomes $I_{av} = 20\ \mu$A. The window thickness selected was $\delta = 0.47$ cm (3/16 inch). Therefore, the power deposited in the window is

$$
\begin{aligned}
P_w &= I_{av}\, \rho \delta \, \frac{dE}{dx} \\
&= 20 \times 10^{-6} \times 2.7 \times 0.475 \times 1.64 \times 10^{6} \qquad (1) \\
P_w &= 42 \text{ watts}
\end{aligned}
$$

No problem exists for any size of the incident beam.[3]

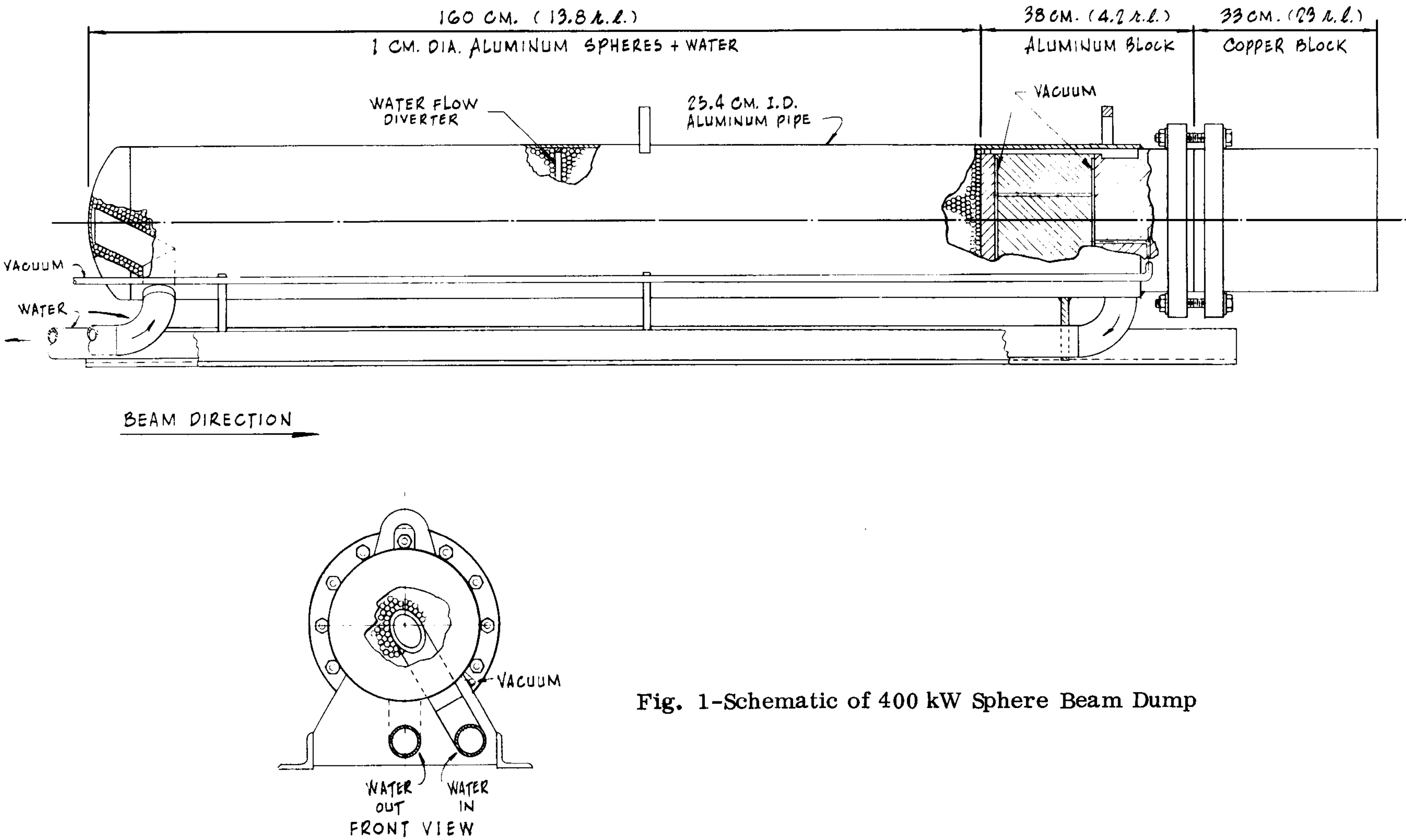

Fig. 1-Schematic of 400 kW Sphere Beam Dump

3. The Spheres

High thermal conductivity, low-strength type 1100 aluminum alloy was chosen as the material for the spheres. It exhibits very good corrosion resistance and can be forged easily. The maximum sphere diameter was obtained from heat transfer considerations at the shower maximum. For a sample calculation, a sphere is selected which is located at the depth where the shower maximum occurs, and whose center coincides with the beam center line.

Assuming an average incident beam power of $P_{av} = 400$ kW at $E_0 = 20$ GeV and using existing shower values,[1] it can be shown that for beams having standard deviations $0.1 \leq \sigma_b \leq 0.3$ cm, the total power deposited in a 1 cm diameter sphere is $P_s \approx 1.1$ kW.

The volume of the sphere is $V_s = (4/3)\,\pi r_s^3 = 0.524\ \mathrm{cm}^3$. Thus, if the Gaussian beam distribution is neglected for the moment and the power is assumed to be deposited uniformly throughout the sphere, the volume heat source becomes

$$s = \frac{P_s}{V_s} = \frac{1.10}{0.524} = 2.1\ \mathrm{kW/cm}^3 \quad .$$

Assuming constant thermal conductivity throughout the material, the temperature distribution in the sphere is described by Fourier's law of conduction

$$k\nabla^2 T + s = \rho c\,\frac{\partial T}{\partial \tau} \quad . \tag{2}$$

For steady-state, no angular variations, and s = constant throughout the medium, Eq. (2) reduces to

$$\frac{d^2T}{dr^2} + \frac{2}{r}\,\frac{dT}{dr} + \frac{s}{k} = 0 \tag{3}$$

with boundary conditions:

at $r = r_0$

and $\qquad T = T_0$

$$q = \frac{4}{3}\,\pi r_0^3\, s = -k\, 4\pi r_0^2 \left(\frac{dT}{dr}\right)_{r_0} , \quad \therefore \left(\frac{dT}{dr}\right)_{r_0} = -\frac{r_0 s}{3k} \quad .$$

The solution to Eq. (3) is readily obtained as

$$T - T_0 = \frac{s r_0^2}{6k}\left[1 - \left(\frac{r}{r_0}\right)^2\right] \tag{4a}$$

The maximum temperature occurs at $r = 0$, i.e., $T_{max} = T_i$ and Eq. (4a) reduces to

$$T_i - T_0 = \Delta T = \frac{s r_0^2}{6k} . \tag{4b}$$

For $s = 2.1$ kW/cm^3, $r_0 = 0.5$ cm, and $k_{1100} \approx 2.50$ watts/(cm^2 $^\circ$C/cm) the temperature difference becomes

$$\Delta T = \frac{2.1 \times 10^3 \times (0.5)^2}{6 \times 2.5} = 35^\circ C$$

and the maximum temperature in the center of the sphere for nucleate boiling conditions on the surface would be approximately 140°C .

Note, this temperature is somewhat lower than the actually prevailing maximum temperature. The discrepancy is due to the fact that power deposition was assumed to be uniform throughout the sphere, whereas in reality it has a rather complicated shape, i.e., it is Gaussian in radial direction normal to the beam center-line and approximately constant in axial direction. The actual temperature is not expected to be in excess of 160°C, which is very modest.

The total surface area of the sphere is $A_s = 4\pi r_s^2 = 3.15$ cm^2. Thus, the heat flux off the surface and into the water becomes

$$q'' = \frac{P_s}{A_s} = \frac{1.10}{3.15} = 0.35 \frac{kW}{cm^2} .$$

The effective heat flux is expected to be somewhat higher because adjacent spheres are in contact with each other, thus reducing the effective surface area.

Local nucleate boiling heat fluxes of 2 kW/cm^2 were found to be safe for flow parallel to a spot-heated flat plate and for high subcooling.[2] In a bed of spheres, one would expect this value to be lower due to lower subcooling close to the beam center-line, the particular geometry of the flow passages, lower water velocity, and the fact that the heat flux is more or less uniform over the effective heat transfer surface area. However, for water velocities in excess of 1 ft/sec and a subcooling of at least 50°C, heat fluxes of $q'' = 0.25$ kW/cm^2 (corresponding to $P_{av} \approx 300$ kW) should present no problems. The author is confident that for adequate mass velocities, heat fluxes of 0.35 to 0.45 kW/cm^2 (corresponding to $P_{av} = 400$ to 500 kW) can be safely transferred off the surface.

4. The Thermal Joint Between Copper and Aluminum

At the end of the aluminum cylinder the shower is attenuated to a level where it is possible to introduce a solid copper block to clean up the remaining shower particles. The amount of power deposited is small enough that the resulting heat can be conducted through the copper cylinder, across a thermal joint into the aluminum cylinder, and through the latter into the water. The thermal joint consists of concentric rings that cause a weak metallic gasket (annealed copper; indium could be used too) to yield due to the clamping force of bolted flanges.

IV. SOME FLOW CONSIDERATIONS

The flow cross-sectional area for the case of perfectly packed spheres is

$$A_0 = D_s^2 - \frac{D_s^2 \pi}{4} = 1.0^2 - \frac{1.0^2 \pi}{4} = 0.215 \text{ cm}^2$$

or 21.5%.

The total open area in a 25-cm diameter tube assuming perfect packing and a perfect fit at the interface with the tube is

$$A_{0,tot} = \frac{25^2 \pi}{4} \times 0.215 = 106 \text{ cm}^2 \ (\equiv 0.114 \text{ ft}^2) .$$

Then the maximum velocity over a sphere and for a flow rate of $w = 100$ gpm ($\equiv 0.222$ ft^3/sec) becomes

$$V = \frac{w}{A_{tot}} = \frac{0.222}{0.114} \approx 2 \text{ ft/sec} .$$

This should be adequate for $P_{av} = 300$ to 400 kW.

The bulk temperature rise for $w = 100$ gpm ($\equiv 378.5$ l/min) and $P_{av} = 400$ kW is

$$\Delta T_w = \frac{P_{av}}{c_p w}$$

$$= \frac{400 \times 10^3 \times 0.239}{1 \times 6300} \approx 15^\circ\text{C} .$$

Finally, the pressure loss for flow through a bed of spheres can be computed from the following general formula for beds of solids[4]

$$\Delta p = \frac{2 f_m G^2 L (1 - \epsilon)^{3-n}}{D_s g_c \rho \phi_s^{3-n} \epsilon^3}$$

where

f_m = a modified friction factor for beds of solids (a function of a modified Reynolds number N'_{Re})

N'_{Re} = GD_s/μ

G = fluid mass velocity, based on the empty dump cross section

D_s = sphere diameter

μ = fluid viscosity

L = depth of bed

ϵ = voidage (fractional free volume)

n = exponent, a function of N'_{Re}

g_c = dimensional constant

ρ = specific gravity of fluid

ϕ_s = shape factor, defined as the quotient of the area of a sphere equivalent to the volume of the particle divided by the actual surface of the particle.

Numerical Values:

$$D_s = 1.0 \text{ cm} \equiv 0.0328 \text{ ft}$$

$$\mu = 67.2 \times 10^{-2} \text{ lbm/(ft sec) at } 68^{\circ}\text{F}$$

$$G = \frac{w}{A} \approx \frac{14}{0.545} = 25.7 \text{ lbm/(sec ft}^2)$$

$$N'_{Re} = \frac{D_s G}{\mu} = \frac{0.0328 \times 25.7}{67.2 \times 10^{-2}} = 1250$$

$$\therefore \quad n = 1.94, \quad f_m = 0.8, \text{ (from Ref. 4)}$$

$$L = 5.2 \text{ ft}, \quad g_c = 32.17 \text{ (lbm)(ft)/(\# sec)}$$

$$\epsilon = 0.3, \quad \phi_s = 1.0, \quad \rho = 62.4 \text{ lbm/ft}^3$$

then

$$\Delta p = \frac{2 \times 0.8 \times (25.7)^2 \times 5.2\,(1 - 0.3)^{3-1.94}}{0.0328 \times 32.17 \times 62.4 \times 1 \times (0.3)^3}$$

$$\Delta p \approx 21 \text{ psi}$$

After completion of fabrication the dump was pressure tested to 150 psig. At the same time the pressure drop through the dump was measured for various flow rates. The measured value for 100 gpm was $\Delta p = 16$ psig, as compared to $\Delta p = 21$ psig as calculated above. Figure 2 gives pressure loss versus flow rate for flow rates up to 100 gpm. The fact that the measured value is lower than the calculated one can be attributed mainly to imperfect packing.

The flow and the pressure loss are uniform throughout the bed of spheres. However, the spheres do not pack well into the circular container. Thus, flow diverters in the form of rings are placed occasionally to crowd the water flow away from the container wall and back into the bed of spheres.

V. A SAFETY FEATURE

All existing beam dumps have one shortcoming in common: It is not possible to readily detect a burnout which may have occurred inside the vessel unless it also affects the window or the shell. This could in some instances have serious consequences for personnel and equipment.

In the sphere dump an attempt was made to remedy this situation and provide more safety. The solid aluminum cylinder actually consists of two cylinders with a vacuum cavity in between them. This cavity communicates with a vacuum connection. In case the water flow is off, or too much power is deposited and dissipated in the dump and this leads to destruction of the bed of spheres by either melting or vaporizing, a low-density, low-Z path can be formed. This would shift the shower maximum downbeam and it would result in excessive power deposition in the aluminum cylinder. The result would be formation of a communication hole between the bed of spheres and the vacuum cavity. If the vacuum cavity were, for example, connected to the beam transport vacuum system (which is interlocked) it would provide an immediate external indication of a burnout condition. At this point the cavity is followed by an additional 25 r.l. of material that offers some short term protection.

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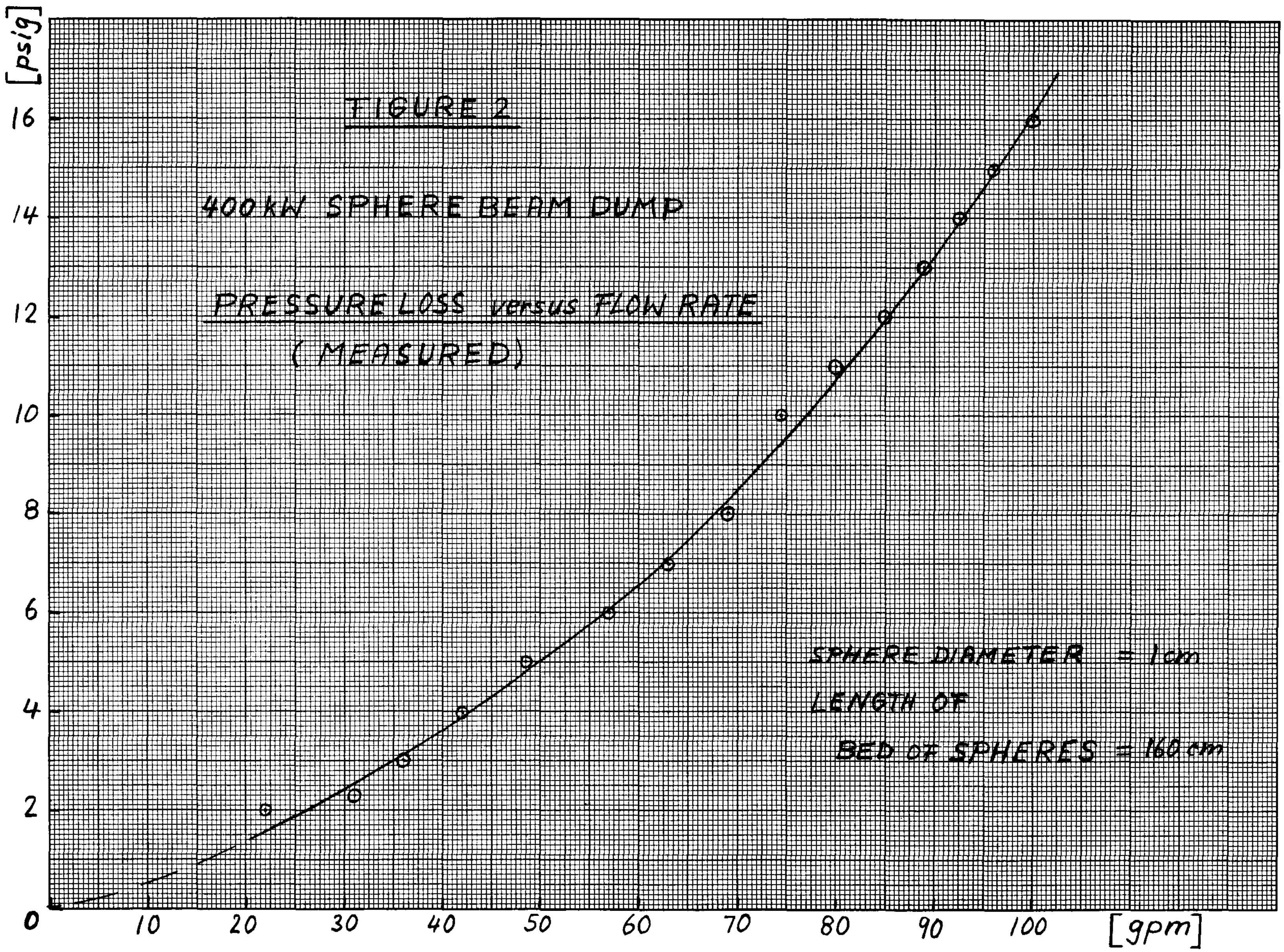

ACKNOWLEDGEMENT

The author would like to thank L. R. Lucas for his efforts in engineering and designing the beam dump vessel. D. Robbins measured and supplied the pressure loss data. His help is much appreciated.

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