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POWER AND FLOW TEST OF A PROTOTYPE OF THE SPHERE BEAM DUMP

SUMMARY

A prototype of the previously proposed "Sphere Beam Dump" was tested to gain some understanding of its maximum power absorption capacity and dynamic behavior, and to detect onset of transient conditions which eventually would lead to burnout and destruction of the apparatus.

The nominal electron beam energy was $E_0 = 18$ GeV. At a pulse repetition rate of 360 pps, the maximum average power delivered by the accelerator and deposited into the beam dump was $P_{av} \approx 495$ kW (this was also a new power record for the accelerator). The cooling water flow rate through the dump was $w = 66$ gpm; this resulted in a water velocity over the surface of the spheres of $V \approx 4.5$ ft/sec.

At this power level the dump performed well. The maximum temperature recorded anywhere in the dump was 170°C, which corresponds approximately to the boiling point of water at the local pressure. Apart from small ($\approx 10^\circ$C) fluctuations resulting from the nucleate boiling, temperatures in the dump were stable, and no transients were detected. Visual inspection of the spheres after the experiment showed no apparent damage.

It can be assumed that at the design flow rate of $w = 90$ gpm the beam dump can safely absorb average beam powers up to 500 kW.

I. INTRODUCTION

A new beam dump concept named the "Sphere Beam Dump" was described in detail in an earlier paper.[1] It provides power absorption and dissipation through use of a water-cooled bed of 1 cm diameter aluminum spheres contained in a tube. Its principle features are relatively low production costs, simple assembly procedures, compactness, and rather high power absorption capacity. Although the dump is rated at about 500 kW, its production costs are competitive with 50 kW designs.

A prototype of this beam dump concept was tested in the C-Beam of the SLAC Beam Switchyard on September 19, 1968. The dump was instrumented with thermocouples to monitor the longitudinal temperature distribution along the nominal beam center line as a function of beam power delivered by the accelerator. At each measuring location both the temperature of a sphere and the temperature of the cooling water in its vicinity were recorded. In order to obtain information about mixing and lateral flow of water in the bed of spheres, three additional thermocouples were placed peripherally.

Unfortunately, the Z of the thermocouples was relatively high, particularly compared to that of water and aluminum. Thus, power deposition was significant in the thermocouples and a net heat transfer from them to the water and aluminum occurred. The film temperature drop from the surface of the water thermocouples to the bulk water was substantial for the higher beam powers. The data recorded were therefore higher than the actual local bulk water temperatures that prevailed and should be used only qualitatively.

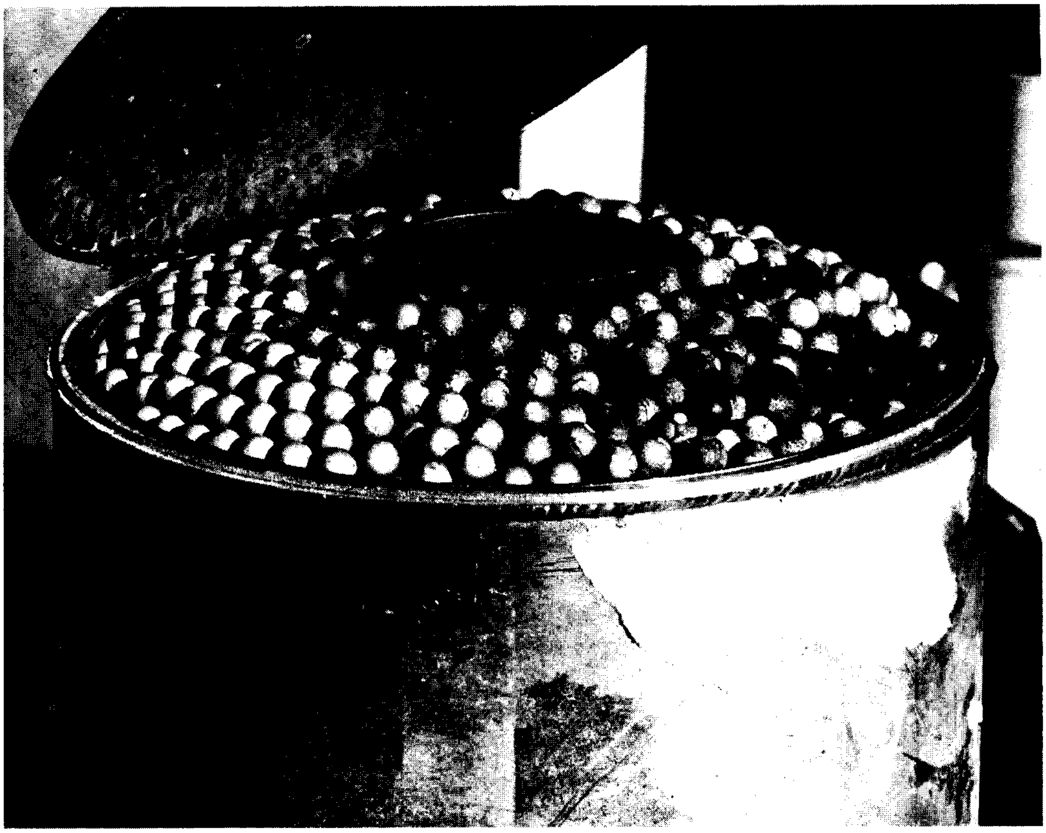
Prior to the power experiment a separate, rather simple flow visualization test was conducted to gain insight into the mixing and flow patterns in the bed of spheres.

II. THE EXPERIMENT

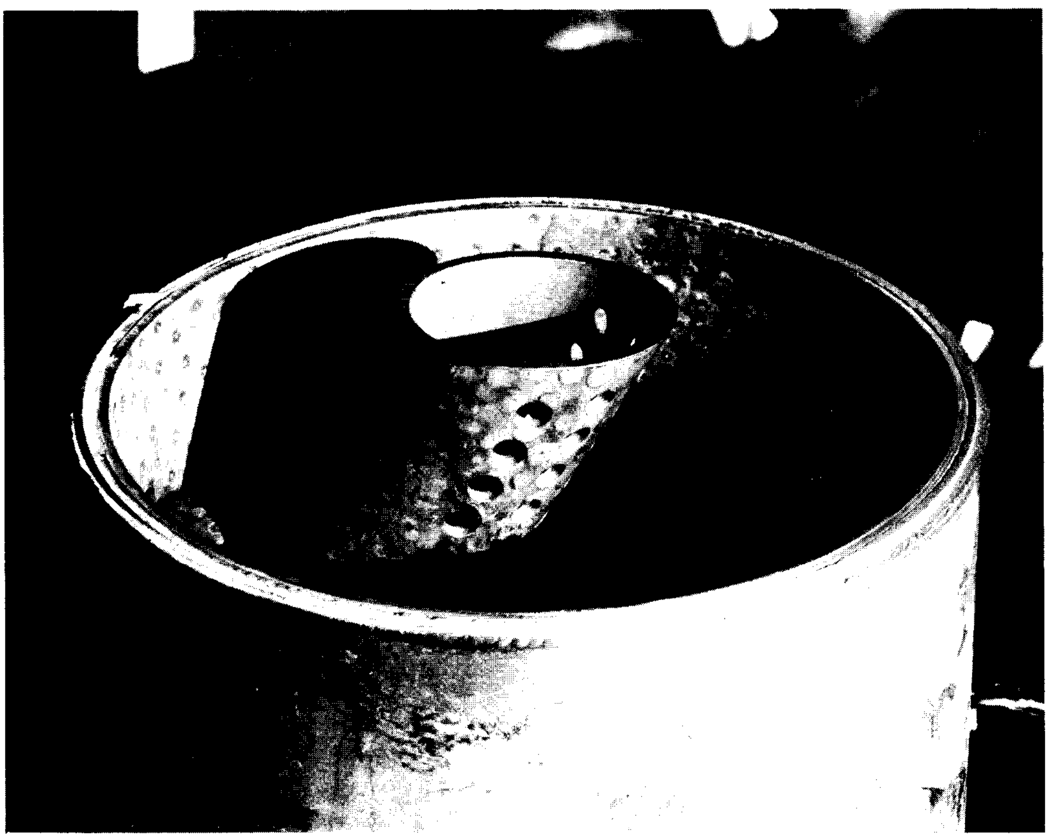
1. Experimental Set-up

A published schematic cross section through a sphere beam dump is available.[1] In accordance with radial shower attenuation in a medium of aluminum and water, 20.3 cm (≡ 8 inches) was selected as the inside diameter of the aluminum tube which housed the bed of spheres. This value is somewhat less than the previously proposed 25 cm since radial beam excursion could be closely controlled in this experiment.

The entrance window was domed and 0.5 cm (≡ 3/16 inches) thick. It was sprayed with ZnS to allow beam profile and position monitoring. A scribe mark indicated the geometrical center of the vessel. Figures 1a and 1b show the front end of the dump after the window was cut off for post experimental inspection. The water inlet manifold can be seen in the center.



(a)



(b)

FIG. 1 - (a) Front View of Test Beam Dump

(b) Front View of Test Beam Dump with Water Inlet Manifold

The length of the bed of spheres was 150 cm ($\equiv$60 inches) which is equivalent to approximately 12.5 radiation lengths (rl). It is estimated that about 10% of the power incident on the dump remains after 12.5 rl of this medium (aluminum spheres and water) at an incident energy of $E_0 = 18$ GeV. Type 1100 aluminum alloy was used to fabricate the spheres and their diameter was 1 cm ($\approx$3/8 inch). At a depth of approximately 12.5 rl the shower is attenuated to a level at which higher Z materials can be employed and water-cooling close to the core of the shower is not an absolute necessity. In the case of the previously proposed beam dump the bed of spheres is followed by a peripherally-cooled solid aluminum cylinder extending to about 18 rl. Also this dump is terminated with a copper cylinder to reduce the leakage of power to a level which is safe for equipment downbeam of it. In this experiment the bed of spheres was backed-up by a large iron shielding block; this in turn, was followed by concrete shielding. The surface temperature of the iron ingot was monitered with a thermocouple at the nominal center line of the shower. The costs of the experimental dump were significantly reduced with this set-up. No valuable information was sacrificed since the main region of interest was the shower maximum.

Chromel-alumel thermocouples (24 gage) were present along the center line of the dump at nominal depths of 1,2,3,4,5,6,8, and 11 rl. Copper-constantan thermocouples (24 gage) were placed at the periphery at depths of 5,8, and 10 rl to obtain an indication of lateral flow of the coolant and of mixing.

Unfortunately, the tips of the thermocouples used to measure the local water temperature in the vicinity of each instrumented sphere were about 1.5 cm away from them due to a misunderstanding during installation. The possible effects of this discrepancy are discussed below.

The water flow rate was w = 66 gpm and remained constant throughout the experiment. The water inlet pressure was about 140 psig, and the pressure drop through the bed was $\Delta p \approx 15$ psig. The maximum velocity over a sphere for w = 66 gpm is readily computed from the flow cross-sectional area. For the case of perfectly packed spheres in form of a hexagonal close-packed structure, the flow cross-sectional area for a unit triangle (whose three corners coincide with the geometrical centers of three spheres) becomes

$$A_0 = A_t - A_{sph} = \frac{2r \times r\sqrt{3}}{2} - \frac{r^2\pi}{2}$$

$$= \frac{r^2}{2}(2\sqrt{3} - \pi)$$

for $r = 0.5$ cm

$$\therefore A_0 = 0.04 \text{ cm}^2$$

which is 9.25%. Note, this is in disagreement with the value of 21.5% as computed previously.* In the earlier publication a different packing factor was assumed (simple cubic lattice) which is not the most dense packing factor possible.

The total open area in a 20.3 cm diameter tube (assuming a hexagonal close-packed structure and a perfect fit at the interface with the tube) is $A_{0,tot} = 30 \text{ cm}^2$ ($\equiv 0.0325 \text{ ft}^2$). Then the maximum velocity over any sphere for a flow rate of $w = 66$ gpm ($\equiv 0.146 \text{ ft}^3/\text{sec}$) becomes

$$V = \frac{w}{A_{0,tot}} = \frac{0.146}{0.0325} = 4.5 \text{ ft/sec.}$$

2. Flow Visualization Test

The apparatus consisted of a section of lucite tubing filled with spheres and placed into a closed-loop water system. A red dye and air bubbles were injected into the center at the upstream end of the bed of spheres. The injection nozzle was a tube comparable in size to the expected electron beam diameter. Various depths of the bed of spheres were examined.

The experiment with the air bubbles showed that gas bubbles are swept through easily at the design mass velocity. No vapor-locking is expected for nucleate boiling heat transfer. The full angle of the cone which enveloped dyed water was a little less than the 60° expected for a hexagonal close-packed structure. It seemed to vary but little with velocity and depth of the bed. The angle of spread was the same for the case where the dye was introduced at the periphery of the bed.

It is interesting to mention that at water velocities well below the experimental level whole groups of neighboring spheres started to rotate and move within localized pockets of the bed of spheres, although originally the bed was rather carefully packed. This is due to imperfect packing, flow turbulence and drag on the spheres. After some period of time voids appeared close to the interface between spheres and the vessel walls, indicating rearrangement of some spheres and closer packing.

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*Page 8 of Ref. 1.

3. Experimental Data

The experimental data are summarized in Table 1. For a nominal incident beam energy of $E_0 = 18$ GeV the shower maximum of the electromagnetic cascade is expected to occur at the following depth:[2]

(a) in aluminum with a material critical energy[3] of $\epsilon_0 = 40$ MeV

$$T_{max}^{(e^-)} = 1.01 \; [\ell n \, (E_0/\epsilon_0) - 1]$$

$$= 1.01 \; [\ell n \, (18 \times 10^3/40) - 1] = 5.16 \text{ rl}$$

(b) in water with $\epsilon_0 = 72.8$ MeV

$$T_{max}^{(e^-)} = 1.01 \; [\ell n \, (18 \times 10^3/72.8) - 1] = 4.55 \text{ rl}$$

These predictions are probably accurate to 10%. As previously indicated, the maximum density of packing spheres is achieved with the hexagonal close-packed structure (HCP). The density of packing or packing factor for this case can be shown to be $(\pi\sqrt{2})/6 \approx 0.74$; i.e., approximately 74% of the total volume is occupied by spheres. The actual packing factor calculated from the measured volume of the dump and the measured weight of all the spheres was only 0.583. This discrepancy is due in particular to imperfect packing at the interface between spheres and the interior surfaces of the beam dump vessel, and to a lesser degree, to imperfect packing throughout the volume. It is estimated that the packing factor in the center of the dump was about 0.65.

One radiation length in a mixture of 65% aluminum and 35% water is then readily calculated to be equivalent to approximately 12.2 cm ($\equiv$4.8 inches). For a packing factor of $\epsilon = 0.65$, and the values for the depth of the shower maximum in aluminum and water as calculated above, the shower maximum is expected to occur at $T_{max} \approx 5.1$ rl. This is also the area of peak power deposition and thus the area where highest temperatures prevail.

Of particular interest are the heat transfer rates off the sphere surfaces in the region of the shower maximum. Based on $P_{av} = 400$ kW at $E_0 = 20$ GeV, and assuming a standard deviation of $\sigma_b \approx 0.3$ cm for the incident beam, it was shown that about 1.1 kW are deposited in a sphere located on the beam center line and at the shower maximum. This resulted in a heat flux off the surface of $q'' = 0.35 \text{ kW/cm}^2$. The effective heat flux was expected to be somewhat higher because adjacent spheres are in contact with each other, thus reducing the effective surface area. The highest power in this experiment was $P_{av} = 496$ kW, which would give a heat flux of $q'' = 0.44 \text{ kW/cm}^2$.

TABLE I

EXPERIMENTAL DATA

Time	Beam Energy E_0	Peak Current I_p	Repe-tition Rate	Pulse Length τ	Average Beam Power P_{av}	THERMOCOUPLE READINGS IN $^{\circ}C$																		
						1s*	2w**	3s	4w	5s	6w	7s	8w	9s	10w	11s	12w	13s	14w	15s	16w	21w	22w	23w
A. M.	GeV	mA	pps	μsec	kW	1rl†	1rl	2rl	2rl	3rl	3rl	4rl	4rl	5rl	5rl	6rl	6rl	7.8rl	7.8rl	10.7rl	10.7rl	5.2rl	7.7 rl	10.2 rl
1:15	---	---	---	---	---	25.3	25.0	24.8	24.8	24.5	24.5	24.5	24.5	24.8	26.3	26.3	26.3	26.3	26.3	26.0	26.3	25.2	25.0	24.8
1:50	18	42	10	1.7	12.9	25.0	25.0	24.8	24.8	25.0	24.8	26.5	25.3	25.8	27.0	28.7	27.3	27.5	28.8	27.0	26.8	24.8	24.8	24.8
1:55	18	43	30	1.7	39.5	25.0	24.8	24.8	24.8	25.3	24.8	30.0	26.5	27.8	28.5	33.5	29.5	30.3	33.8	29.3	28.0	24.8	25.3	26.2
2:06	18	44	60	1.7	80.5	25.3	25.0	25.0	25.0	25.5	25.3	32.0	26.8	28.8	28.5	34.0	29.5	30.3	34.0	29.3	28.0	25.0	25.3	26.2
2:12	18	44	90	1.7	121.0	Lost Vacuum on Protection Collimator PC-90. No Data Taken.																		
7:24	---	---	---	---	---	26.0	26.0	25.5	25.3	25.0	25.0	25.0	25.0	25.0	26.3	26.3	26.3	26.3	26.3	26.3	26.3	24.0	24.0	23.2
7:26	18	39	90	1.7	107.5	26.0	26.0	26.8	25.3	26.3	28.5	67.3	42.8	40.7	35.7	52.2	51.2	43.4	61.7	35.7	31.2	24.0	25.7	28.0
7:32	18	41	120	1.7	150.5	26.0	26.0	27.5	25.3	27.0	31.2	81.4	55.1	47.6	42.7	65.6	66.8	51.5	74.5	38.5	33.0	25.2	26.7	30.0
7:35	18	41	180	1.7	225.0	26.8	26.8	28.8	26.0	27.5	32.8	106.1	59.3	61.7	69.7	45.9	73.8	60.3	96.5	44.6	35.9	25.7	28.1	33.5
7:42	18	41	210	1.7	264.0	27.0	26.8	29.5	26.3	28.5	35.7	119.3	67.8	67.3	79.8	49.8	84.3	69.0	108.4	47.3	37.1	25.7	28.6	34.8
7:47	18	40	240	1.7	294.0	26.5	26.5	30.3	26.3	29.3	39.0	133.0	78.3	74.5	88.1	54.4	97.9	78.6	119.7	50.5	38.5	25.7	28.8	35.3
7:51	18	40	270	1.7	330.0	26.8	26.8	31.3	26.0	29.7	41.5	141.0	86.9	82.2	95.7	64.2	107.4	85.7	129.9	53.7	39.5	25.7	29.0	36.9
7:55	18	40	300	1.7	367.0	27.0	26.8	32.0	26.3	30.5	47.1	141.0	98.3	96.0	114.2	79.8	121.7	93.7	141.0	55.4	40.8	26.2	29.8	37.5
7:59	18	40	330	1.7	404.0	27.2	27.0	33.0	26.5	31.7	48.5	143.0	105.7	97.9	125.2	76.9	129.6	100.0	149.0	57.5	42.2	26.2	30.6	38.1
8:02	18	40	360	1.7	440.5	27.2	27.0	33.5	26.5	32.7	49.8	142.0	118.8	114.7	142.0	88.1	148.0	106.1	156.0	60.8	43.2	26.4	30.6	39.0
8:05	18.86	38	360	1.7	438.5	27.7	27.5	34.2	26.8	33.8	54.7	137.0	122.5	101.3	145.0	107.3	149.0	108.1	156.0	62.2	43.7	26.2	30.6	38.6
8:10	18.86	43.2	360	1.7	496.3	27.3	27.0	34.8	26.8	33.8	55.4	157.0	138.0	132.0	159.0	112.2	169.0	101.5	164.0	63.4	46.8	26.4	31.0	41.3
8:13		Beam Off																						
9:07	---	---	---	---	---	26.3	26.5	26.3	26.0	25.8	25.5	25.5	25.5	25.5	26.8	26.8	26.8	26.8	25.5	26.8	27.0	23.8	24.0	23.3

* s denotes a thermocouple attached to a sphere

** w denotes a thermocouple recording the water temperature

† rl denotes radiation length

An alignment and steering problem made it necessary to impinge the beam about 0.5 cm above the geometric center of the dump vessel, or about one third the way between the instrumented spheres and the water thermocouples. This lowers the heat flux for $P_{av} = 496$ kW to $q'' \approx 0.35$ kW/cm^2. The curves representing temperature versus incident beam power in the area of the shower maximum have an additional scale added to give the temperature versus heat flux relationship, based on $q'' \approx 0.35$ kW/cm^2 for $P_{av} \approx 500$ kW.

4. Discussion of the Experimental Data

Figure 2 shows the longitudinal temperature distribution of the spheres in the dump for several incident beam powers. Although there is more scatter in the data than was hoped for, it was possible to draw reasonable curves for the temperature distribution. As expected, the shape of the curves is similar to shower curves. The major deviation occurs in the attenuation region of the shower, where shower curves exponentially approach zero, and the test curves flatten out and asymptotically approach the bulk water temperature after complete mixing has taken place. Figure 2 was plotted on semi-log scale in order to demonstrate this behavior.

The data recorded by thermocouple 5s at a depth of 3 rl were unreasonably low and are omitted in the graph. Examination of the dump vessel and its contents revealed that the sphere to which this thermocouple was attached was approximately 2.5 cm from the true beam center line. At this depth no significant radial shower development had taken place yet and the sphere was hardly exposed to the shower at all.

As can be seen, the highest temperature recorded for each power level occurred at a depth of about 4 rl. This is in discrepancy to the 5.1 rl as predicted above. Two explanations are offered: first, it may well be that the thermocouples located at 5 and 6 rl gave values that are even lower than the true values one would guess from the graphical representation. A significant radial offset from the true beam center line could have existed despite the fact that such an offset was not apparent during disassembly of the dump. The significance of such an offset diminishes with increasing depth due to radial shower spread. Secondly, it may be that the assumed packing factor of $\epsilon = 0.65$ is too low and that it actually approached the HCP configuration value of $\epsilon = 0.74$. Such a change would not materially affect the predicted location of the shower maximum

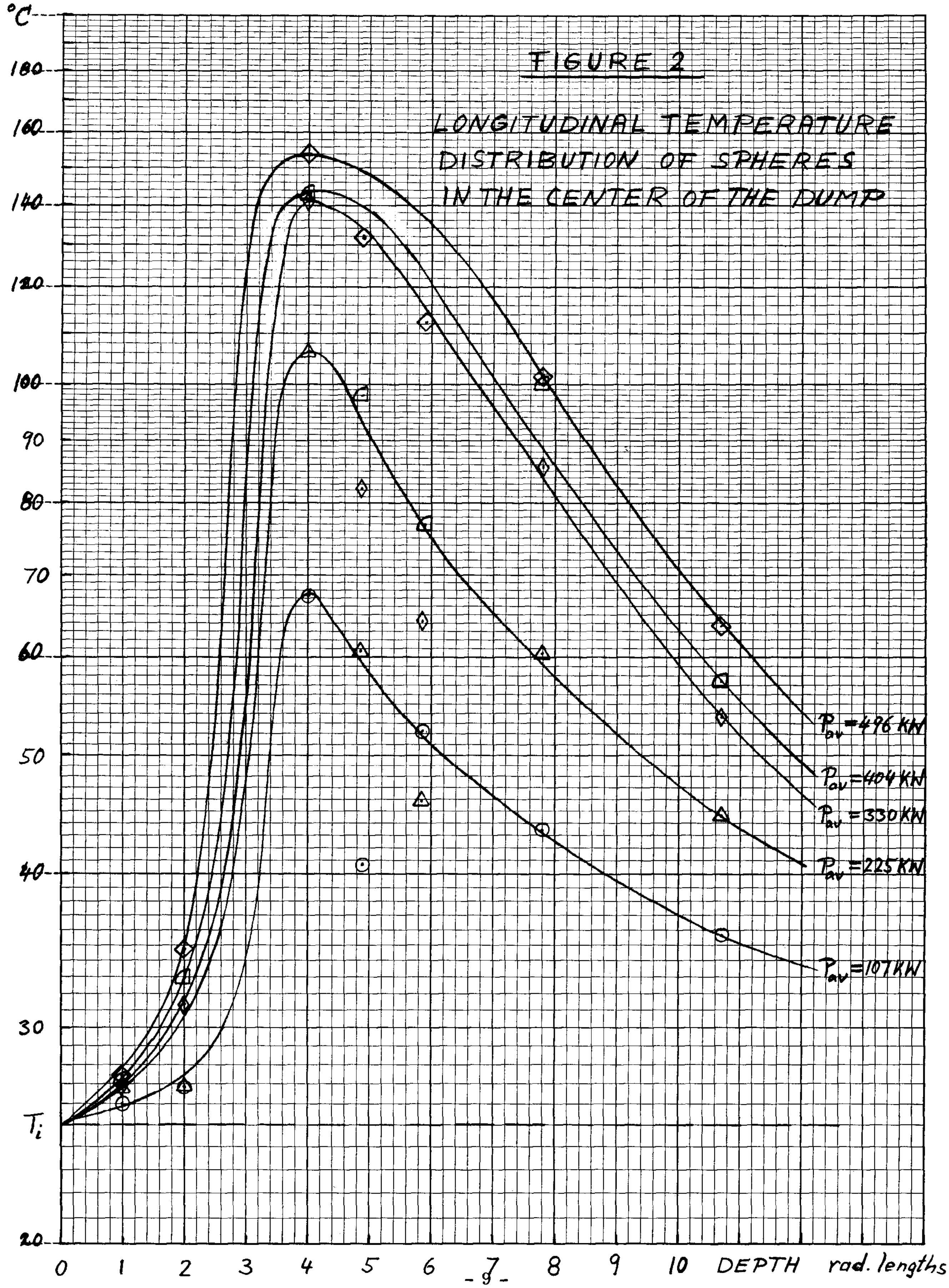


FIGURE 2
LONGITUDINAL TEMPERATURE DISTRIBUTION OF SPHERES IN THE CENTER OF THE DUMP
°C
180
160
140
120
100
90
80
70
60
50
40
30
Tᵢ
20
0
1
2
3
4
5
6
7
8
9
10
DEPTH rad. lengths
Pav=496 KW
Pav=404 KW
Pav=330 KW
Pav=225 KW
Pav=107 KW

at 5.1 rl. However, it would increase the depth in radiation lengths of the thermocouples. For example, the present value of 4.04 rl for thermocouple No. 7s would increase to about 4.35 rl. This is still short of the 5.1 rl as predicted and the discrepancy is probably due to a combination of both factors discussed above.

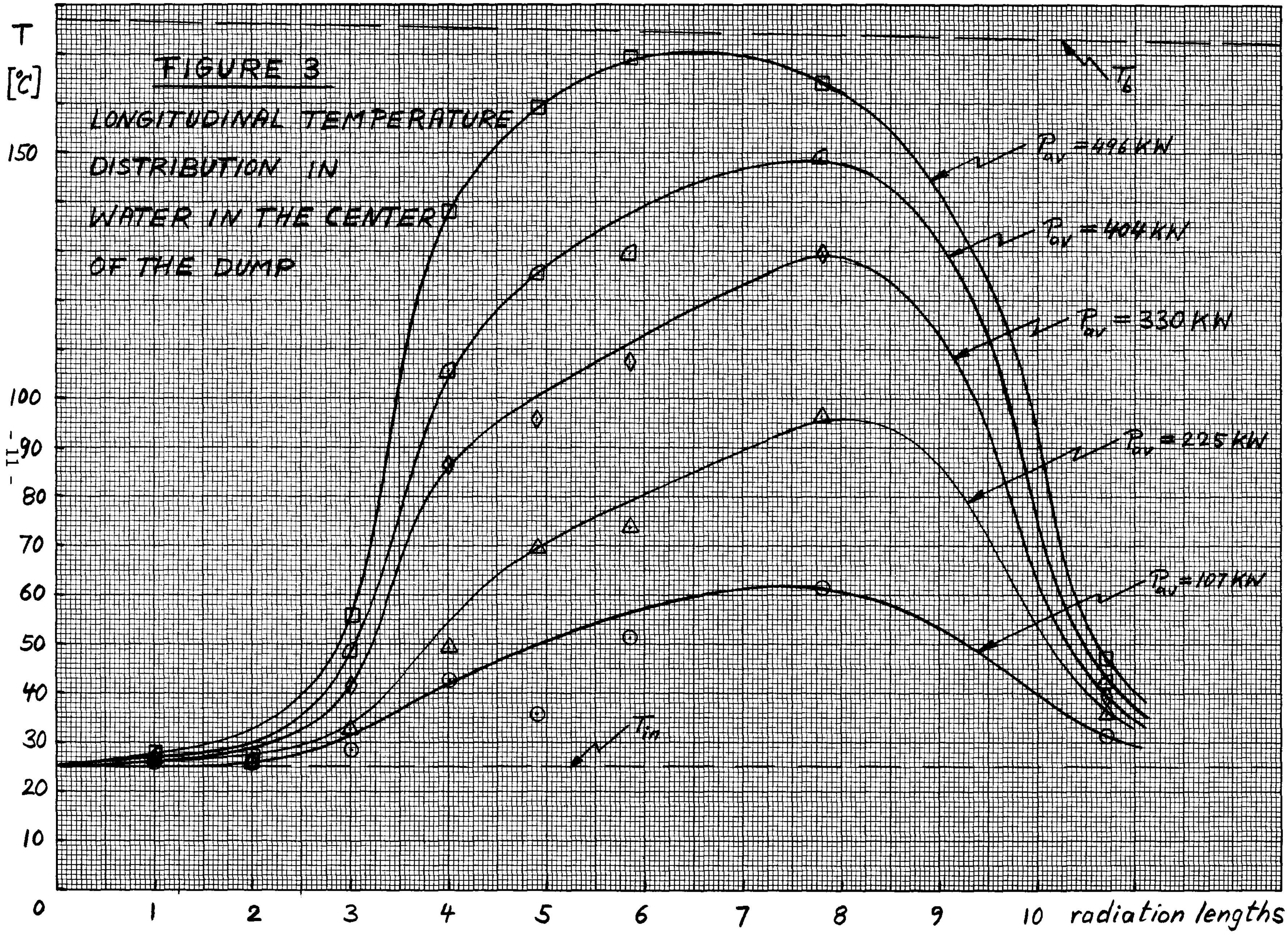
The broken line marked by T_b gives the boiling temperature of water at the local pressure for comparison. It is a function of the pressure drop through the system and thus a function of depth.

The longitudinal temperature distribution in water parallel to the beam center line at a distance of about 1 cm is presented in Fig. 3. In contrast to Fig. 2 where the temperature distributions somewhat resemble shower curves, the ones in water show much broader peaks. For powers up to about 400 kW the peak temperatures were recorded at a depth of about 8 rl — as compared to only 4 rl in the spheres. The broadness of the peaks and their depth is easily explained by the fact that a significant amount of power is deposited in the region of exponential attenuation of the shower. This shows up as a continual temperature rise to a depth where lateral flow and mixing of the water remove more heat from the shower than is deposited by it.

The curve for P_{av} = 496 kW shows an even broader peak and the water temperature approaches the local boiling point. Heat transfer by nucleate boiling occurred over a wide range of depths. It should be pointed out that most of the temperature points in the region between 4 and 8 rl and for P_{av} > 300 kW are the peaks of temperature fluctuations. The amplitude of these fluctuations increased with increasing power and was typically 10 to 15^{o}C at P_{av} = 496 kW. Time pressure unfortunately did not permit recording of more data to further analyse these fluctuations.

Nucleate boiling is thought to be responsible for these fluctuations. A positive fluctuation can be caused by a water vapor bubble or group of bubbles passing by the thermocouple. Subsequent exposure to bulk water will cause a temperature decrease. These fluctuations can also be due to boiling heat transfer off the thermocouple as examined below.

It is interesting to speculate why none of the temperatures recorded actually reached the local boiling point of water, although nucleate boiling was evident and average heat transfer rates off the surface of the spheres were well above the level at which onset of nucleate boiling is thought to occur in this medium.


T
[°C]
FIGURE 3
LONGITUDINAL TEMPERATURE
DISTRIBUTION IN
WATER IN THE CENTER
OF THE DUMP
T_b
P_{av} = 496 KW
P_{av} = 404 KW
P_{av} = 330 KW
P_{av} = 225 KW
P_{av} = 107 KW
T_{in}
150
100
90
80
70
60
50
40
30
20
10
0
1
2
3
4
5
6
7
8
9
10
radiation lengths

A likely explanation can be found in the fact that the bubbles are small compared to the size of the spheres and comparable to the size of the thermocouple tips. The bubbles pass by the thermocouple at about the water velocity and exposure time is small. The heat capacity of the thermocouple is then too large to allow a temperature rise to the boiling point before it is again exposed to the bulk water. A smaller thermocouple wire gage would have reduced this error.

Special attention was given to an early detection of temperature transients leading to a runaway situation and eventual burnout. This can occur when the heat flux increases to a level where water vapor bubbles emerging from individual nucleation sites combine with neighboring bubbles to form a vapor film on the sphere surface. This power absorption medium appears to be particularly vulnerable in that respect due to the closeness of adjacent spheres and the small amount of water present. The water vapor film would begin to form close to the points of contact of neighboring spheres and spread from there over the rest of the surface. It would act as a good insulator and cause a rapid rise in temperature and eventual burnout.

Figures 4 and 5 show both the sphere and the water temperature as functions of average beam power and calculated heat flux off the sphere surface in the region of peak power deposition.

Figure 4 is at a depth of 4 rl and the sphere temperature is as expected higher than that of the water. The former rises almost linearly up to an incident power level of approximately 300 kW beyond which it flattens out. This rather constant temperature indicates stable nucleate boiling conditions. Finally, a significant temperature rise is indicated beyond 450 kW. If the last point at 496 kW is correct a change in the boiling pattern and formation of a film boiling region is suspected, even though no temperature transient was detected.

Except for a flat region between 150 and 225 kW the water temperature distribution is as expected. No explanation is offered for this flat region, but it may have been caused by a small change in the location of the incident beam. Several steering adjustments were made during the early part of the experiment and the radial shower spread is not appreciable at 4 rl.

Figures 5, 6, and 7 show the same temperatures as Fig. 4 at the depths of 5, 6, and 8 rl. The water temperature in Fig. 6 shows the same behavior as just discussed in Fig. 4. Additionally, at 5 and 6 rl the sphere temperatures show a flat behavior or even a dip. A closer examination of the heat flux off the

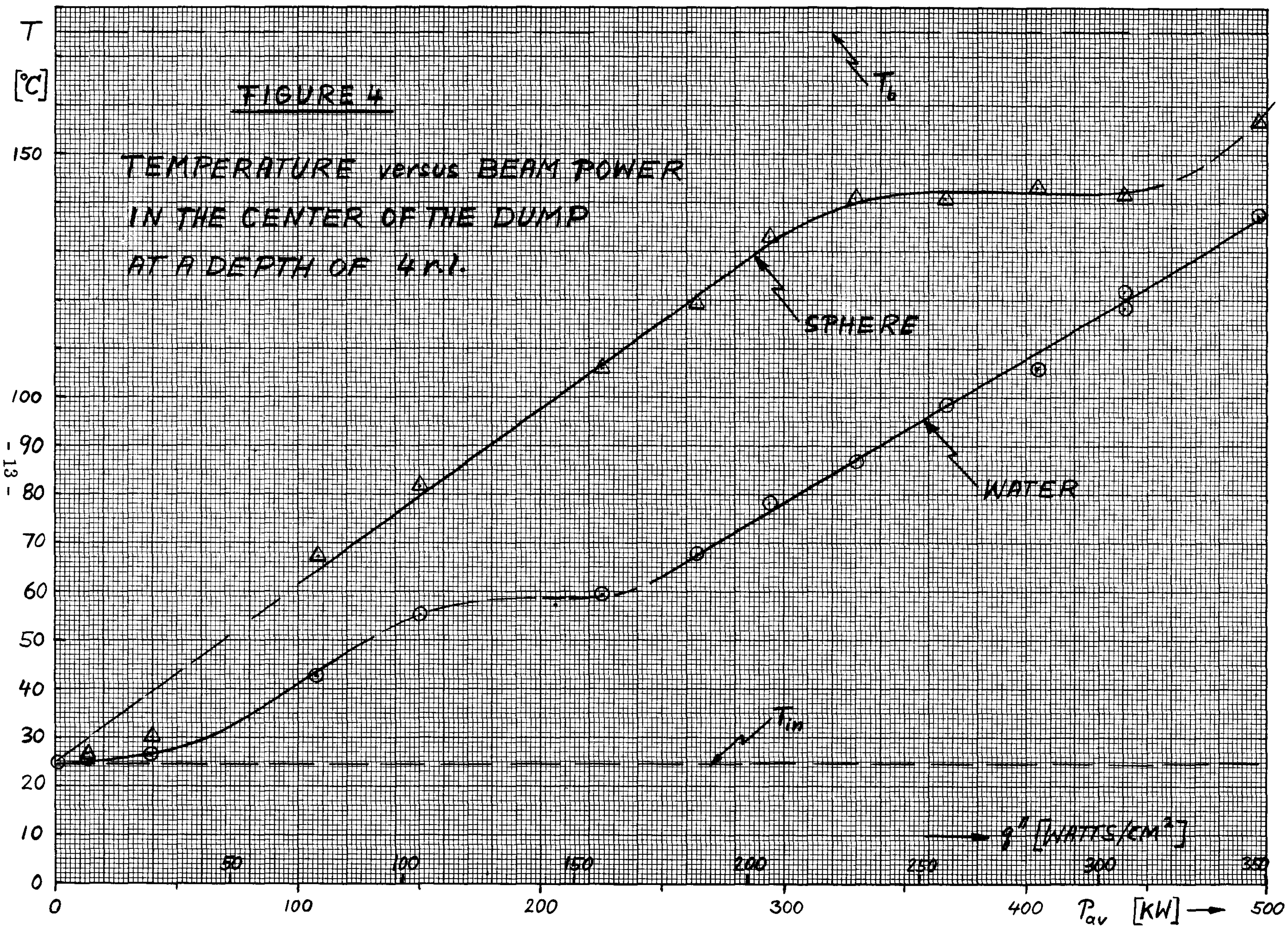


FIGURE 4
TEMPERATURE versus BEAM POWER
IN THE CENTER OF THE DUMP
AT A DEPTH OF 4 r.l.
T
[°C]
150
100
90
80
70
60
50
40
30
20
10
0
T_b
SPHERE
WATER
T_{in}
q" [WATTS/CM²]
50
100
150
200
250
300
350
0
100
200
300
400
500
P_{av} [KW]

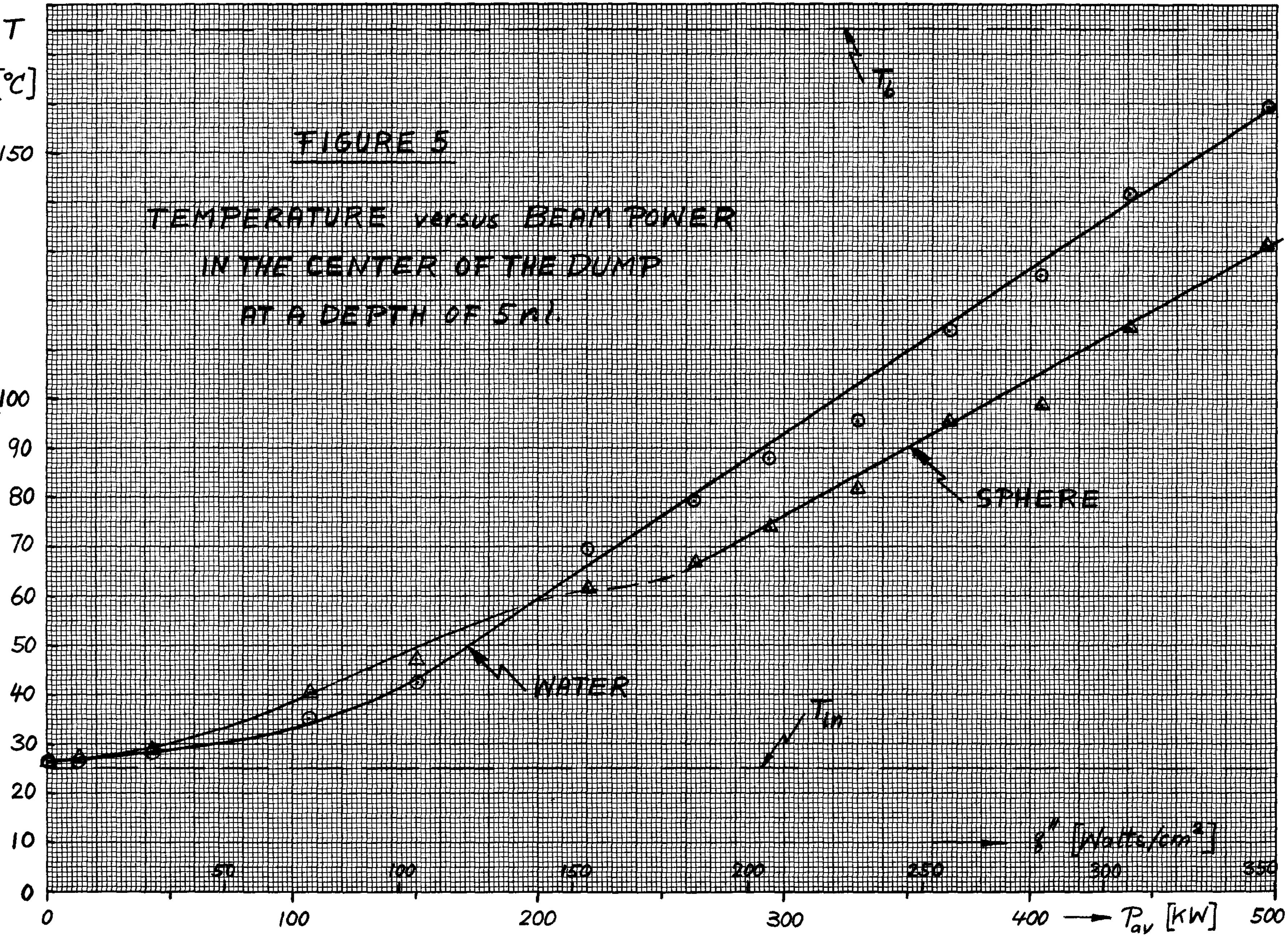


FIGURE 5

TEMPERATURE versus BEAM POWER IN THE CENTER OF THE DUMP AT A DEPTH OF 5 r.l.

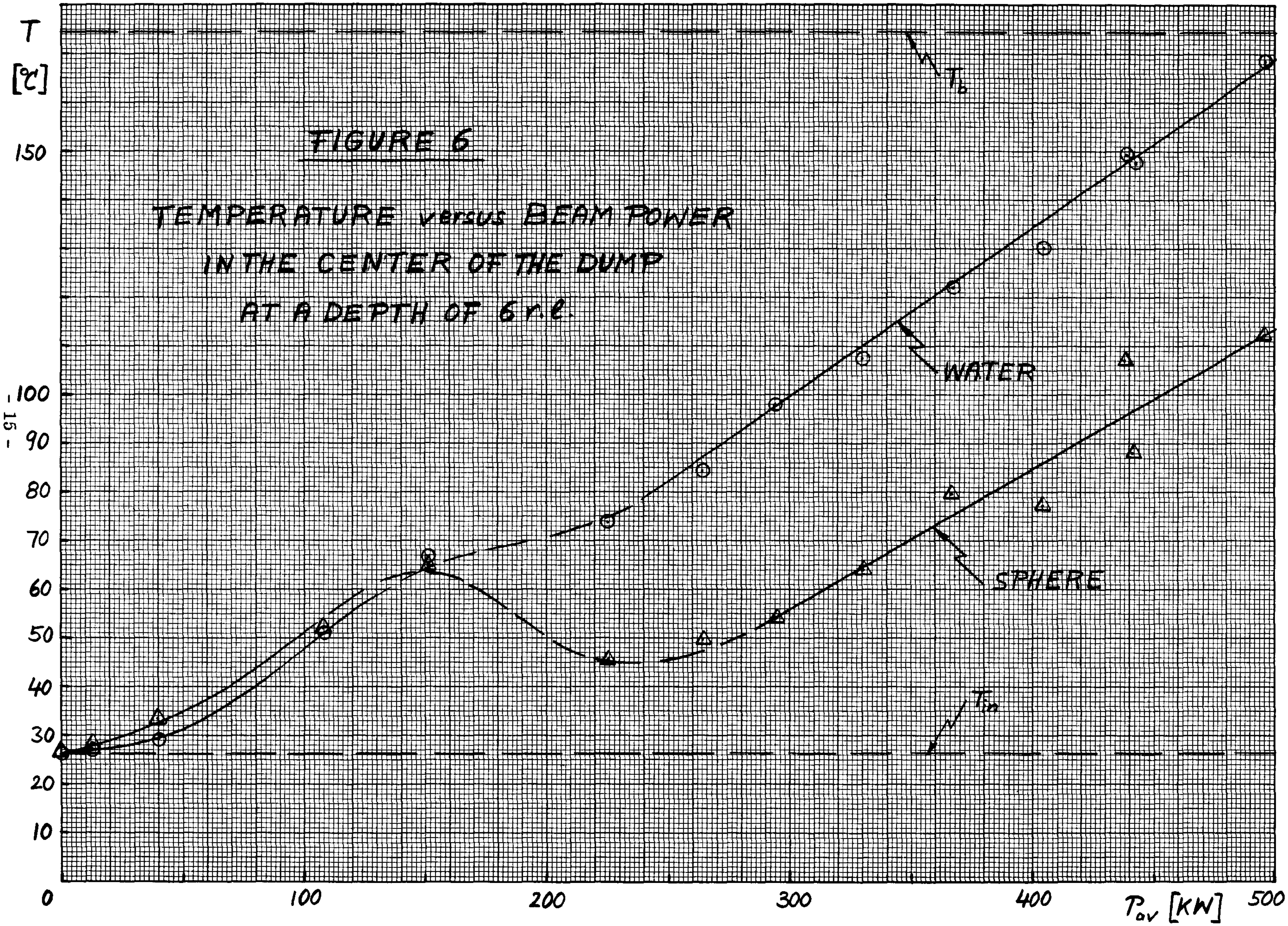


FIGURE 6

TEMPERATURE versus BEAM POWER
IN THE CENTER OF THE DUMP
AT A DEPTH OF 6 r.l.

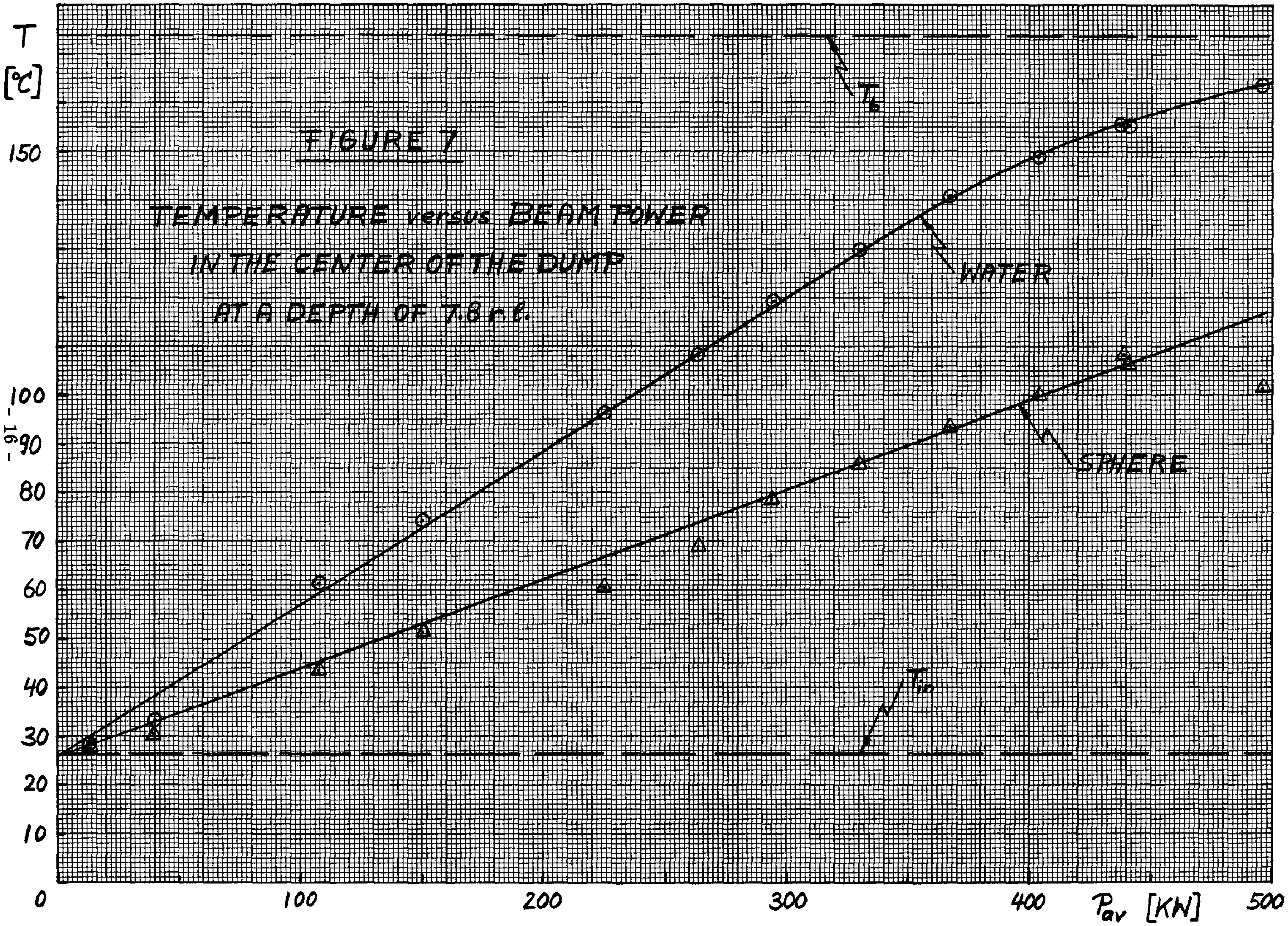


FIGURE 7
TEMPERATURE versus BEAM POWER
IN THE CENTER OF THE DUMP
AT A DEPTH OF 7.8 r.l.
T
[°C]
150
100
90
80
70
60
50
40
30
20
10
0
100
200
300
400
500
P_{av} [KW]
T_b
WATER
SPHERE
T_{in}

sphere surface indicates a possible change in the mode of heat transfer from forced convection to nucleate boiling, the latter being a much more efficient process. On the other hand, the sphere temperatures were significantly below the boiling point at the local pressure and this explanation must be ruled out.

It is surprising to see the temperature of the water exceed that of the neighboring spheres and by a not insignificant amount. This is physically impossible since aluminum has a much higher **Z** than water and heat transfer is from the spheres to the water. The previously discussed radial difference in location of each pair of thermocouples cannot account for such a large discrepancy.

A detailed examination of all the variables resulted in the following rather unfortunate finding: the thermocouples were chromel-alumel and of much higher Z than either water or aluminum. Thus significant amounts of beam power were directly deposited in the thermocouples. The result was a net heat flux to the water which caused an additional temperature rise of the thermocouple over the bulk water due to the film temperatue drop.

In the following an estimate is made of the heat flux off the surface of the thermocouple located at the shower maximum. Both, chromel and alumel are high nickel contents alloys (> 90%) and assumption of the same Z as copper is a valid approximation. For $E_0 = 18$ GeV, $P_{av} = 500$ kW, and an effective incident beam radius of $\sigma_b = 0.3$ cm, power is deposited at the shower maximum in copper[3] and at $r = 0$ at $s \approx 45$ kW/cm^3. The thermocouple wire thickness was 24 gage with a diameter of $d \approx 0.05$ cm ($\equiv 0.0201$ inches). If a circular cylinder of 1 cm length is considered, the volume is $V = 2 \times 10^{-3}$ cm^3 and the cylindrical surface area is $A = 0.15$ cm^2. The power deposited in the cylinder is then $P = s \times V = 45 \times 10^3 \times 2 \times 10^{-3} = 90$ W and the resulting heat transfer rate off the cylinder surface, neglecting axial conduction losses, becomes $q'' = P/A = 90/0.15 = 600$ W/cm^2. At a distance of $r = 0.5$ cm from the beam center line $s = 14$ kW/cm^3 and $q'' \approx 185$ W/cm^2. Both values are in the nucleate boiling range and nothing can be said about the bulk water temperature.

The error is expected to be somewhat smaller in the case of the thermocouples brazed into the aluminum spheres, since the thermal resistance across the brazing interface is negligible and the volume of the sphere is large compared to that of the thermocouple.

Figure 8 finally shows the water and sphere temperatures at 10.7 rl in the center and the water temperature at 10.2 rl at the periphery. The temperature

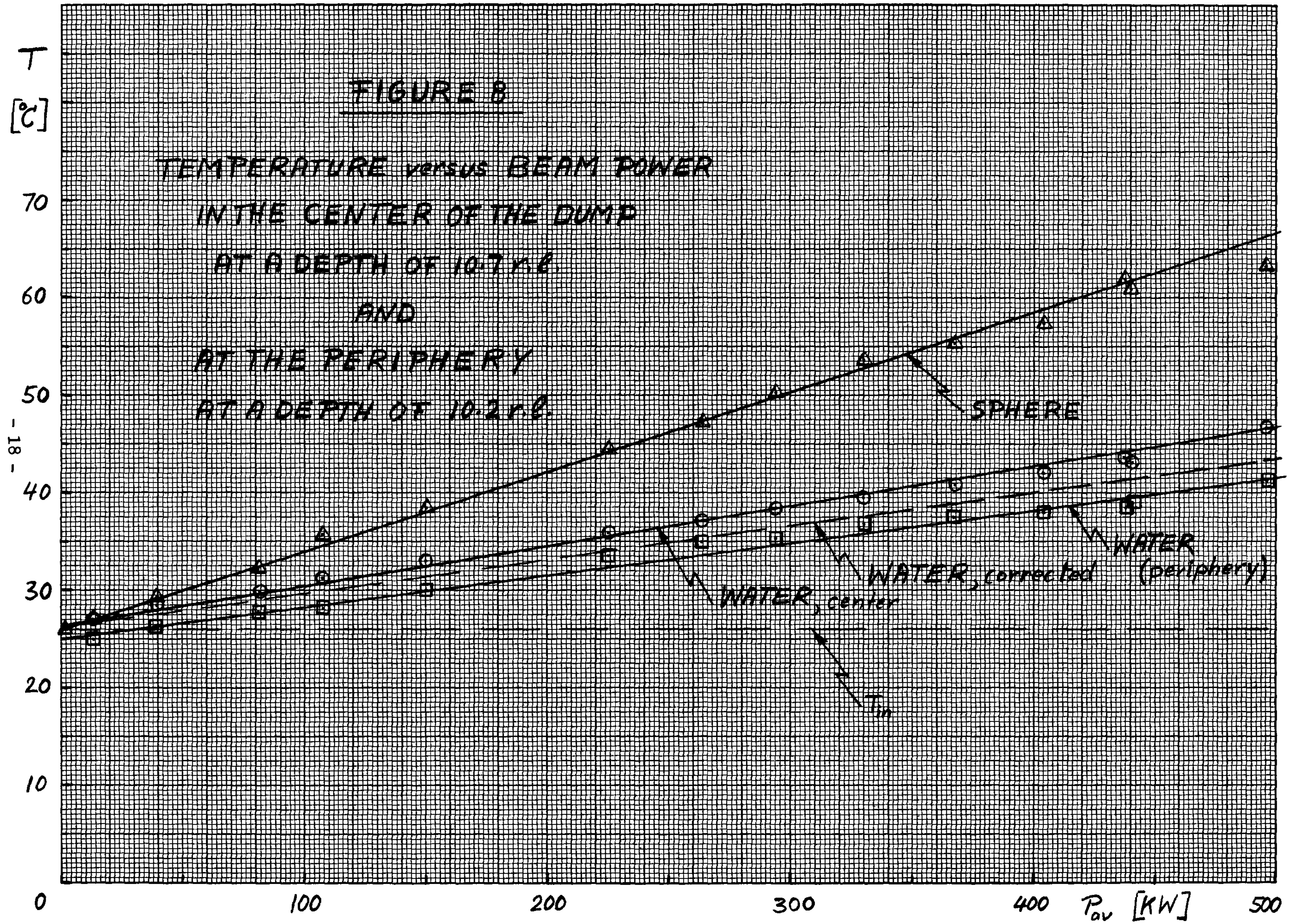


FIGURE 8
TEMPERATURE versus BEAM POWER
IN THE CENTER OF THE DUMP
AT A DEPTH OF 10.7 r.l.
AND
AT THE PERIPHERY
AT A DEPTH OF 10.2 r.l.
T
[°C]
70
60
50
40
30
20
10
0
100
200
300
400
500
P_av [KW]
SPHERE
WATER (periphery)
WATER, corrected
WATER, center
T_in

distributions are probably fairly representative of the actual conditions, since radial shower spread made the thermocouple readings less location-sensitive at that depth and since heat fluxes off both the spheres and the thermocouples are much below the limit for nucleate boiling. At $P_{av} = 500$ kW the temperature at the periphery was within less than $3^{o}C$ or approximately 15% of that in the center (after a parallel offset in initial temperature was corrected for; note, the copper-constantan of the peripheral thermocouples gave slightly lower temperatures). The actual difference was even less because the depth of the two thermocouples was not identical.

5. Post-Experimental Inspection of the Dump Vessel

The dump vessel was cut open after the residual activity was down to 25 mR/hr on contact. Figure 1 shows the front end with the window removed. The portion of the dump shown on the left side of the photograph was at the bottom during the experiment. The close packing caused by the water and described above is evident, as well as imperfect packing on the top (righthand side of photograph) and close to the periphery.

The spheres had taken on a more or less pronounced grey appearance during the experiment. It is thought that the deposit is cupric oxide from the copper water system and possibly some carbon from traces of hydrocarbons (oils) left on the surface of the spheres during fabrication. It is interesting to note that no such deposits were found in the region of highest temperatures around the shower maximum. The boiling heat transfer process probably caused their removal, or there were no deposits at all. None of the spheres showed any visible damage.

CONCLUSION

It was demonstrated that a beam dump using a water-cooled bed of 1 cm diameter aluminum spheres as power absorption medium can safely dissipate average beam powers up to 500 kW at a flow rate of 66 gpm. If the flow rate were increased to the design value of 90 gpm, resulting in a water velocity of 6 ft/sec over the sphere surfaces, such a beam dump would probably be able to safely dissipate the expected full SLAC Stage I power of $P_{av} \approx 600$ kW.

It has been shown that commercially available thermocouples suchas chromel-alumel, copper-constantan and others are not suitable to obtain quantitative data in applications where theyare directly exposed to high-power beams.

A new high power slit for the B-Beam is presently being developed. Its principle power absorption medium is a bed of water-cooled spheres.

Although the flow visualization test demonstrated that essentially the same cone angle for mixing as in the center of the dump vessel can be expected if the beam is introduced close to the periphery, a power test should probably be conducted. It is not clear that the axi-symmetric beam causes temperatures similar to those recorded above when introduced into a non-symmetric geometric such as the beam defining edge of a slit.

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REFERENCES

1. D. R. Walz, "400 kW Sphere Beam Dump," Report No. SLAC-TN-68-7, Stanford Linear Accelerator Center, Stanford University, Stanford, California (April 1968).
2. B. Rossi, High-Energy Particles, (Prentice Hall Inc. New York, 1952); p. 257.
3. R. B. Neal, (ed.), The Stanford Two-Mile Accelerator, (W. A. Benjamin Inc., New York, 1968); p. 709-711.