

# Optimisation of a Storage Facility used to Effect Power Control in the PBMR Power Cycle

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This article presents the optimization of a gas storage facility used to effect power control in South Africa's PBMR power cycle. It was shown in the article, a multi-tank storage facility to affect power control in the PBMR power cycle<sup>1</sup>, that a multi tank design with heat capacitance improves storage effectiveness, which could make the system cheaper. This storage facility is known as the Inventory Control System (ICS). The focus in this article is to determine an optimum number of tanks and heat capacitance that will achieve a specified performance for the lowest possible cost. Please note the values used in this exercise are not the actual values used by PBMR. However this article serves to demonstrate an approach to achieving an optimum solution for the ICS.

## 1. Background to the PBMR Power Cycle

The Pebble Bed Modular Reactor (PBMR) offers a safe, clean and cost effective means of converting nuclear energy for the purposes of electricity production<sup>2</sup>. The current PBMR power plant concept features a single shaft, recuperative Brayton cycle with two-stage intercooled compression. Helium gas is the preferred working medium owing to its chemical and radioactive inertness. The Main Power System (MPS) of the PBMR, which runs on the Brayton cycle, circulates helium through the core of the reactor and through a configuration of turbo-machinery, the latter of which constitutes the Power Conversion Unit (PCU) (See figure 1).

The helium flow-path can be traced along the route numbered 1 to 16, then back to 1 to complete the cycle. Within this cycle, **load following** is performed by withdrawing gas at the HPC outlet (14), if the need is to reduce power output to the grid, and by injecting the gas at the PC inlet (7), if the need is to increase power output to the grid. With the Brayton cycle in operation, the power output to the grid is more or less proportional to the amount of helium gas in circulation, provided all gas bypass valves are closed and the Reactor Outlet Temperature (ROT) is maintained at its design point of 900°C.

## 2. Background to Varying the Number of ICS Tanks

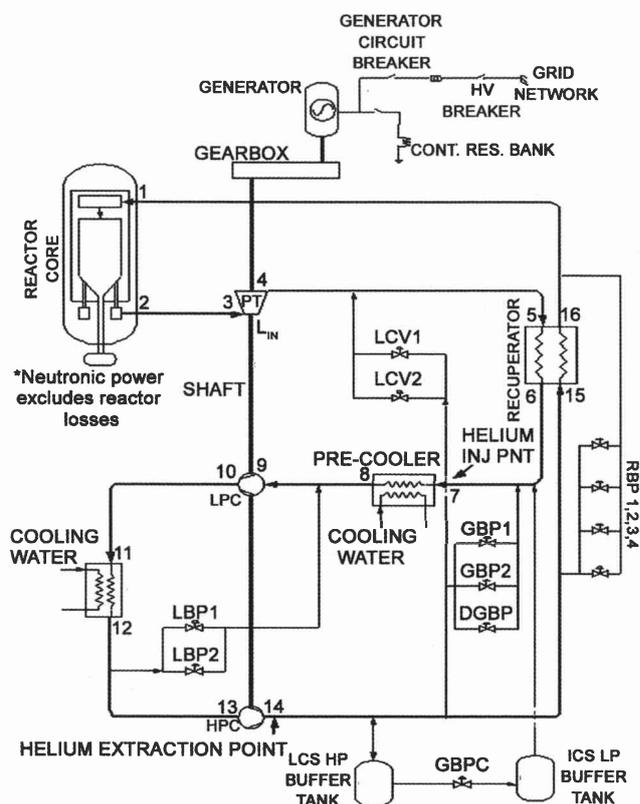
An extensive description of the ICS operation is given in the article describing the multi-tank arrangement of the ICS article<sup>1</sup>.

The article<sup>1</sup> shows graphically with the aid of the equation;

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$L_{in}$  = INLET LEAKAGE,  $L_{out}$  = OUTLET LEAKAGE, GBP = GAS CYCLE BYPASS VALVE, DGBP = DIVERSE GAS CYCLE BYPASS VALVE, GBPC = GAS CYCLE BYPASS CONTROL VALVE, LCV = LOW PRESSURE COOLANT VALVE, RBP = RECUPERATORS BYPASS VALVE, LPB = LOW PRESSURE COMPRESSOR BYPASS VALVE, HPC = HIGH PRESSURE COMPRESSOR

Figure 1: PBMR power cycle

$$V_{t,total} = \sum V_{t,i} = \frac{V_{sD} T_{tD}}{T_{sD}} \sum_{i=1}^{i=n} \left( \frac{P_{sD,i-1,2} - P_{sD,i,2}}{P_{sD,i,2} - P_{tD,i,1}} \right), \quad (1)$$

how increasing the number of tanks reduces the total storage volume.

where

- $V_{t,total}$  = Total storage volume of vessels
- $V_{t,i}$  = Volume of individual vessel
- $V_{sD}$  = Volume of pressure boundary with the Brayton cycle
- $T_{tD}$  = Temperature of vessel
- $T_{sD}$  = Average temperature of pressure boundary
- $P_{sD,i-1,2}$  = Initial pressure of pressure boundary
- $P_{sD,i,2}$  = Final pressure of pressure boundary
- $P_{tD,i,1}$  = Initial pressure of vessel

A slightly different approach is taken in this article with the aid of some values.

To demonstrate the value of a multi-tank arrangement, assume the following

- A PBMR Brayton cycle<sup>9</sup> with the high pressure compressor outlet operating between 8 500 and 3 100 [kPa]
- A total of 5 300 kg of helium circulating in the Main Power System (MPS) of the PBMR

□ A linear relation between the net power output and the helium mass in closed loop circulation

Mass transfer occurs using only the pressure differential between the HPC outlet and the ICS. If only one ICS tank were used to store all the helium required to reduce power from 100 % to 40 % power i.e. removal of 60 % of the total mass which is 3 180 kg, then applying the equation of state and assuming an ambient temperature of 25°C (298K), the volume of the tank would be

$$V_t = \frac{mRT}{P} = \frac{3180 \times 2077 \times 298}{3100 \times 10^3} = 635 \text{ m}^3 \quad (2)$$

If two tanks are used to achieve the exact same performance (i.e. 100 % to 40 % power), then it can be arranged that the one tank stores half the helium 1 590 kg and in so doing reduces the power and HPC outlet pressure by half the prescribed range, that is 70 % power and 5 800 kPa respectively. The other half of the helium is stored in the other tank which completes the performance range by bringing down the pressures from 5 800 kPa to 3 100 kPa. Applying the equation of state to determine the volume of each tank and assuming an ambient temperature of 25°C (298K);

$$V_{t,1} = \frac{m_1RT}{P_1} = \frac{1590 \times 2077 \times 298}{5800 \times 10^3} = 170 \text{ m}^3$$

$$V_{t,2} = \frac{m_2RT}{P_2} = \frac{1590 \times 2077 \times 298}{3100 \times 10^3} = 318 \text{ m}^3 \quad (3)$$

$$V_{total} = V_{t,1} + V_{t,2} = 487 \text{ m}^3$$

Adding these two volumes shows that by applying two tanks instead of one yields a greater storage effectiveness, because the helium storage is apportioned between a higher storage pressure which requires less volume, and the rest of the gas can be stored at a lower pressure tank which is made smaller because it only has to carry half the mass, albeit at a lower pressure and temperature.

This idea is extended to three tanks and so on. Table 1 shows how the storage pressure is apportioned as the number of tanks is increased. The arrangement is such that the range of storage pressures is equally divided amongst the tanks. Table 2 shows

Number of tanks [n]	Total Volume [m <sup>3</sup> ]	V <sub>1</sub>	V <sub>2</sub>	V <sub>3</sub>	V <sub>4</sub>	V <sub>5</sub>	V <sub>6</sub>	V <sub>7</sub>	V <sub>8</sub>	V <sub>9</sub>	V <sub>10</sub>
		[m <sup>3</sup> ]									
1	635	635									
2	487	170	318								
3	444	98	134	212							
4	423	69	85	111	159						
5	411	53	62	75	94	127					
6	404	43	49	57	67	82	106				
7	398	36	40	45	52	61	73	91			
8	394	31	34	38	42	48	55	65	79		
9	391	28	30	33	36	40	45	51	59	71	
10	389	25	27	29	31	34	37	42	47	54	64

Table 1: Storage pressures for 1 to 10 tanks

the corresponding volumes for these pressures.

Table 2 shows that the total volume and individual tank volumes become progressively smaller with increasing number of tanks. Figure 2 illustrates further.

Number of tanks [n]	Total Volume [m <sup>3</sup> ]	V <sub>1</sub>	V <sub>2</sub>	V <sub>3</sub>	V <sub>4</sub>	V <sub>5</sub>	V <sub>6</sub>	V <sub>7</sub>	V <sub>8</sub>	V <sub>9</sub>	V <sub>10</sub>
		[m <sup>3</sup> ]									
1	635	635									
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3	444	98	134	212							
4	423	69	85	111	159						
5	411	53	62	75	94	127					
6	404	43	49	57	67	82	106				
7	398	36	40	45	52	61	73	91			
8	394	31	34	38	42	48	55	65	79		
9	391	28	30	33	36	40	45	51	59	71	
10	389	25	27	29	31	34	37	42	47	54	64

Table 2: Storage Volumes for 1 to 10 tanks

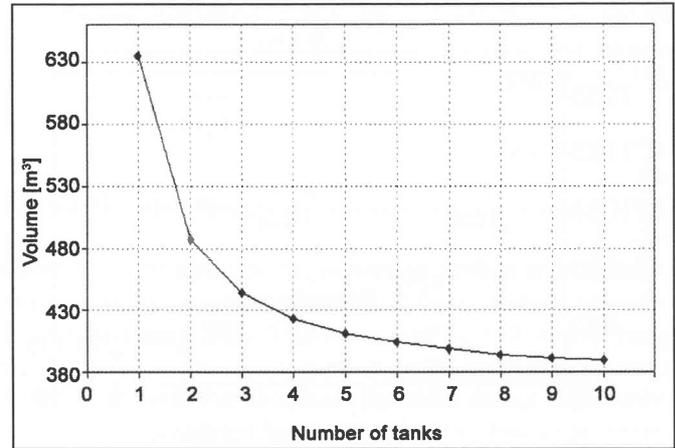


Figure 2: Total volume vs. number of tanks

Table 2 also shows that for a given set of tanks, say 10 tanks, the volume of each tank becomes larger as the storage pressure decreases, albeit each tank stores the same amount of helium. Figure 3 illustrates further.

Although a spherical vessel yields the best volume to surface area ratio, cylindrical tanks are opted for in the design of the

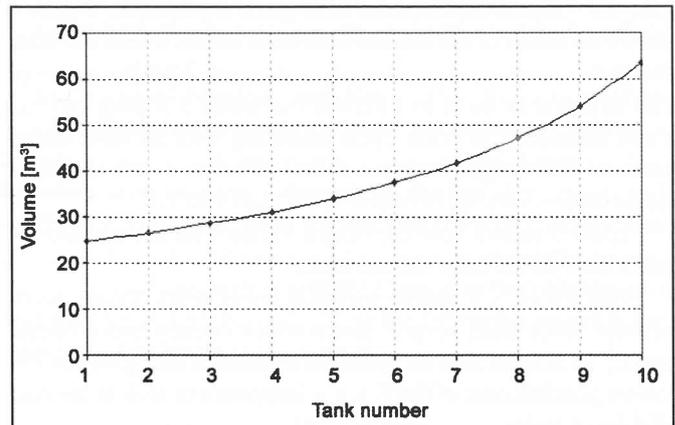


Figure 3: Volumes for a set of ten tanks

ICS, for the following reasons

- it may be easier to build maintenance and access structures around cylindrical tanks, than spherical tanks
- cylindrically shaped vessels may easier and cheaper to manufacture than their spherical counterparts

Furthermore, the cylindrical tanks are made uniform. This can be beneficial when it comes to manufacturing the vessels, as there will be a single tool configuration cost for all tanks. Another benefit is realized when the ICS has to store all the helium during a maintenance outage. At this stage all helium is removed from the MPS, and compressor power is used when pressure differential is used up<sup>1</sup>. If all tanks are uniform, then all tanks eventually store equal amounts of helium at the same pressure. The pressure rating for all tanks will therefore be the same, which again may add a cost benefit during vessel manufacture and testing. This section is an illustrative way of showing storage capacity. The next section is concerned with how the actual example of the ICS.

### 3. Modelling the ICS for the PBMR

Based on the above discussion the following constraints are imposed on modeling and optimizing the ICS for the PBMR.

The heat capacitance or heat sink adds value to the storage effectiveness by acting as a temperature reservoir as described in<sup>1</sup>.

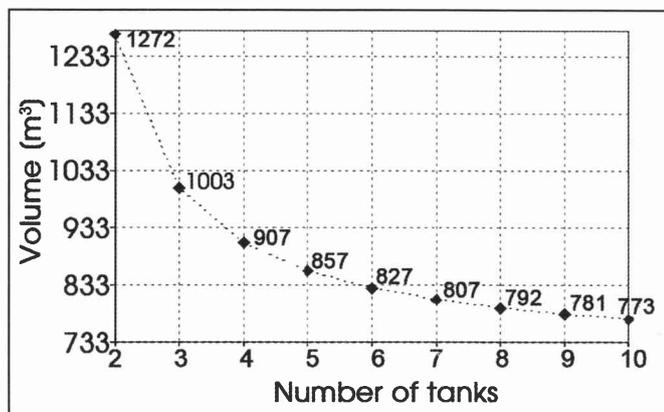


Figure 4: Total ICS volume vs. number of tanks

The above constraints are applied in a detailed thermo-hydraulic model<sup>7</sup> which includes the principles of conservation of mass, energy and momentum. With the tank outer radius fixed and all tank volumes uniform, then the only thing that can change as the number of tanks is increased is the tank height. So as the number of tanks increases, their uniform height is reduced. Like the volume, this decrease in height is asymptotic. Figure 4 shows the result of the thermo-hydraulic model which includes the above-mentioned constraints and targets a performance of 100 % power to 40 % in a PBMR that holds 5 300 kg and has a self sustaining Brayton cycle operating with an HPC outlet pressure that ranges between 8 500 kPa and 3 100 kPa, and temperatures varying between 110°C and 900°C.

Figure 5 shows how the height varies with the number of tanks for cylindrically shaped tanks.

From figure 5, it can be seen that fewer tanks occupy more vertical space than several tanks which occupy more lateral space. To help us find an optimum solution which gives us the lowest possible cost of the ICS it is important to look at the cost of a set of tanks.

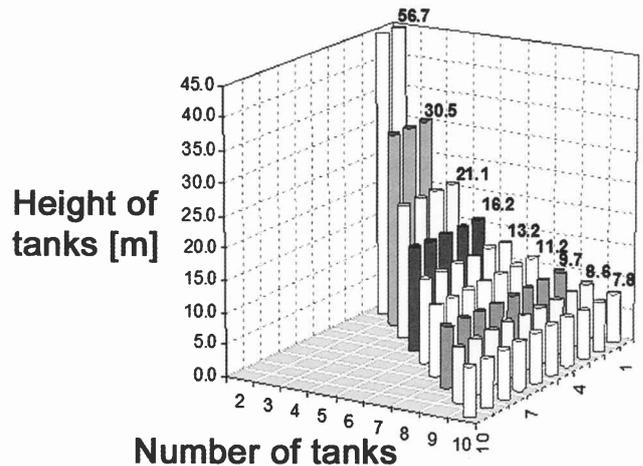


Figure 5: Height of ICS tanks

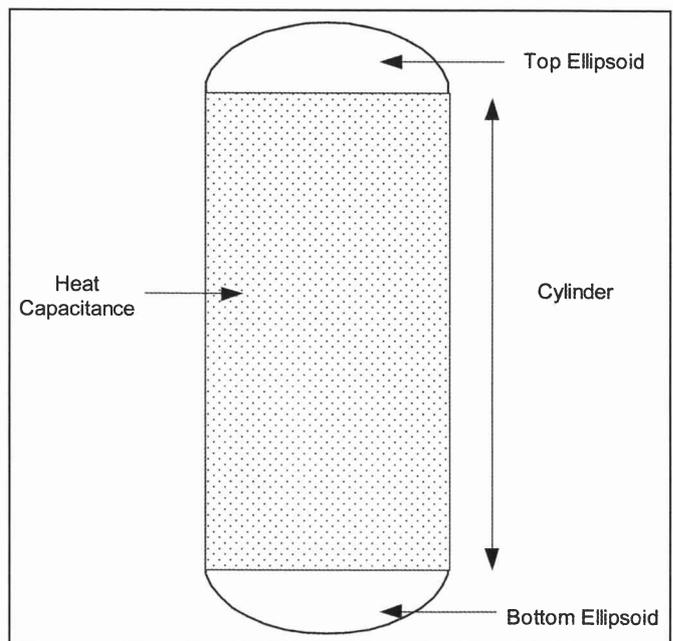


Figure 6: Basic structure of ICS tank

The cost of each tank can be broken down into 4 categories

- The cost of the cylindrical part of the tank
- The cost of the ellipsoidal part of the tank. The ellipsoid covers the top and bottom of the cylinder
- The cost of the heat capacitance
- The cost of a set of valves per tank

The cost of the cylindrical part and ellipsoids is calculated by multiplying the density by the volume of the material which is made of a type of steel, by the cost per kilogram from table 3.

The cost of the heat capacitance and valve is taken as a ratio of the per kilogram value of the steel used to make the tank. Using a cost ratio in the model suggests that the choice of heat capacitance will be built around its relative cost to the steel. Thus should the cost per kilogram of the capacitance be comparable with that of the tank material, then less value is derived from the capacitance.

Figure 7 shows how the total cost of the ICS behaves as the number of tanks is increased. Initially the ICS becomes cheaper, since tanks are becoming smaller and less tank material is being used. Beyond 4 tanks, the ICS becomes increasingly expensive.

Figure 8 shows the cost breakdown of the ICS. Initially the

Description	Value
Cylindrical tank outer radius	2 [m]
Cost of tank material per kg	R50/kg
Ratio of Capacitance cost to tank material	0.9
Ratio of a set of valves per tank to the cost of tank material	0.02
Capacitance packing ratio by volume	0.025
HPC Outlet Pressure 100% power [kPa]	8500
HPC Outlet Pressure at 40% power [kPa]	3100
Power Ramp	10% / min

Table 3: ICS constraints\*

total cost of the ICS is dominated by the cylindrical component. However since the cylindrical component becomes shorter with more tanks, its contribution to the total cost is progressively less.

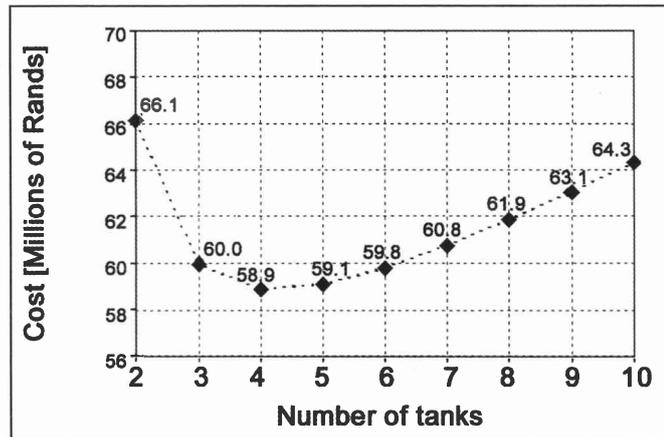


Figure 7: Total cost of ICS

The cost of the capacitance tends to decrease with more tanks. This is because the capacitance packing ratio (this is the ratio of the volume occupied by the capacitance to the volume of the pressure vessels) is fixed at 2.5 % of the internal volume of the ICS tanks, so as the volume decreases, the amount of capacitance decreases leading to a decrease in its cost.

The cost of valves (which includes piping), increases with the number of tanks simply because each tank requires a set of valves.

The ellipsoids also increase in cost because more of them are

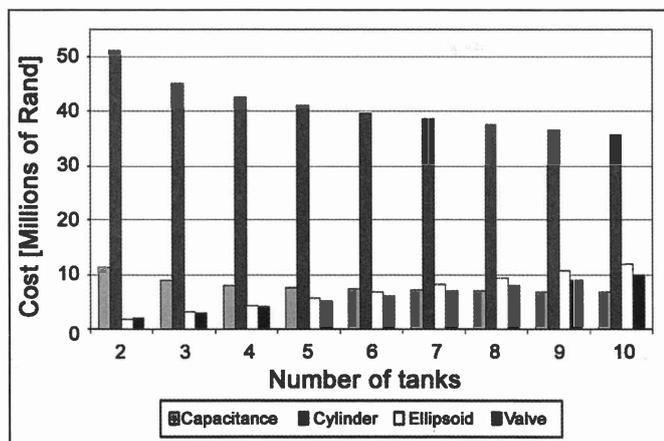


Figure 8: Cost breakdown of ICS

required as the number of tanks increase. Unlike the cylindrical part which decreases in height, the ellipsoid has fixed outer dimensions since the tank outer diameter is fixed.

Figure 9 takes a closer look at the cost breakdown. The right hand axis of the graph is scaled for the cost of the ellipsoids, capacitance and valves. For the range of tanks chosen this scale is much less than that of the cost of the cylinder which is scaled on the left hand axis of the graph.

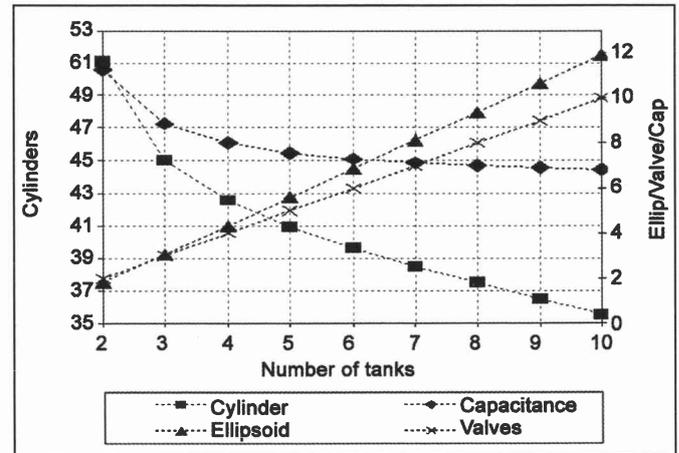


Figure 9: Cost breakdown of ICS

From the above results it can be seen that a 4-tank design gives the best value for performance. However, the height of this system may be brought into question especially if we now add a constraint that the tanks cannot be higher than 14 m due to other facilities which have to be part of the plant. The next best choice will then be a six tank design, which is fractionally more expensive, but fits into the height constraint.

### 3.1 Varying the heat capacitance

Having decided on a six tank ICS design, the amount of heat capacitance is now varied to obtain an optimum value. The same boundary and target values as described earlier are used.

Figure 10 shows how the tank height varies with capacitance. Initially, increasing the capacitance packing ratio makes it possible to use progressively smaller tanks, since the former provides thermal inertia which slows down the pressure build-up when helium is transferred to the tank under pressure differential. This allows more helium to be stored per unit volume. However, beyond 6.5 % of capacitance packing ratio, progressively larger tanks have to be used to meet the performance, since

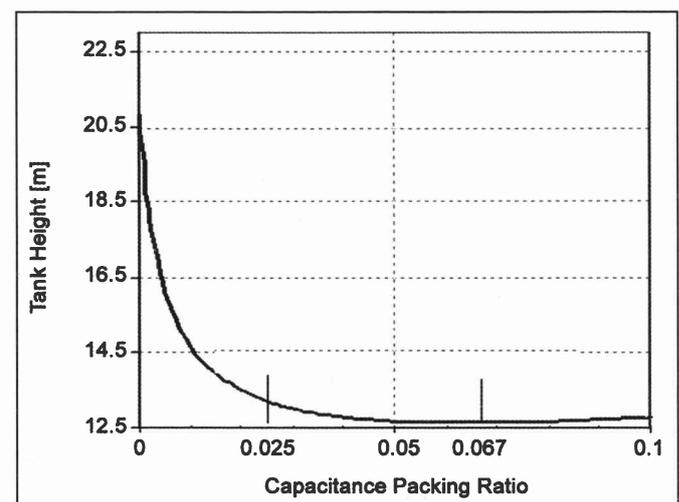


Figure 10: Varying the heat capacitance

\* Please note the values used in this exercise are not the actual values used by PBMR. However this article serves to demonstrate an approach to achieving an optimum solution for the ICS

the increasing capacitance starts to “eat away” the gas storage volume. Hence a value of 6.5 % packing ratio gives the most effective storage volume.

As can be expected the total ICS cost will change with a variation in capacitance as shown in figure 11. The minimum system cost occurs at a packing ratio of 2 %. From the graph it can be seen that increasing the packing ratio to 6.5 % (which gives the minimum storage volume) results in relatively huge increase in cost - approximately 10 million Rand. Such a large increase is not justified. As a result, a packing ratio of 2.5 % is chosen as this gives a cost which is fairly close to the minimum and not too far from the minimum height (or storage volume).

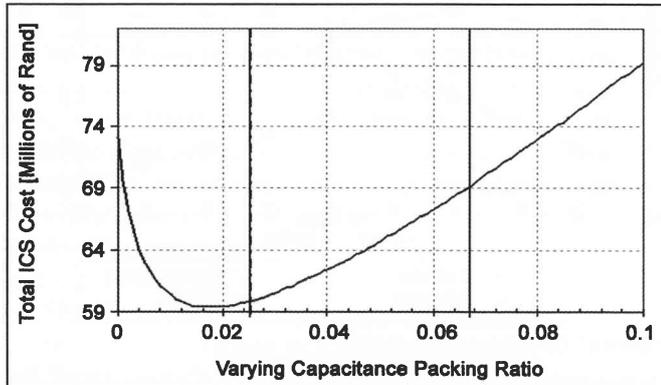


Figure 11: Varying the heat capacitance – cost

To get more value out of the capacitance, a lower cost ratio (cheaper capacitance) can be used, so that the cost of the capacitance has less influence on the total cost. Figure 12 shows the impact of varying the cost ratio.

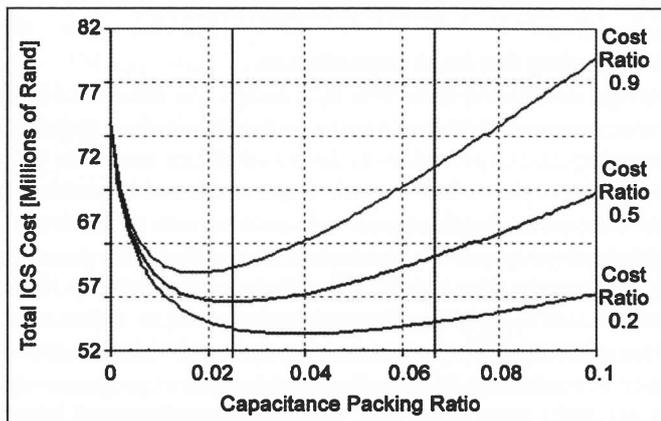


Figure 12: Capacitance cost sensitivity

Compared to a cost ratio of 0.9, a low cost ratio of 0.2 gives a minimum system cost at a packing ratio of 4 %, which is closer to the packing ratio (6.5 %) that would give the minimum volume. Since the influence of the heat capacitance on cost is low for a cost ratio of 0.2 it may be possible to implement a packing ratio of 6.5 % as the total system cost will then be very close to the minimum value.

### 3.2 Design solution and conclusion

In conclusion, a PBMR Brayton power cycle operating with a HPC outlet pressure that varies between 8 500 kPa and 3 100 kPa, and holds 5 300 kg of helium at full power, requires an Inventory Control System characterized by six uniform tanks each measuring 13.2 m high and 4 m in diameter with a total volume of 827 m<sup>3</sup>, to effect power control from 100 % to 40 % power at 10 % power per minute. Although this solution is not

the absolute cheapest, it meets the design criteria for space and is marginally more expensive than the 4-tank system.

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