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PREPARED BY G.A.M.

CHECKED BY G.A.M.

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OTTAWA, CANADA

LABORATORY MEMORANDUM

SECTION Engine Laboratory

NO. NAE-ENG-59

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ENGINE LABORATORY
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SUBJECT

NOTES ON REGENERATIVE HEAT STORAGE FOR REFRIGERATION OF CELL No. 4

PREPARED BY **G. A. MACAULAY**

ISSUED TO INTERNAL

NOTES ON REGENERATIVE HEAT STORAGE FOR REFRIGERATION OF CELL No. 4

1.0 SUMMARY

Two schemes are outlined to meet the Engine Laboratory's refrigeration requirements, using a regenerative type of heat storage. In this way it may be possible to save more than $100,000, with no loss of effectiveness, convenience or safety.

2.0 INTRODUCTION

The Engine Laboratory's refrigeration requirement has been set as 10°F inlet air temperature to a 280 lb./sec. engine for one hour on a +40°F day. Taking into account the effect of atmospheric humidity, Baxter (1) has shown this to require a rate of 927 Standard Tons of Refrigeration for one hour and to require 57,300 gal. of liquid in an all-trichloroethylene system. At the current price of 15.9¢/lb. this would be $135,000 for the fluid alone.

The suggestion was made by Ringer, of using a combined system of trichlor and $CaCl_2$. The economics of this have been shown by Baxter (1) to be governed by the required surface area and cost of the $CaCl_2$ containers. This is now being investigated experimentally by Low Temperature Laboratory.

Ringer had also considered a large mass of scrap iron or iron wire in a tank of "trichlor," but had found that it did not work out economically.

Following along the lines of this suggestion by Ringer, other materials have been considered and the idea of a trichlor.-flooded brick regenerator was evolved (2). Mr. Kuhring then suggested that we should consider crushed and washed limestone.

The present memorandum develops these ideas a little and points out some interesting possibilities.

3.0 RELATIVE COST OF HEAT STORAGE

Other things being equal, the cost of heat storage in any material is:

$$C_h = \frac{\text{Cost per lb.}}{\text{Sp. Ht.}} = \frac{\frac{\$}{\text{lb.}}}{\frac{\text{Btu}}{\text{lb.}\,^\circ\text{F}}} = \frac{\$}{\text{Btu}/^\circ\text{F}}$$

Table I following, gives some examples.

TABLE I
RELATIVE COST OF HEAT STORAGE

Material	Cost per lb. $\frac{\$}{lb.}$	Sp. Ht.* (av. 0 to -65°F) $\frac{Btu}{lb.°F}$	Heat Storage Cost C_h $\frac{\$}{Btu/°F}$	Relative Cost %
Trichloroethylene	0.159	0.22	0.725	100.
Concrete Brick	0.007	0.15	0.0465	6.5
Vitrified Brick	0.010	0.15	0.0665	9.
Pig Iron	0.0312	0.12	0.260	36.
Crushed Limestone	0.00117	0.15	0.0078	1.

* Some of these have been estimated approximately from Sp. Ht. at higher temperatures. Specific heat falls off with temperature and these are lower than values given in handbooks for higher temperatures.

4.0 FULLY FLOODED REGENERATIVE SYSTEMS

4.1 General

If we now consider solid materials in a tank through which trichlor. is pumped as a heat transfer medium, it is apparent that the cost of the brine to fill the voids is an important factor.

Table II compares systems of this type, assuming that the necessary heat transfer rate can be obtained.

TABLE II
COST OF HEAT STORAGE MATERIALS FOR 927 STANDARD COMMERCIAL TONS OF REFRIGERATION FOR ONE HOUR IN A FULLY FLOODED REGENERATOR

System	Solid		Voids	Fluid		Total
	lb.	$	%	Gal.	$	$
All "Trichlor." at 15.9¢/lb.	-	-	100	57,300	133,000	133,000
Concrete Brick - "Trichlor."	1,130,000	9,160	9.2	5,200	11,600	20,760
Vitrified Brick - "Trichlor."	1,130,000	13,100	9.2	5,200	11,600	24,700
Pig Iron - "Trichlor."	1,380,000	43,000	30	6,500	15,100	58,100
Crushed Limestone - "Trichlor."	865,000	1,000	43	17,000	40,000	41,000

Sample Calculation Vitrified Brick - "Trichlor." System.

Let subscripts 1 and 2 stand for Brick and "Trichlor." respectively, and ω, C_p and ρ for weight, specific heat and density.

For 927 Standard Commercial Tons in one hour with a 60°F temperature drop in the brine (1) we have:

$$\frac{Q}{\Delta t} = \frac{927 \times 12{,}000}{60} = W_1 Cp_1 + W_2 Cp_2$$

$$= W_1 \times 0.15 + W_2 \times 0.22$$

If V = the void ratio = 0.092

$$W_2 = W_1 \left(\frac{\rho_2}{\rho_1}\right) V$$

$$= W_1 \left(\frac{1.55}{2.2}\right) 0.092 = 0.065 W_1$$

W_1 = 1,130,000 lb. brick

= 226,000 five-lb. bricks

= $13,100 at $58/M

W_2 = 73,000 lb. trichlor. = 5,200 gal.

= $11,600 at 15.9¢/lb.

Total cost = $24,700

4.2 Vitrified Brick-"Trichlor." System

1) The brick-"trichlor" regenerators show the lowest costs in Table II. They have other advantages perhaps equally important. Fired brick seems preferable to cement brick here, due to its greater resistance to dusting.

By stacking as in Figure (1), the path of the fluid through the bricks can be arranged to give, in effect, counter-flow heat exchange. Here the rows of bricks laid on edge are placed leaving a 1/4-inch liquid passage between rows. The bricks laid on their sides are butted edge to edge to encourage the flow pattern outlined by the arrows to be followed during pull-down and the reverse path during a refrigerated run.

Stacking three layers on edge to one layer on their flats gives a cross-sectional area of flow of 1.35 ft^2 in each of 14 passes through a stack of bricks 24 ft. wide x 20 ft. long x 20 ft. high.

This gives a Reynolds No. = 72,000 at 960 gal./min., and a calculated pressure loss of 0.7 p.s.i. for smooth walls. This figure could be about doubled for the roughness of the brick.

2) Heat Transfer Behaviour

To determine the behaviour of such a regenerator analytically appears to the author to be a rather formidable task. However, a relationship is given (3) for determining the temperature t_c at the centre of a body, originally at uniform temperature t_o, at any time after the surface is suddenly altered to and maintained at a new temperature t_1.

This is plotted in Figure 2 and indicates that, for the temperatures with which we are concerned, t_c would very closely approximate the new wall temperature of a brick in one hour.

This suggests that the heat transfer rate within the solid is of about the order we require.

Both the heat transfer behaviour and the pressure losses appear to lend themselves readily to pilot investigation if desired.

3) Pros and Cons

Some good and bad features of the brick-"trichlor." system are given below.

Advantages	Disadvantages
(a) First cost.	(a) Lack of experience with this type of regenerator.
(b) Segregation.	
(c) Lower hazard of loss. a) Of valuable liquid. b) Lower attendant safety hazard.	
(d) Final disposal.	

Advantages

(a) The initial cost saving is of the order of $108,000.

(b) No really satisfactory method of segregating warm and cold fluid in an all-"trichlor." system has yet been devised. Stacking of bricks as in Figure 1 gives in effect both segregation and counter-flow heat exchange.

(c) Lower hazard of loss refers to the potential loss of $133,000 worth of liquid by an accidental break in the system. Safety hazard refers to the potential hazard of a break in system flooding a building with 57,000 gal. of a toxic liquid.

(d) Eventually the system will have to be disposed of after it has become obsolete. Some investigation would be required to judge between the difficulty of disposing of 57,000 gal. of used trichloroethylene as against 226,000 contaminated bricks.

Disadvantages

(a) This proposal has the disadvantages of "the devil we don't know." However, if it is unique as a method of storing refrigeration, there may be useful experience to be gained.

5.0 PERCOLATING SYSTEM

The crushed limestone-"trichlor." system does not show up too well in Table II. This is due to the large percentage of voids which are filled with "trichlor." If we consider a large tank filled with crushed limestone with a much smaller volume of "trichlor." being continuously sprayed at the top, trickling through the crushed rock body and being collected in a sump at the bottom as in Figure 3, we get the following results:

TABLE III

COST OF HEAT STORAGE MATERIALS FOR STAGE II REQUIREMENTS IN A "PERCOLATING" SYSTEM

System	Solid		Fluid		Total
	lb.	$	Gal.	$	$
Crushed Limestone - Trichlor.	1,190,000	1,400	2,000	4,650	6,050
Equiv. all-Trichlor. System			57,000	133,000	133,000

This would be an 83,000-gal. tank or a 24-ft. cubical enclosure filled with limestone.

This system does not have the advantage of counter-flow heat exchange, but is more than offset by the economy of materials.

A complication with this system would be the rapid rate of "breathing." This indicates an air drier to handle about 1,000 cu. ft. of air as the temperature was dropped from +40°F to -65°F, and proportional volumes throughout the season when not in use.

6.0 CONCLUSIONS

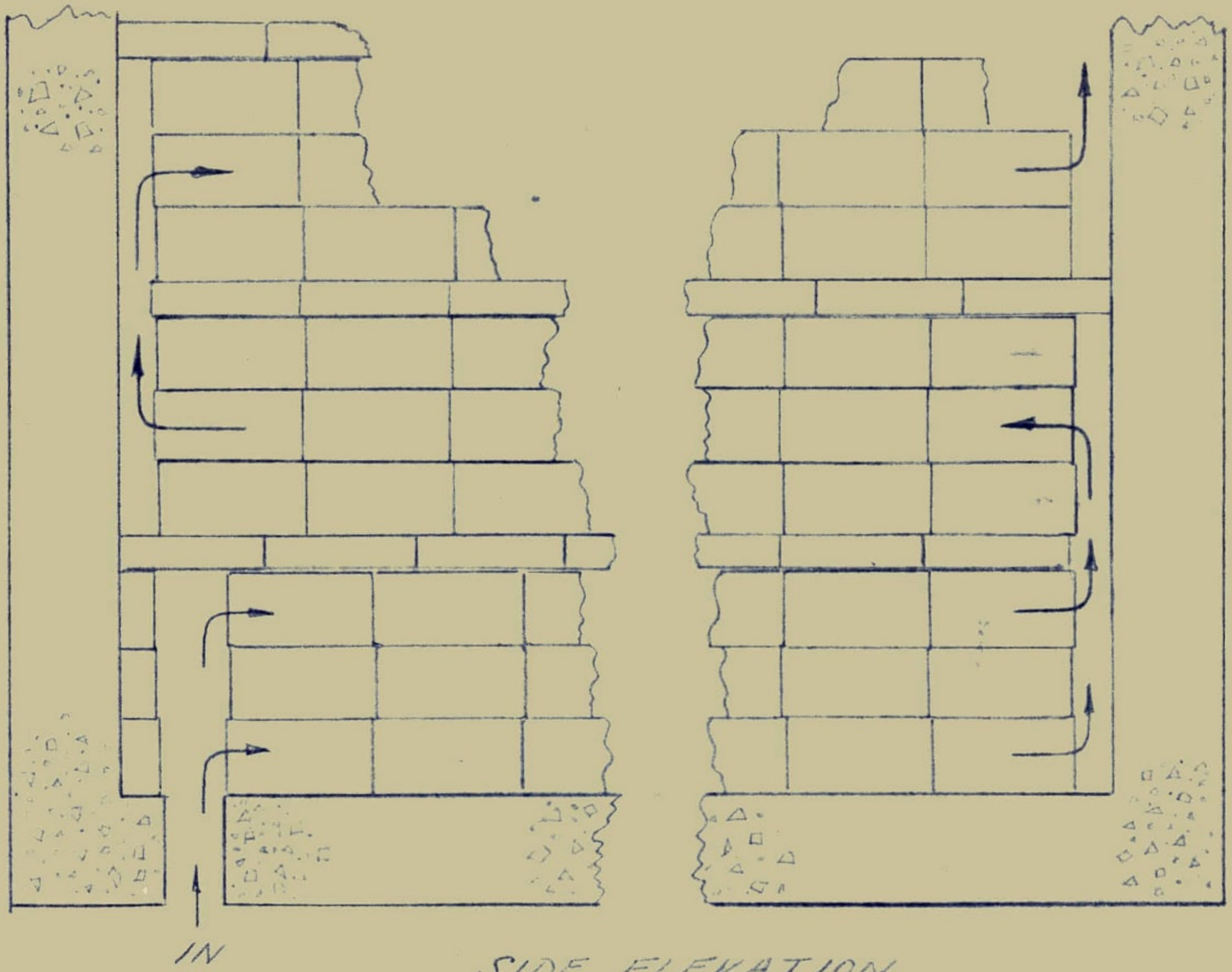
The idea of using a solid heat storage and liquid heat transfer medium as outlined seems to have much to recommend it. It is suggested that this should be investigated further before any much more costly installation is planned.

7.0 REFERENCES

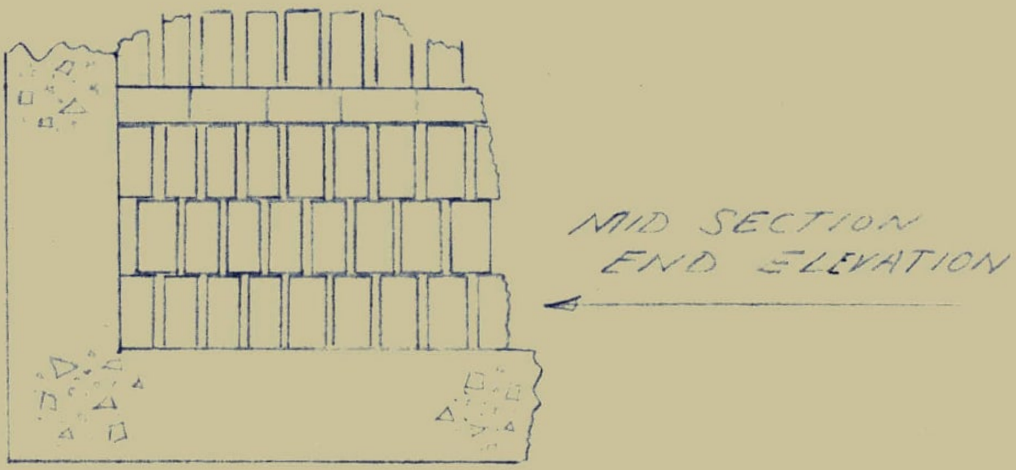
1) Baxter Low Temperature Laboratory Memorandum LT-103

2) Memorandum to Mr. Kuhring, 20 February, 1958.
File: M6-18-11

3) Fishenden and Saunders Heat Transfer.



SIDE ELEVATION



MID SECTION
END ELEVATION

FIG. I

FLOODED BRICK REGENERATOR

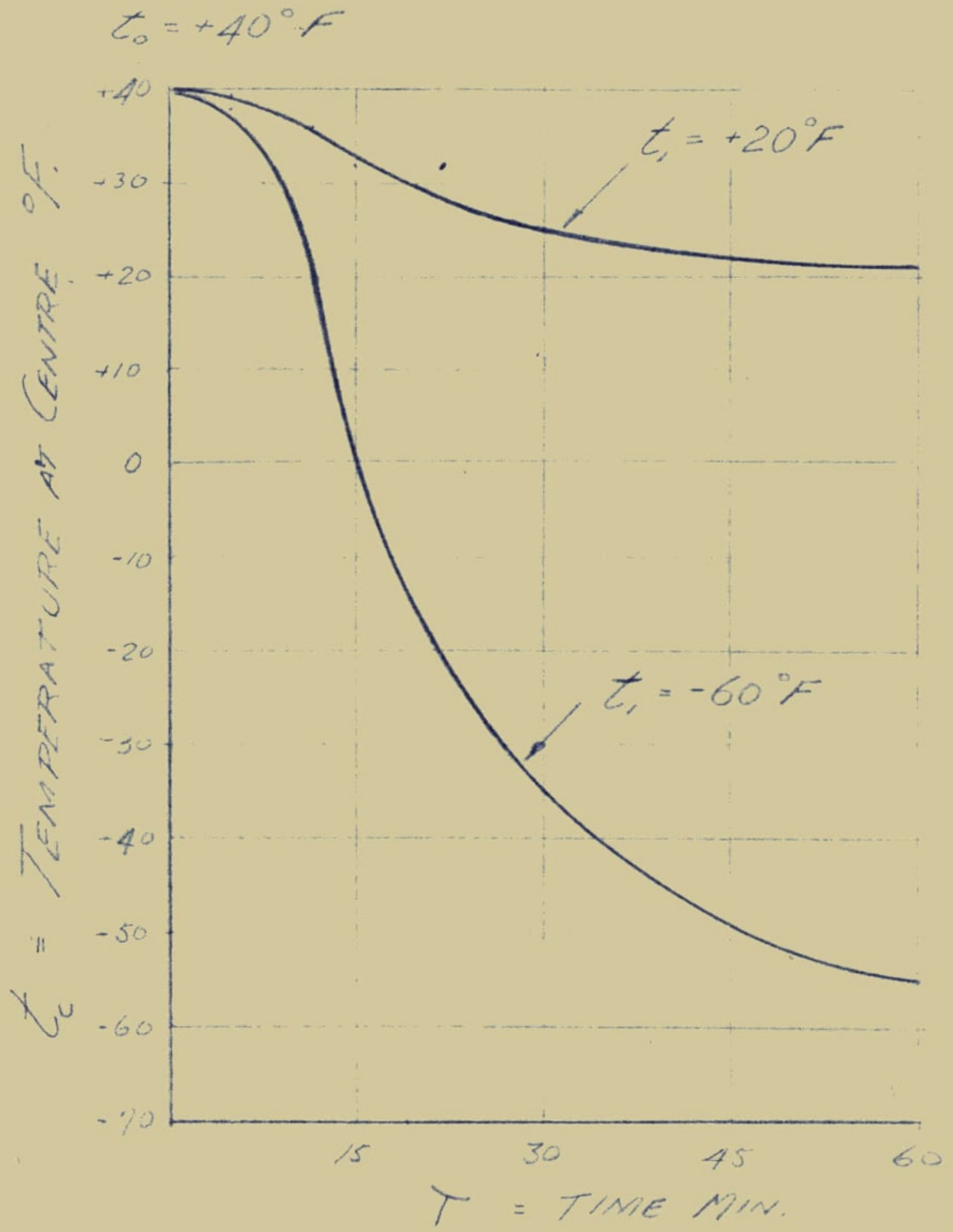


FIG 2

TEMPERATURE t_c AT CENTRE OF BRICK INITIALLY AT UNIFORM TEMP t_o AT ANY TIME T AFTER SURFACE TEMP. SUDDENLY ALTERED TO AND MAINTAINED AT t_1 (REF. 3)

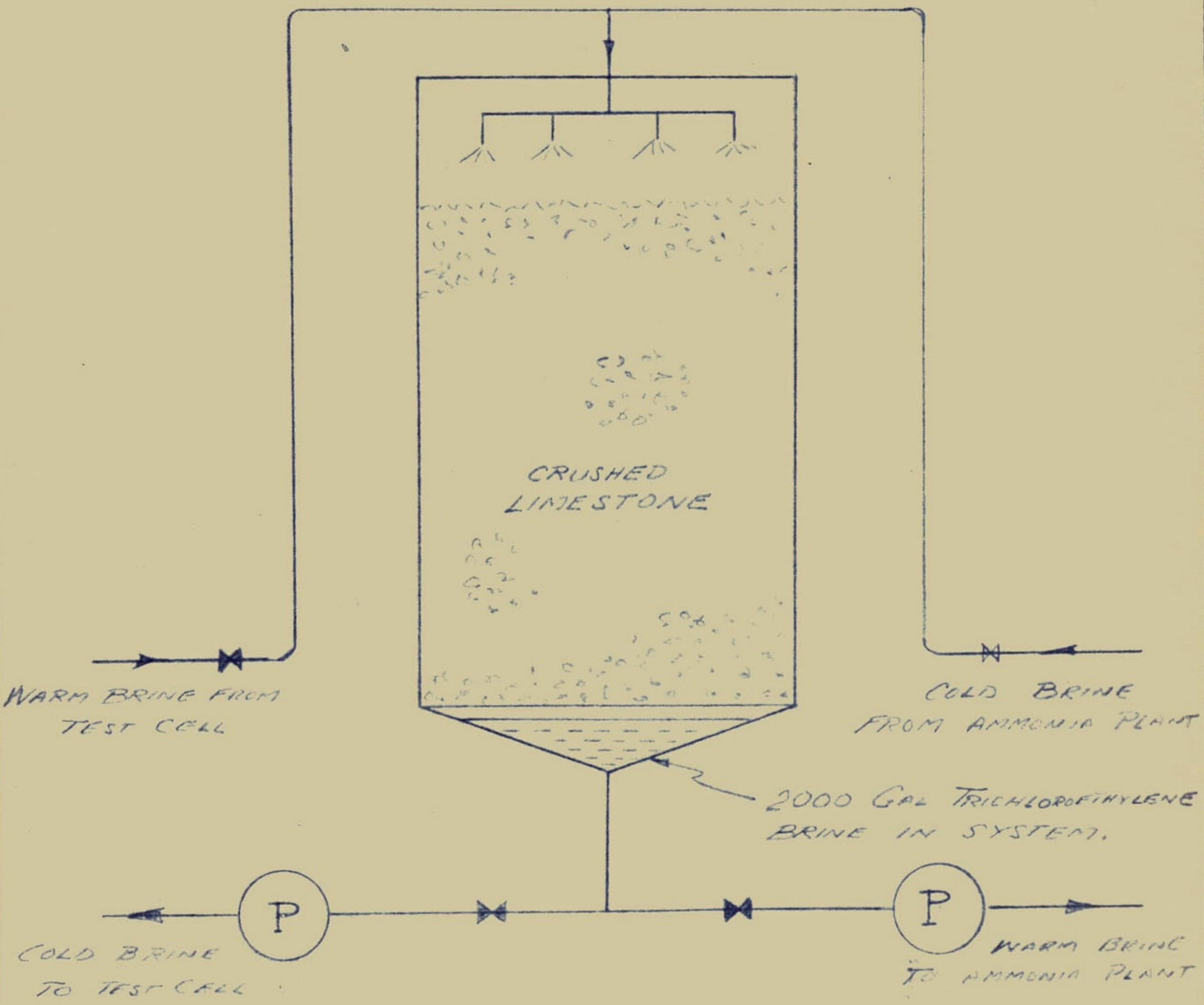


FIG. 3.

PERCOLATING SYSTEM