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Results of Sextant Warm-Up Transient Analysis

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June 1994

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USDOE Office of Science (SC)

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RHIC PROJECT

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Introduction

RHIC design criteria dictates that, for the purposes of component repair or replacement, a sextant be warmed from its operating temperature (4°K) to a serviceable temperature in approximately 24 hours. This warming will be accomplished by means of two integral electric heating circuits which loop back through every ~30 m of magnet (two dipoles, two CQS assemblies). Each of the pair of heating loops is staggered such that the terminals of one circuit penetrate every CQS. Each circuit can be closed independently.

Unfortunately there is interconnecting piping and certain intermediate components which have significant thermal mass yet cannot be exposed to direct warming from the heater. In order that large temperature differentials are not created locally, provisions have been made for the circulation of helium gas through the magnet string such that all points in the sextant are warmed at nearly equal rates; i.e., no cold spots are left.

The helium, of course, will offer an additional source of heat wherever it is warmer than the magnet. It is therefore important to know the effects of varying the controllable parameters: rate of heat generation (G), flow rate of helium gas (m), inlet properties of the helium (T,p), and variation of the flow path (flow reversals).

Quantitatively, up to 395 W/m of magnet of heat generation and flow rates of 20 to 100 g/sec of 300°K, 5 atm helium gas are available. A sextant is roughly 650 m long. Warm-up is completed when all points are 293°K or higher. It is important too that no magnet reach a temperature over 305°K as this will permit creep in the plastics used in the magnets and will release pre-stresses designed into the magnet coils. An ideal warm-up procedure is one where all points in the sextant have uniform temperature at all times; i.e., the temperature profile is flat and rises steadily to room temperature (300°K).

A Fortran (Microsoft 5.0) computer program using a finite difference method has been written to model a sextant with flowing helium and electric heat generation. Temperature dependent properties of metal and gas, including variable density are accounted for.

The following pages display the results of the program applied to various warm-up procedures (control parameter settings). Some conclusions are drawn. Firstly the simplest, 'full throttle' warm-up will be discussed.

'Full Throttle' Warm-up (fig. 1)

The parameters were as follows: inlet pressure and temperature of gas, 5 atm and 300°K; mass flow rate, 100 g/sec; continuous heat generation, 334 Watts/m (85% of capacity). Figures 1A and 1B show the temperature profile for the magnet core and for the gas when the maximum temperature in the magnet has reached the peak allowable 305°K (t=2.11 hr, x=8.05 m). The profile is for the first 150 meters of continuous magnet (constant mass/length).

It is interesting to note that a short length of magnet has, even at this early stage, reached steady state; i.e., the temperature at some points along the inlet of the magnet is no longer changing with time. These temperatures match the analytical steady state solution (see appendix) to within 0.2 %.

This profile is significantly flatter than that for a similar run with mass flow rate of 20 g/sec. Still it is obvious that the majority of the sextant will remain below 293°K. We must therefore develop a more sophisticated plan for warmup. The following variations have been considered:

Proposed Warm-up Methods

PLAN 1. Allow the magnet to warm as above except at the instant 305°K is reached, reverse the flow; i.e., shut flow (say CW) through the sextant then open identical flow (say CCW) to the opposite end of the sextant. Continue to reverse the flow whenever a peak is reached. (fig. 2)

PLAN 2. Reverse flow at the end of every time period (say 1 hr.). (fig. 3)

PLAN 3. Use of a buffer. Firstly, to install at the inlet of the warming helium, a thermal mass to be cooled to 4°K with the magnets. Secondly, using some inlet length of unheated magnet (without electric heat generation) as a buffer.

PLAN 4. Pre-cool inlet helium to flatten the leading peak of profile. (fig. 4)

PLAN 5. Allow the magnet to warm-up as above except at the instant 305°K is reached in a double cell of magnets (four dipoles, four quadrupoles), turn off heat generation in that local circuit (double cell) only. (fig. 5,6,7)

PLAN 6. Use temperature transducers located at each heater junction to, upon sensing a magnet temperature of 300°K, open the heater circuits immediately following (down stream from) that junction. (fig. 8)

PLAN 7. Use of a counter-flow heat exchanger to transfer heat from the flowing helium at the outlet of the sextant to the inlet, as it is circulated by the main compressor, while all heaters warm continuously. (fig. 12)

Results of Proposed Methods

PLAN 1. This run (figs. 2A and 2B) uncovers an interesting phenomenon which occurs with the reversing of flow direction. That is that whereas in the continuous forward flow temperature profile of figs. 1A and 1B the peak of the wave propagates forward (toward the center of sextant), here it tends to remain stationary as it dances left then right. At the same time the flat portion of the profile continues to rise steadily.

This is very desirable since one could insert a buffer at either end (inlet) to the sextant which would be capable of sustaining the large temperature differential at the lead of the wave. This buffer could then be less massive (shorter) since the peak is stationary, not moving toward the center.

That this scheme allows the peak 305°K to be reached before flow reversal, necessitates a buffer since the cooling effect of the reversed flow is overcome by the added heat from the element. The peak temperature continues to rise above 305°K.

PLAN 2. To offset this imbalance the second run shows reversed flow after the first hour (well before 305°K) and every hour thereafter.

Figure 3 shows the results of this run. The profiles are for the end of every forward direction flow cycle. 305°K is reached shortly after the eleventh hour.

Again the desirable flattening of the downstream side of the profile is seen; it also rises steadily. Note that the longer period between reversing cycles means a longer portion of magnet or buffer is subject to the large differential; i.e., the peak is "tighter" with more frequent cycling.

PLAN 3. The proposition of installing a buffer, an added "sacrificial" thermal mass, at the ends (inlets) of a sextant has been discussed here in 1 and 2.

Some important notes about a buffer; obviously, the increased mass will significantly add to the sextant warm-up time, as well as to cooldown time.

In a system with buffers at either end of the sextant, since the helium flowing to the end of the sextant would otherwise be warmed by the far buffer, it may be desirable to short circuit the buffer back to compressor. This is because the net enthalpy change of the helium would be small and the warming of magnet is minimized. In essence, heat would be simply traded between buffers as the flow is reversed.

If a length of magnet at the inlet of a buffer had no electrical heat generation, it could act as a buffer to the downstream magnet. The outcome of this arrangement is shown in figure 4. Here, the first 60 meters of magnet used no electrical heat generation while down stream heaters were on continuously. Conditions otherwise are as in figure 1.

Note that the time to 305°K is significantly lengthened (t=8.2 hr). At this time a significant portion of magnet is less than 293°K. It would be possible however to determine a lead length of "buffer" magnet such that the peak 305°K occurs at a time (t~22 hr) when all downstream magnets are above 293°K.

An inherent problem with this arrangement is that if the prescribed warm-up parameters are deviated from significantly the peak may arrive at the heat/no heat junction either too late, leaving a gap of cold magnet just before the junction or too early, causing a premature 305°K.

PLAN 4. A continual flow of pre-cooled helium intended to dampen the peak of the profile will simply move the peak to a point further toward the center of the sextant. No practical temperature will allow the theoretical peak to occur beyond a sextant length. This can be seen by the form of the steady state analysis given in the appendix.

PLAN 5. This is a promising method. It insures that no excess heating takes place as the helium will act as a heat sink to all points at the leading peak, including those with heat generation turned off.

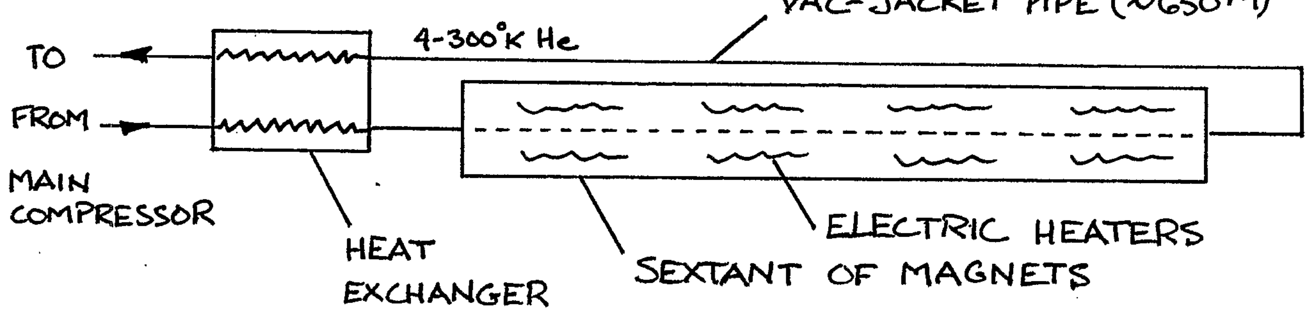
With regard to the problem of determining where in each double cell, 305°K will be reached: it occurs in exactly the same location (at different times) in each double cell _if_ all points upstream of the peak have reached steady state. Since one can predict exactly where the peak 305°K will occur, proper placement of a minimal number of temperature transducers will allow accurate closed loop control of warm-up. This assumes, of course, controlled parameters are not allowed to deviate from their prescribed setting, especially as 305° is approached. This will be difficult to assure.

The propagating wave in the temperature profile is still seen (towards the center of sextant) but here the peak of the wave oscillates slightly between 300°K and 305°K rather than continually rising (see figs. 5 and 6B).

PLAN 6. This plan eliminates the critcality of temperature transducer placement. In figure 8 (note the scale on the ordinate axis) the plots are snapshots at the occurrence of 300°K at a heater junction. Consider, also, that the peaks flatten with time then later redevelop at the next junction. After 15 hours the peak remains comfortably below 305°K. At least two more peaks will occur before all down stream magnets have been warmed to 293°K (mostly by the heaters after 22 hours). The localized temperature differentials are fairly small in the region of the peaks. This method works but does not leave room for error; the peaks are a concern.

PLAN 7. Since the electric heaters alone can raise the temperature of the magnet they are contained within to 300°K in less than 24 hours, and these magnets represent most of the systems thermal mass, the circulation of uniform temperature helium (starting at 4°K and increasing to 300°K) through the sextant will track the magnet temperature in an acceptable fashion.

This method uses one of the existing vacuum-jacketed process lines within the cryostat to recirculate helium to a local heat exchanger; if this is not objectionable, and the additional hardware is affordable, this is a sure fire way to a successful warm-up (see fig. 12).



Closing Points

1. The large bore magnets in the injection region, with large thermal mass, require more powerful heaters for warm-up within the specified period.

2. Under failure of a single heating circuit certain magnets will be warmed to a greater extent by the flowing helium. An initial dip in the temperature profile at, and just after, the failed circuit is realized. The dip is small (a few degrees) and shortly the profile is smoothed until the point of failure is unrecognizable (reference fig. 6A). The net effect is a negligible increase in the period for warming downstream magnets. This can not be said for any warm-up method that does not use continual helium flow.

3. The results discussed here assume a continuous mass per length along the sextant. In fact a significant portion of the length is interconnecting piping, the longest of which (~37 m) connects the magnets Q3 to Q4. The ratio of the thermal mass per unit length of this connector to that of the magnet is roughly 1:28.7; it is similar then, though not dynamically, to a portion of unheated magnet 1.3 meters long. In the manner described above (2), the effect from this interconnect alone is small; but for the total of all interconnecting piping it may be meaningful initially to the transient analysis.

4. Ultimately the time to warm-up is determined, in all methods, by the rate of heating of the electric elements and is therefore the same for all. At some point downstream the contribution of the helium is negligible and the temperature versus time plot of this portion of magnet is shown in figure 9.

5. The positive slope of the profile in method 7 is due to the lag time for helium returning to the heat exchanger in the unheated process line.

Conclusion

Limitations imposed by magnet design criteria disallow 'full throttle' warm-up. A more sophisticated scheme must be expended; a variety has been discussed. Each has some drawbacks the least of which are those of methods 6 and 7. Method 6 is to turn off a heater circuit each time the temperature of the magnet located at the beginning of the circuit reaches 300°K. Small localized peaks do occur. Sensors exist for quench detection, but the control requirement is a disadvantage; also 100 g/sec of helium must be assured.

Method 7, the recirculation of helium through a counter-flow heat exchanger warms a sextant uniformly within the desired period. Control requirements are minimal; it is fool-proof. The disadvantage is the cost. Quotes on the required exchangers (per pc. for 5 pieces) average $15,000.

Warming a sextant by means of heaters alone with a final flush of helium to handle interconnects has two serious concerns: large radial and axial temperature gradients develop, and the inevitable failure of a single, or parallel pair of heater circuits leaving magnets unwarmed.

References

1. J. Cottingham, Magnet Division Note # 270-16 (RHIC-MD-73), April 19, 1988.
2. J. Cottingham, Magnet Division Note # 320-16 (RHIC-MD-88), April 12, 1989.
3. W.J. Schneider, "Transient Response of a Thermal Buffer; A Study For Isabelle", 1981 Cryogenic Engineering Conference, San Diego, California.
4. A. Klingenberg, "Heat Transfer in Counter-Flow Heat Exchangers and Packed Beds", Industrial and Chemical Engineering, Vol.46 No.11, November 1954.
5. Hausen, pp.282-287, Heat Transfer by Max Jacob, Wiley and Sons, 1929.

Figure Index

Appendices

As appendices, included for the purpose of a program check are comparisons with:

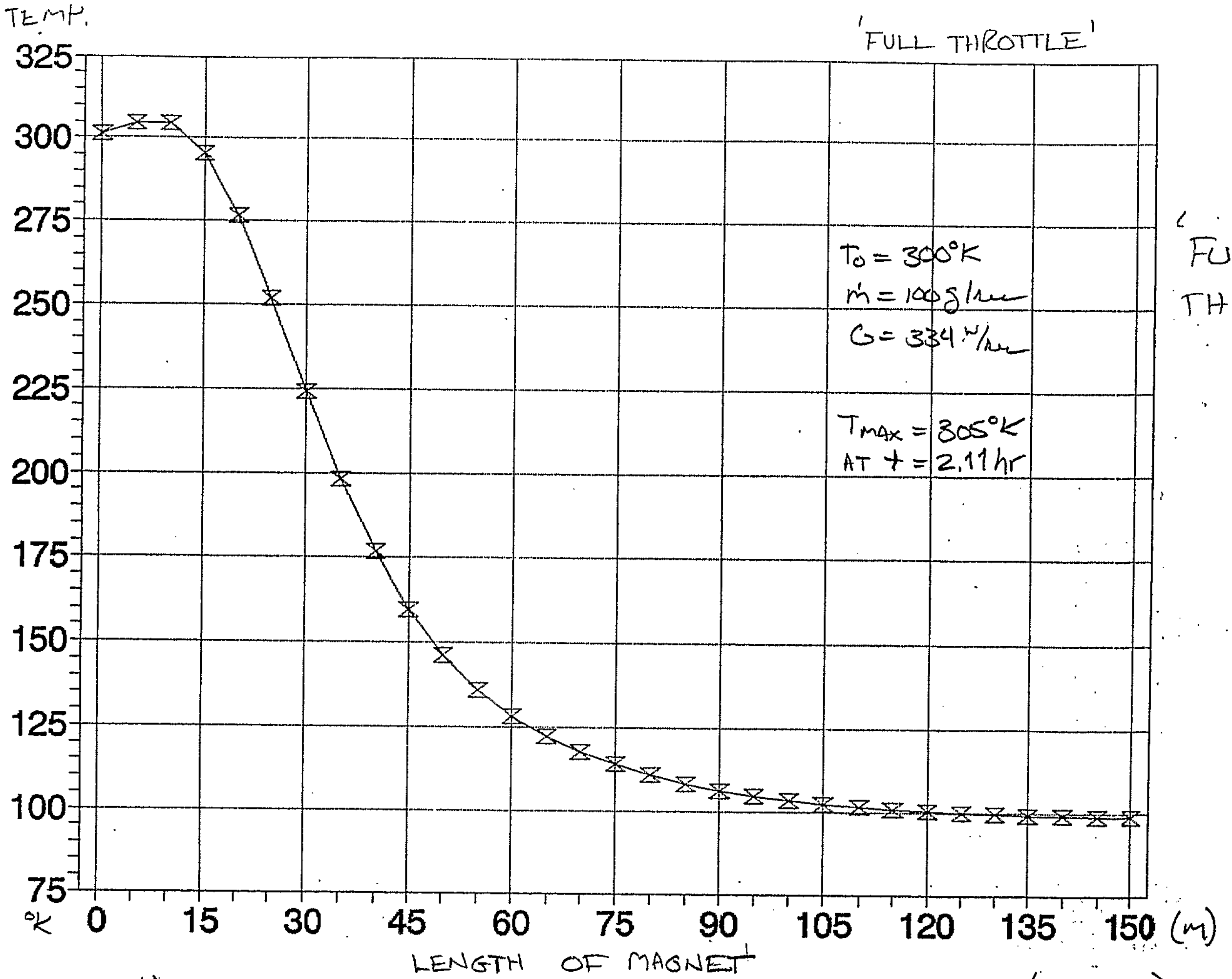
1. Exact steady state solution (variable properties, G=334 W/m, m=100 g/s).

2. Klinkenberg's error series solution (constant fluid and metal properties, G=0, m=20 g/s; figures 10A & 10B).

3. Backward difference program by K.C. Wu (constant fluid and metal properties, G=0, m=20 g/s; figs. 11A & 11B).

4. Total heat balance in Joules (net heat added=heat stored).

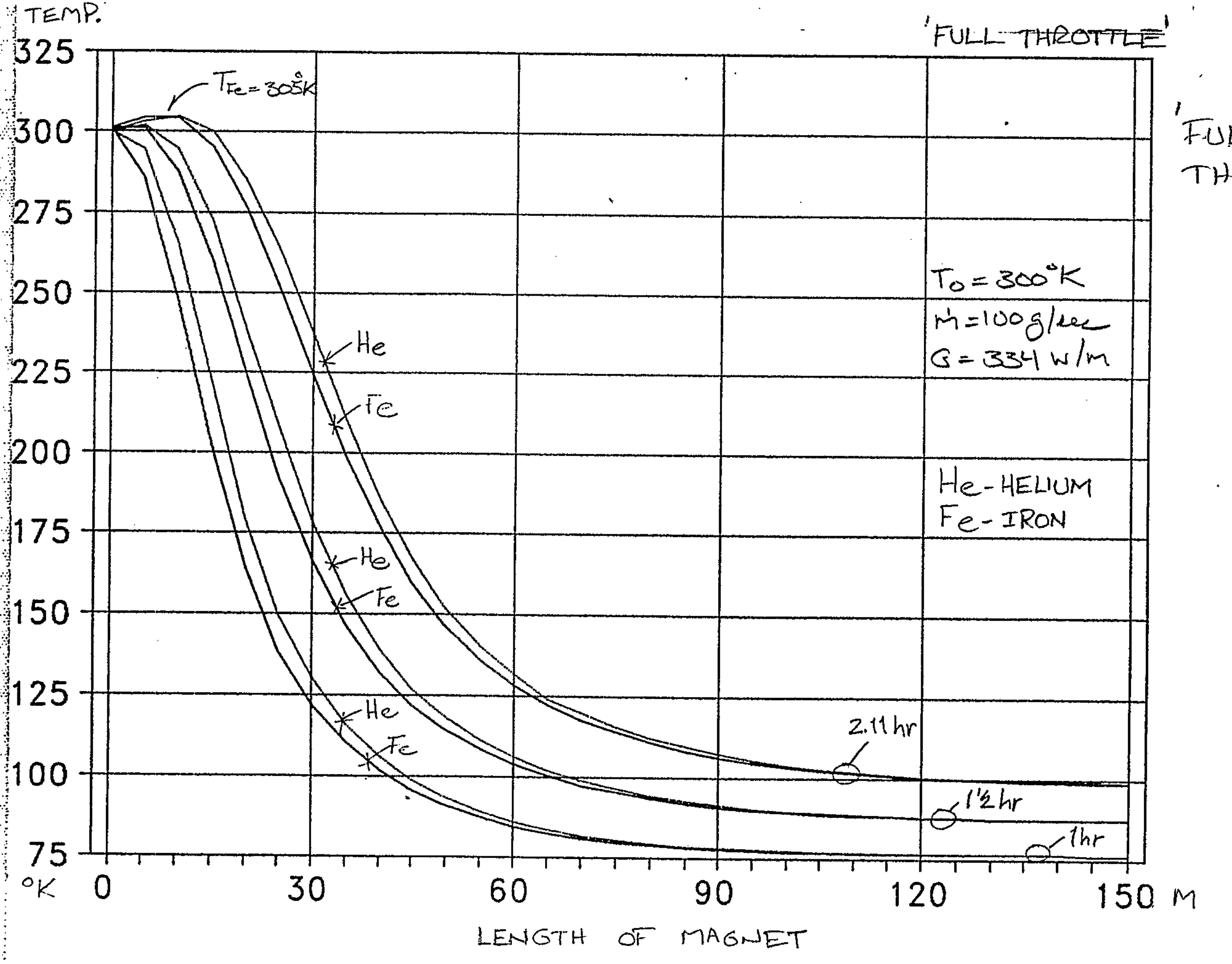
'FULL THROTTLE'



'FULL THROTTLE'

FIG.1A: MAGNET TEMP. PROFILE AT FIRST PEAK OF 305°K (t=2.11 hr)

~~'FULL THROTTLE'~~



'FULL THROTTLE'

FIG. 1B: HELIUM AND IRON MAG. TEMP. PROFILES VERSUS TIME

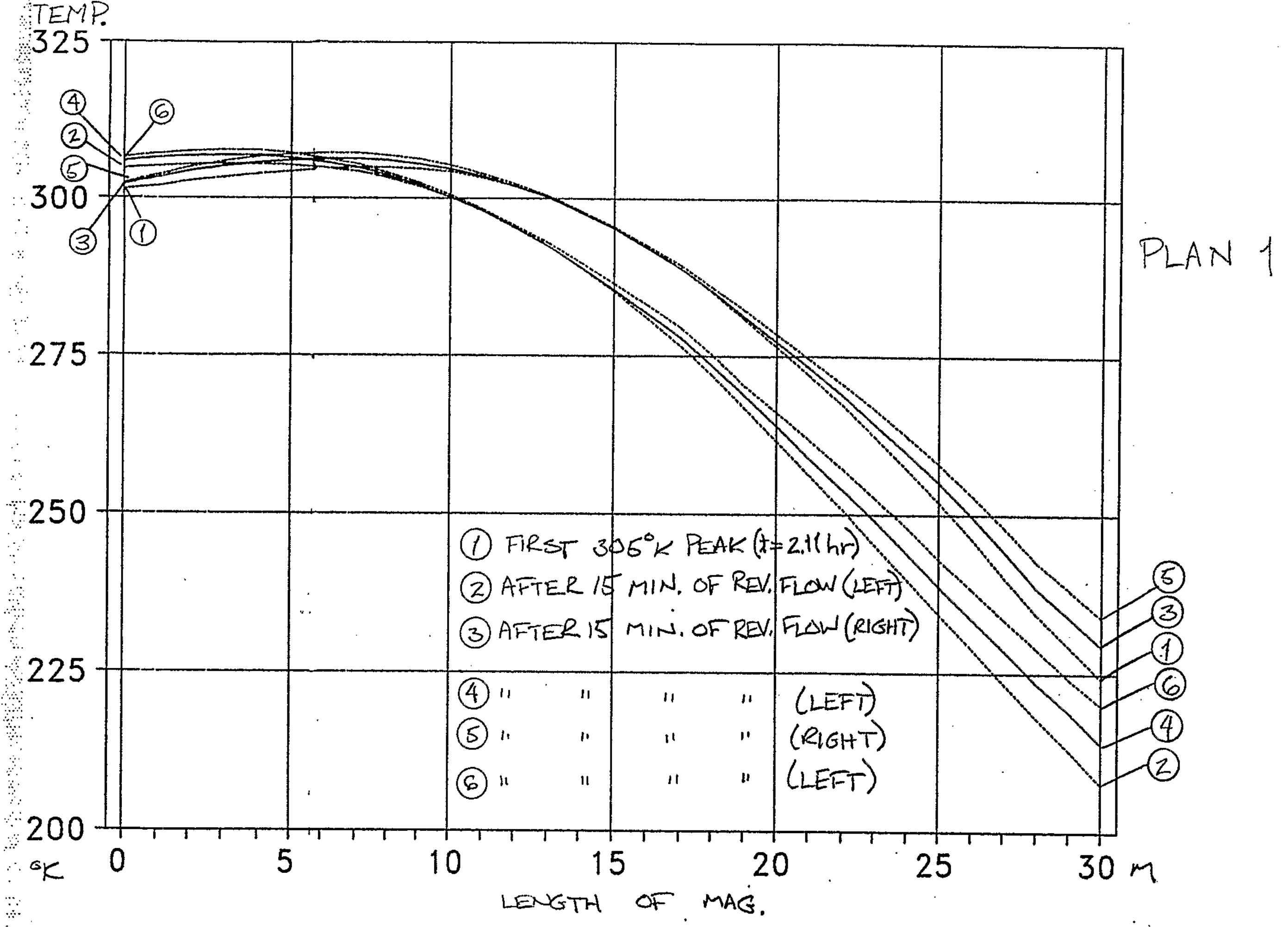


FIG. 2A: SHOWS THE EFFECT ON THE PEAK OF REVERSING FLOW

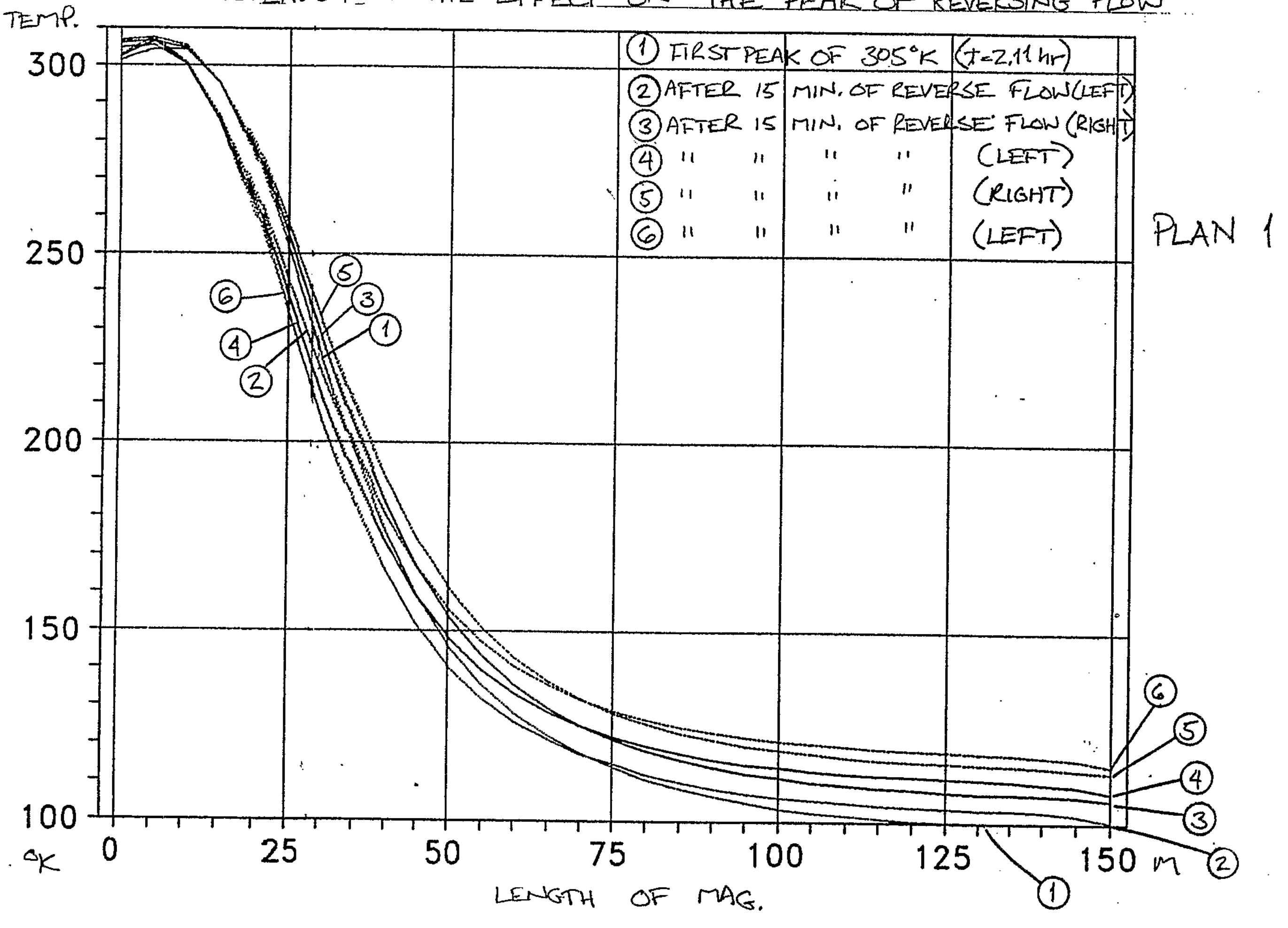
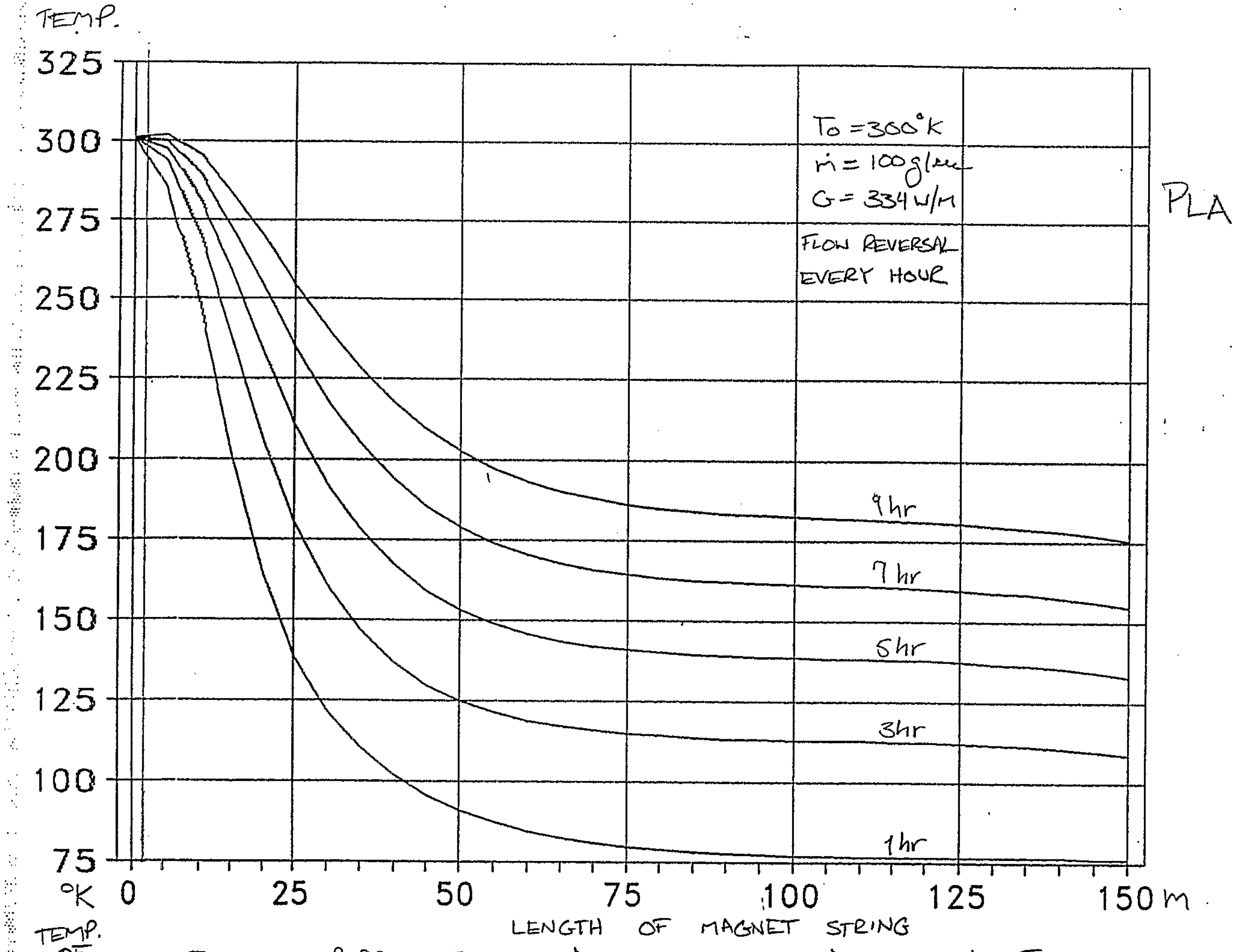
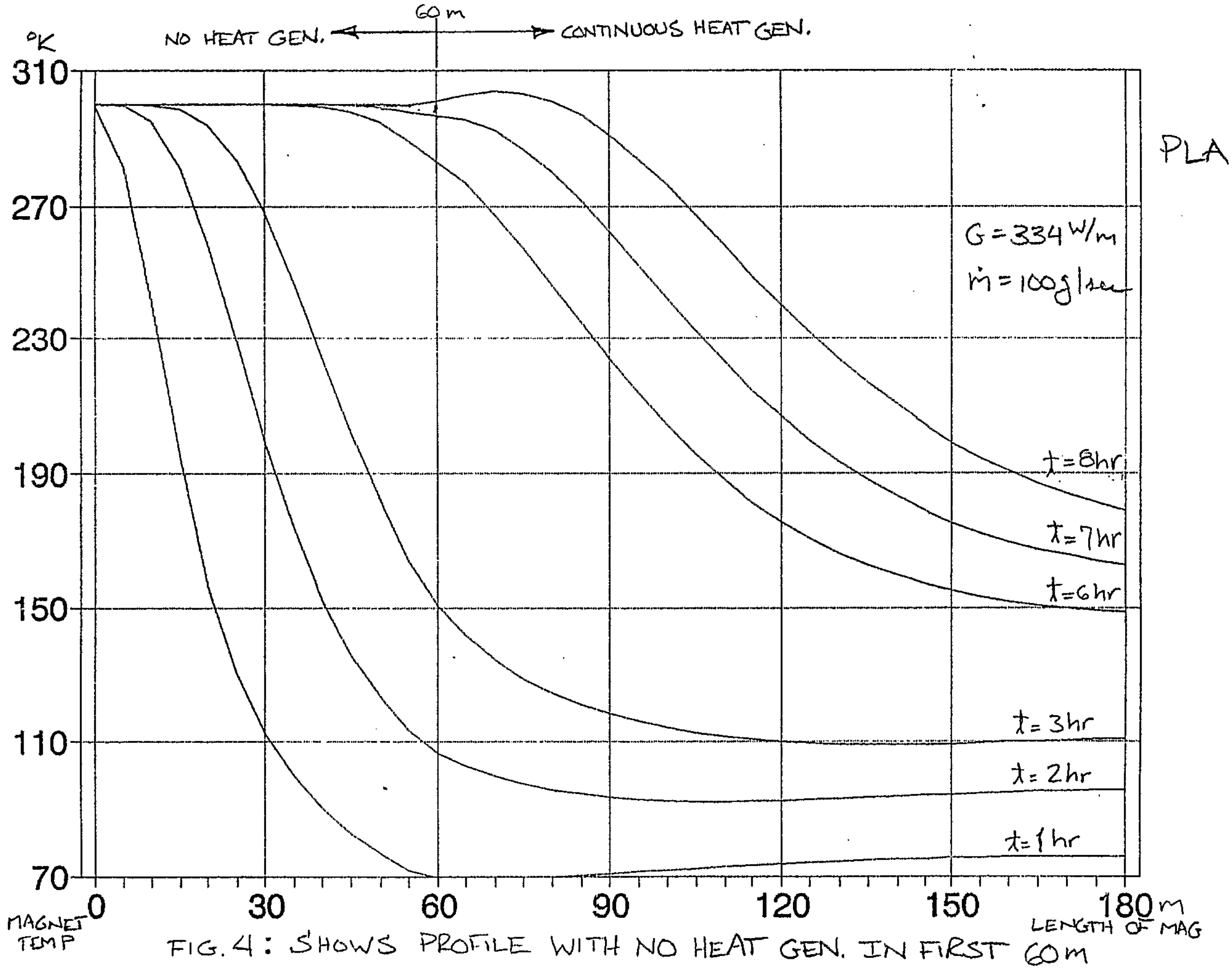


FIG. 2B: SHOWS EFFECT ON PROFILE OF REVERSING FLOW



PLAN 3

FIG. 3: TEMP PROFILE AT END OF EACH FORWARD FLOW CYCLE



PLAN 4

FIG. 4: SHOWS PROFILE WITH NO HEAT GEN. IN FIRST 60 m

10

PLAN 5

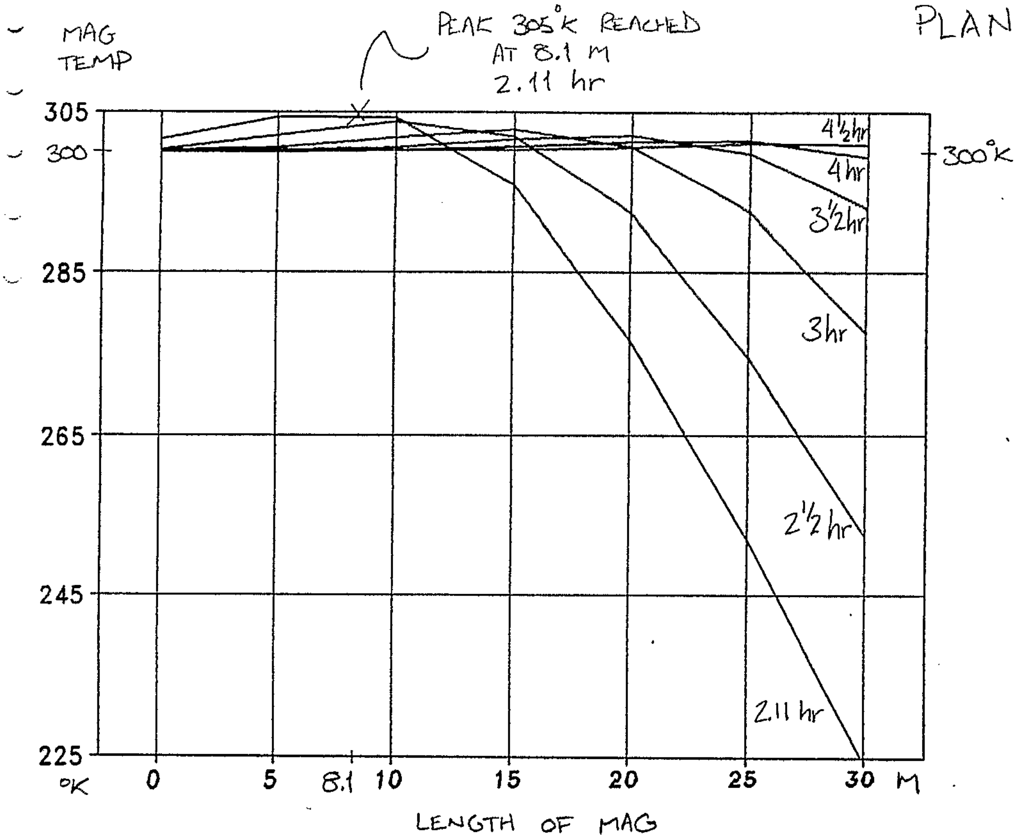


FIG. 5 SHOWS DAMPENING OF FIRST PEAK AS LOCAL HEATER IS TURNED OFF AFTER TEMP. OF 305°K IS REACHED.

PLAN 5

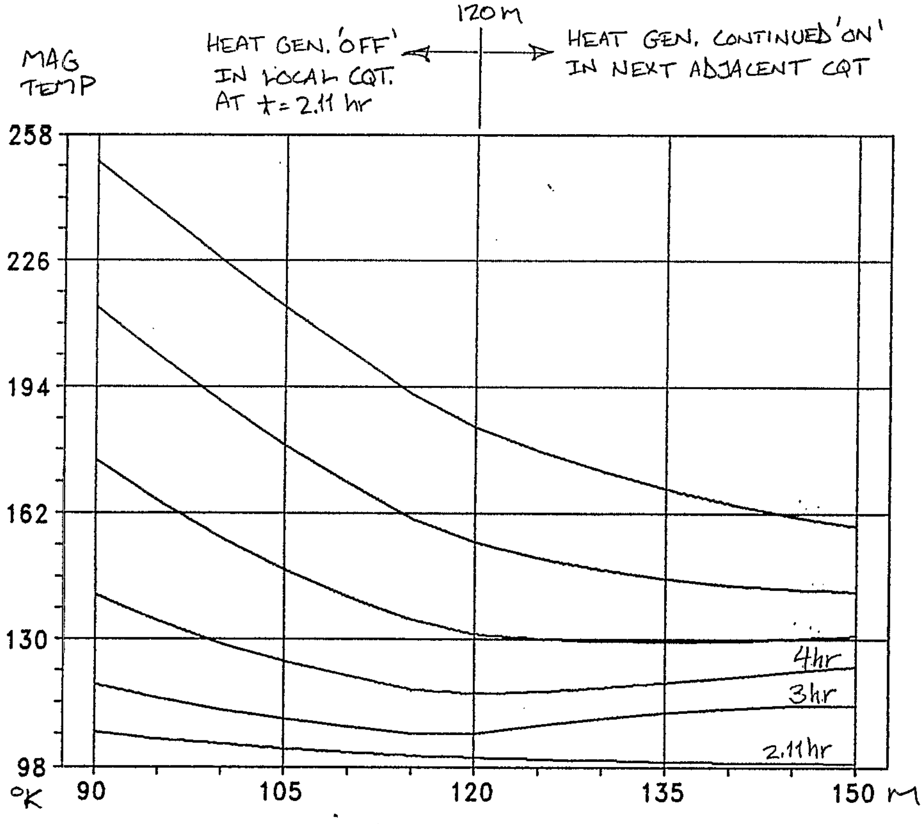


FIG. 6A: SHOWS DEVELOPMENT OF SECOND PEAK AND SMOOTHING OF PROFILE AT HEATER ON/OFF JUNCTION (AT 120 m)

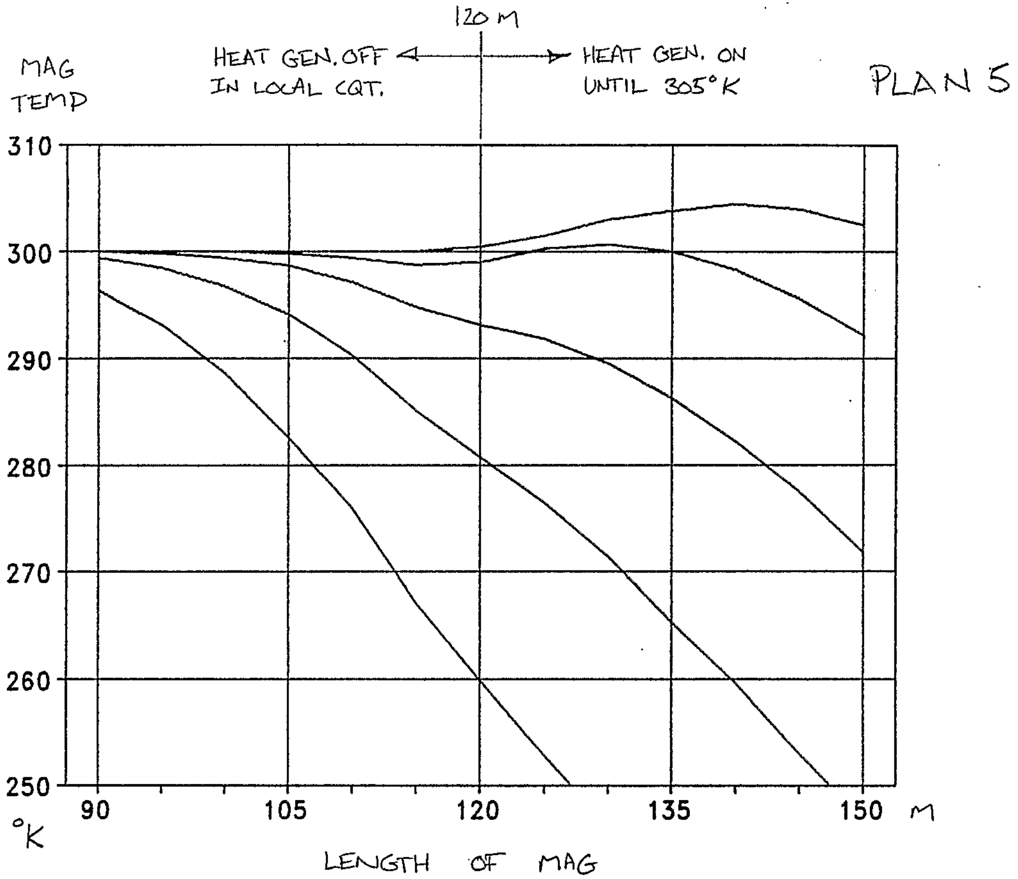


FIG.6B: SHOWS PROPOGATION OF SECOND PEAK TOWARDS 305°K.
NOTE THE LEVELING TO 300°K OF UPSTREAM MAGNET.

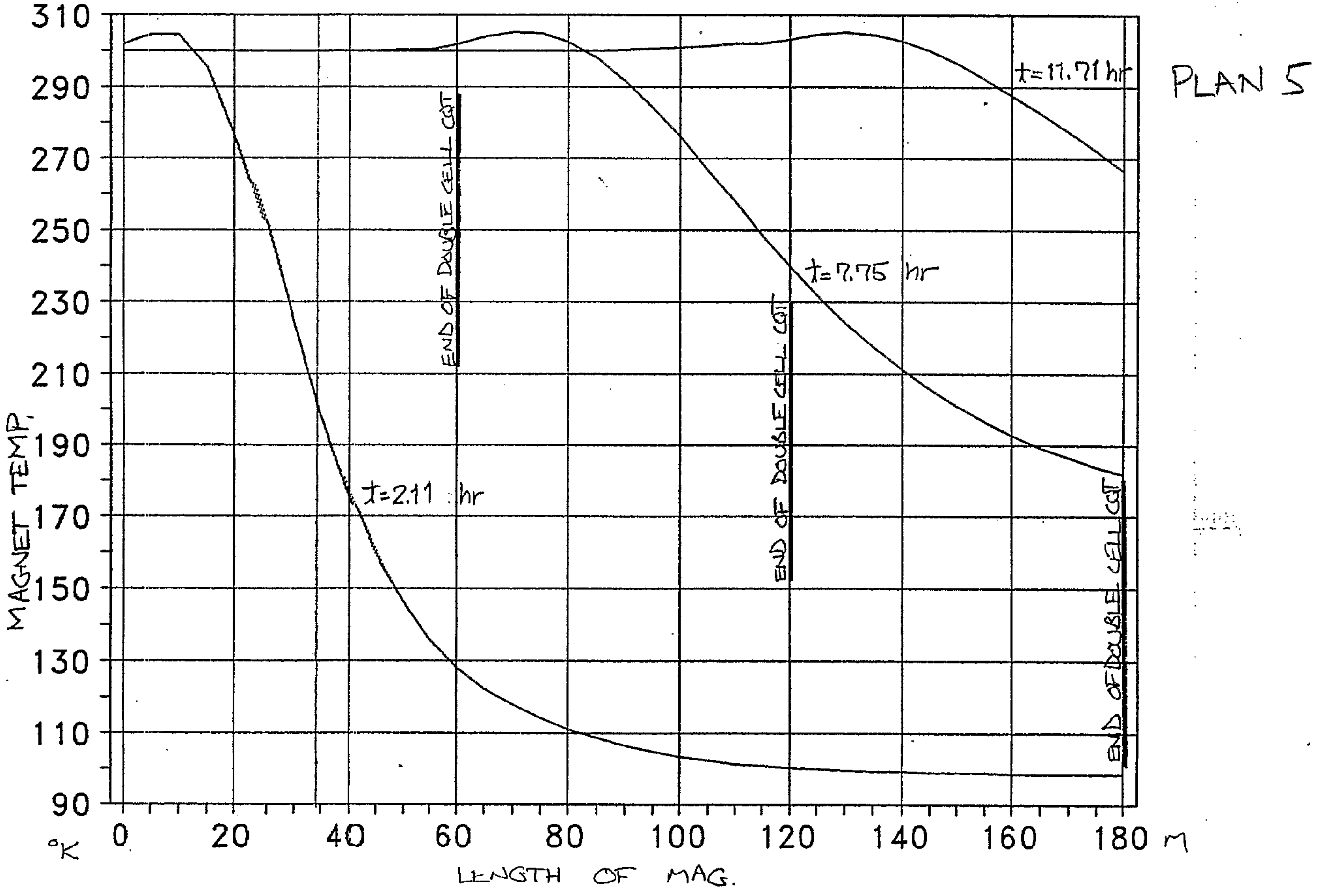


FIG.7: SHOWS PROFILE AT OCCURRENCES OF 305°K PEAK
JUST BEFORE LOCAL HEATER CQT IS TURNED OFF.

PLAN 6

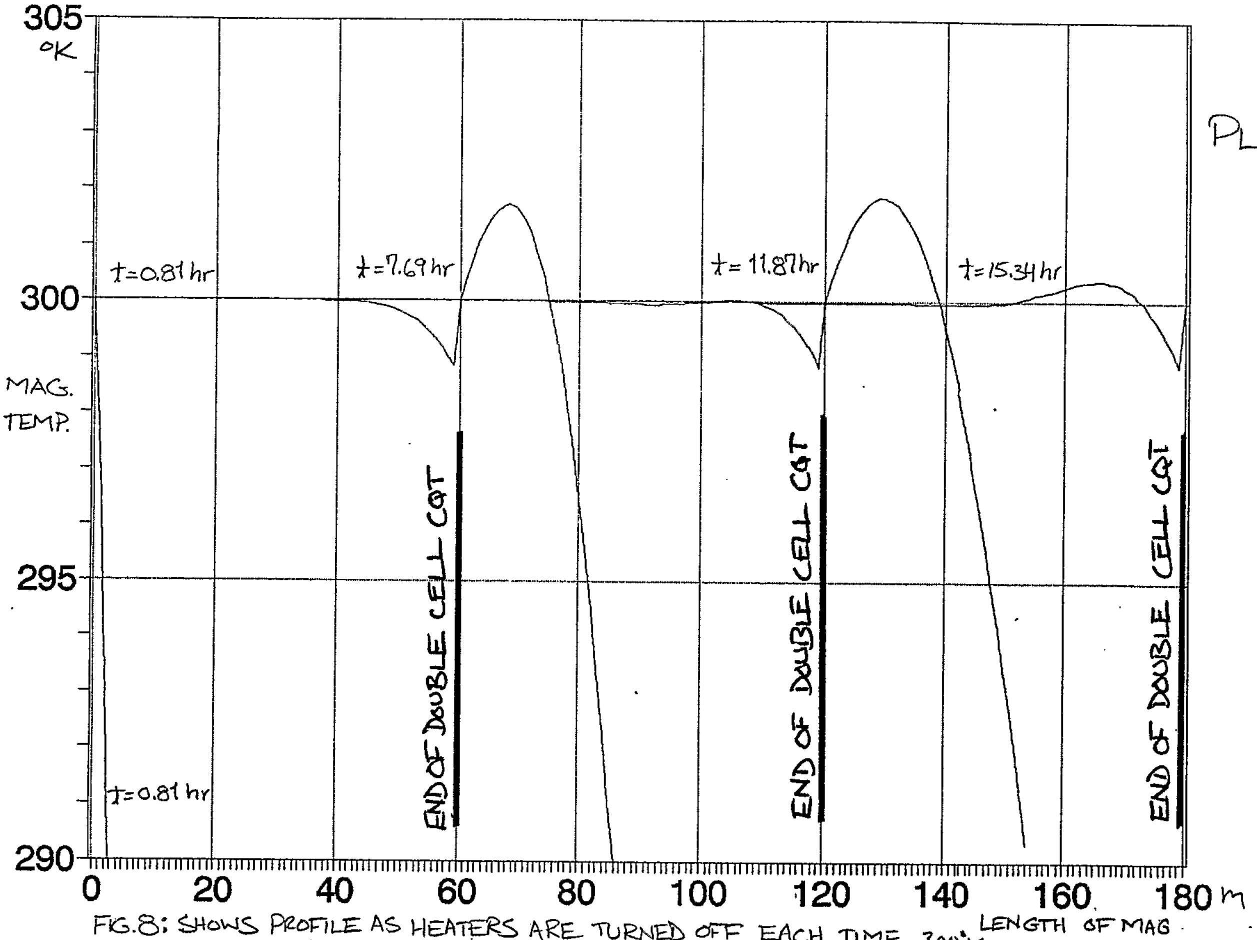


FIG.8: SHOWS PROFILE AS HEATERS ARE TURNED OFF EACH TIME 300°K IS REACHED IN THE MAGNET LOCATED AT THE BEGINNING OF THAT CIRCUIT.

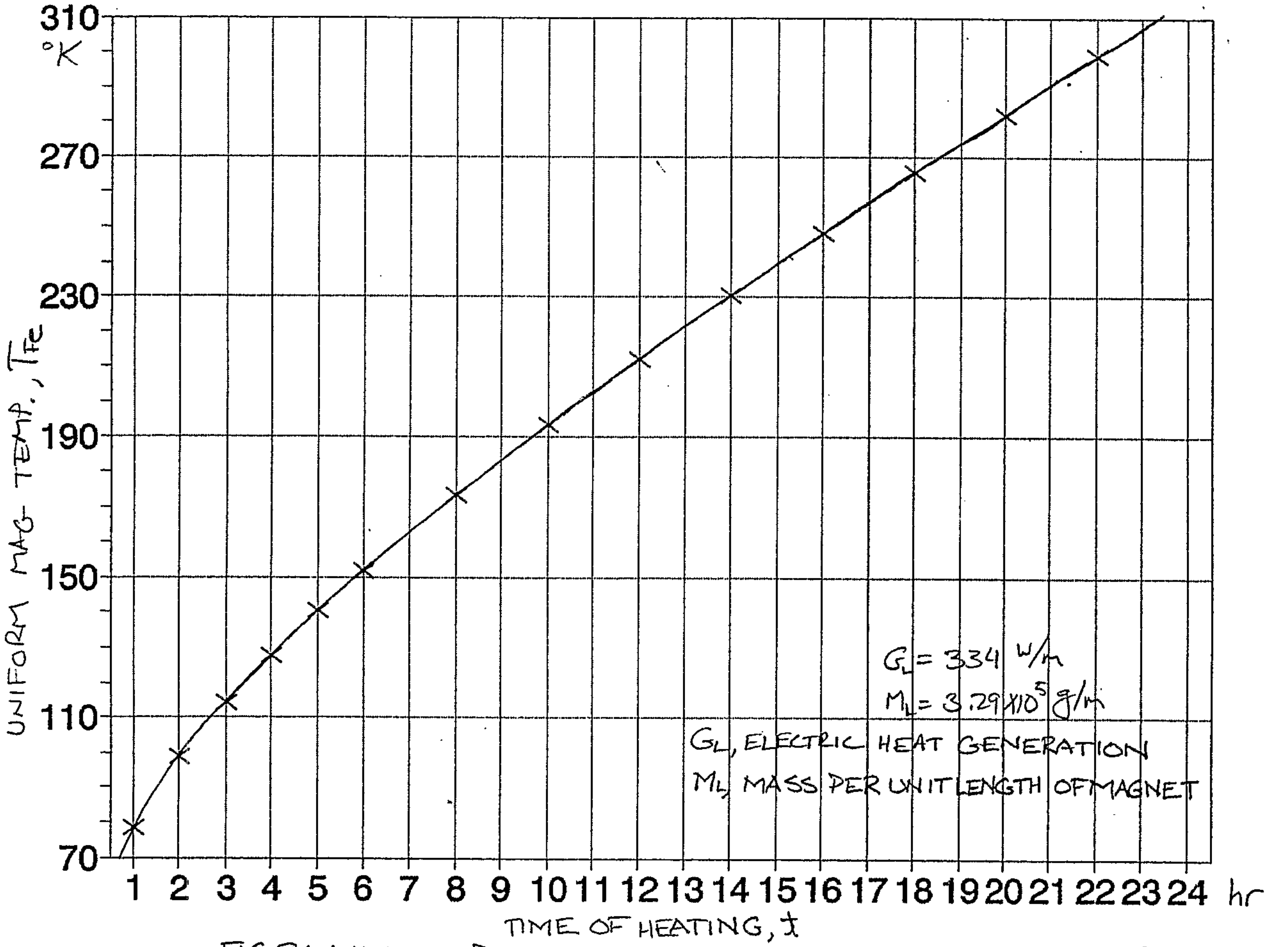
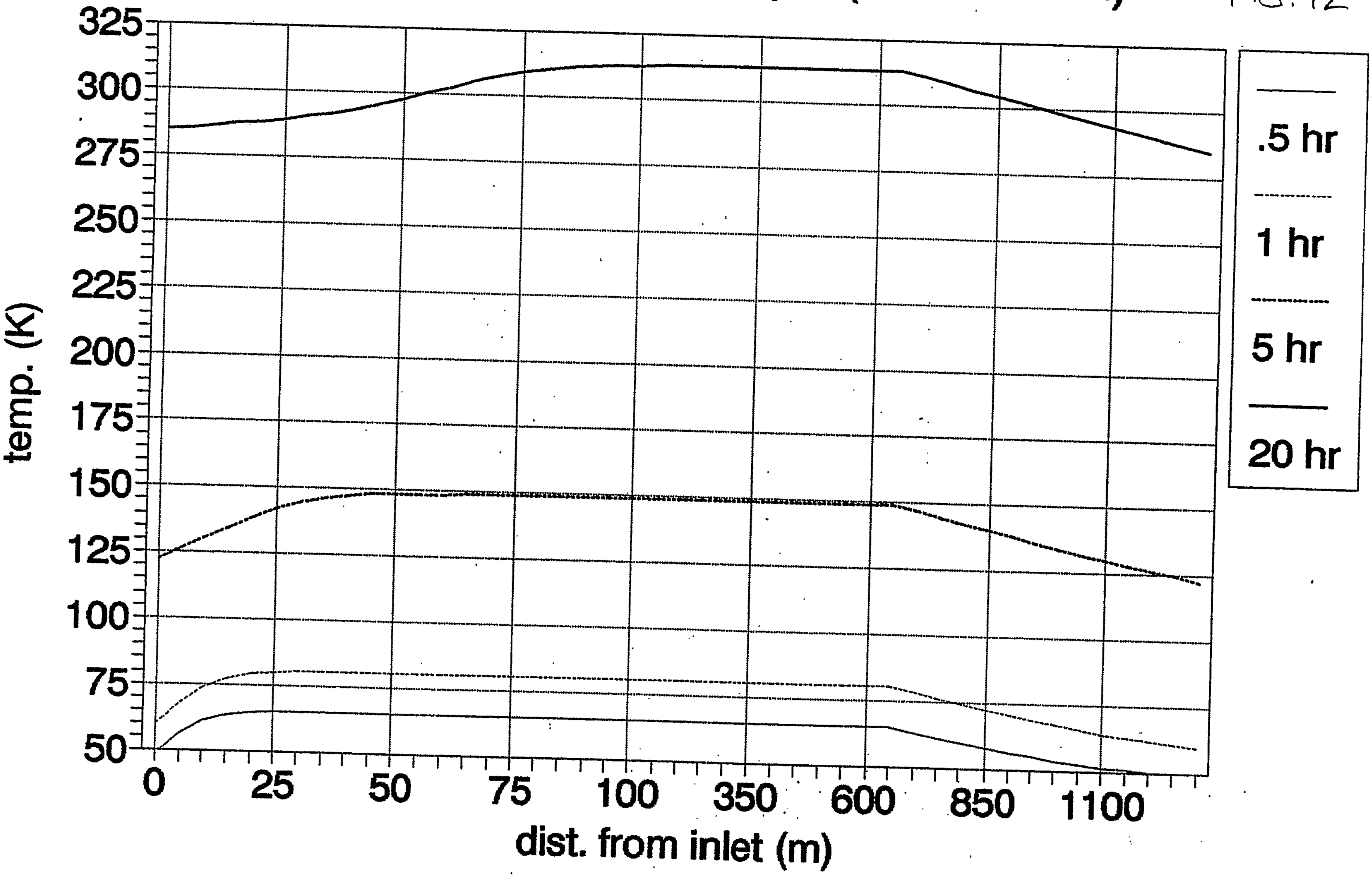


FIG.9: MAG TEMP vs TIME WITH HEAT GENERATION ALONE

HX Warm-up Sextant Temp. Profile

Mag (0-650m)/ Return Pipe (650-1300m)

FIG. 12

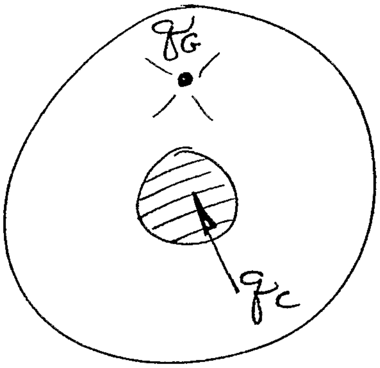


STEADY STATE SOLUTION

APPENDIX 1

AT STEADY STATE

ALL GENERATED HEAT IS CONVECTED TO FLOWING HELIUM; i.e., THERE IS NO STORED ENERGY BEING INTRODUCED TO MAGNET CORE.



SIMPLIFIED X-SECTION

q_S = STORED HEAT
q_c = CONVECTED HEAT
q_G = GENERATED HEAT

$q_S \rightarrow 0$

HEAT BALANCE $q_c = q_G$

$$q_c = hA_L(T_{Fe} - T_{He})\Delta X = \dot{m}_{He} C_p (T_{He}' - T_{He})$$
$$q_G = G_L \cdot \Delta X$$

where:

G_L = RATE OF ELECTRIC HEAT GENERATION; W/m
h = CONVECTIVE HEAT TRANSF. COEFF.; $W/m^2 \cdot {}^\circ K$
A_L = TOTAL OF PERIMETER OF BYPASS HOLES; $\frac{m^2}{m}$
T_{Fe} = IRON MAGNET (AVG. X-SECT.) TEMP.; °K
T_{He} = LOCAL HELIUM (AVG. X-SECT.) TEMP.; °K
T_{He}' = DOWNSTREAM HELIUM (AVG. X-SECT.) TEMP.; °K
ΔX = INCREMENTAL MAGNET LENGTH; m
$\dot{m}_{He}$ = MASS FLOW RATE OF HELIUM; g/sec
C_p = SPECIFIC HEAT OF HELIUM AT T_{He}; $J/g \cdot {}^\circ K$

then:

$$hA_L(T_{Fe} - T_{He})\Delta X = G_L \Delta X$$
$$\dot{m}_{He} C_p (T_{He}' - T_{He}) = G_L \Delta X$$

$$\boxed{T_{He} + \frac{G_L}{hA_L} = T_{Fe}}$$
$$\boxed{T_{He} + \frac{G_L \Delta X}{\dot{m} C_p} = T_{He}'}$$

I.C.

$IX = X = 0$
$T_{He_0} = 300°K$

IX	T_{He} (°K)	h	G_L/hA_L	T_{Fe} (°K)	X (m)
1	300.0	622.668	1.4138	301.414	0.1
2	300.06425	622.685	1.4137	301.478	0.2
3	300.1285	622.701	1.4137	301.542	0.3
4	300.1927	622.717	1.4137	301.606	0.4
5	300.2570	622.734	1.4136	301.671	0.5
6	300.3213				

APPENDIX 2

FIG.10A: KLINKENBERG'S ERROR FUNCTION SOLUTION

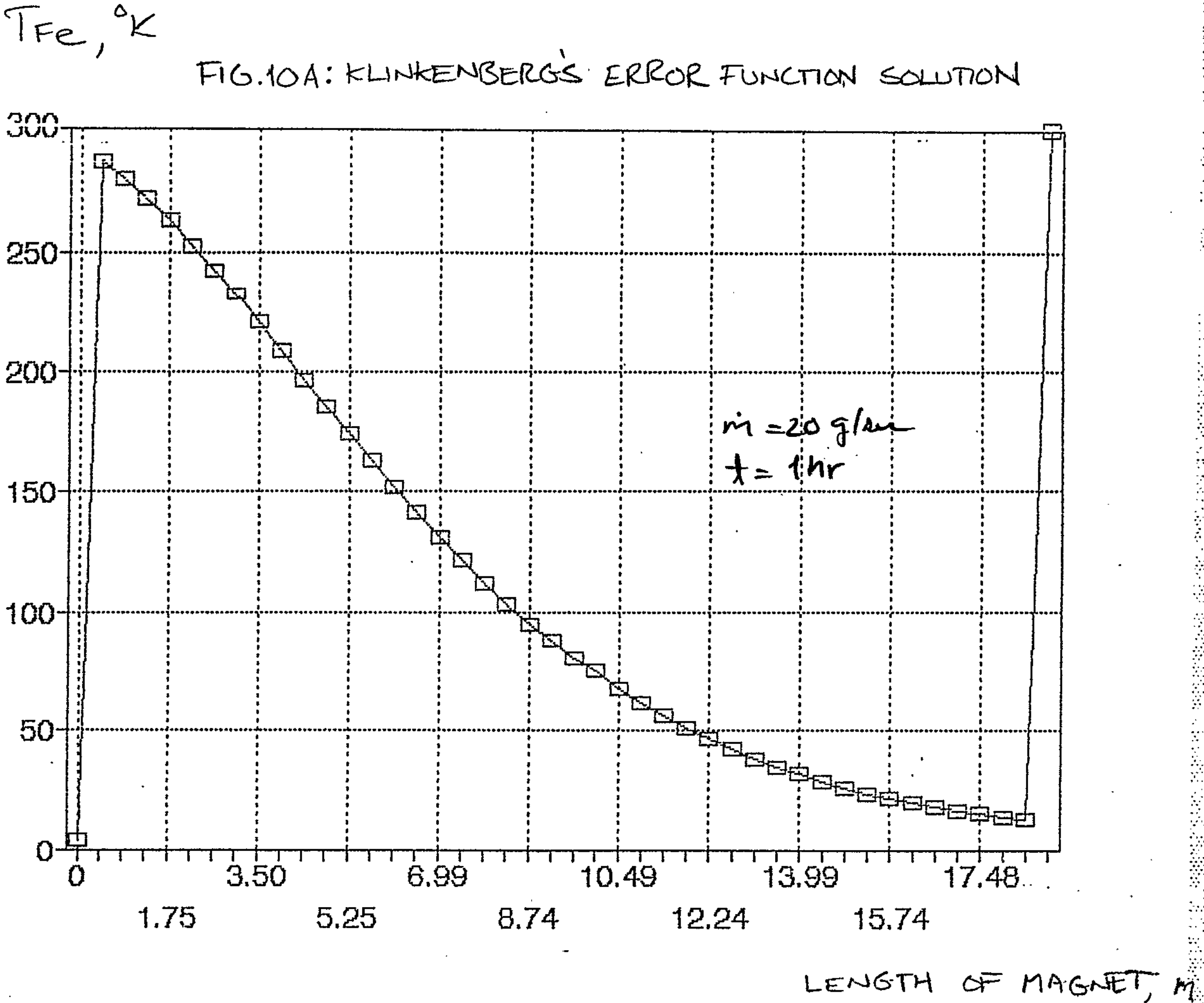
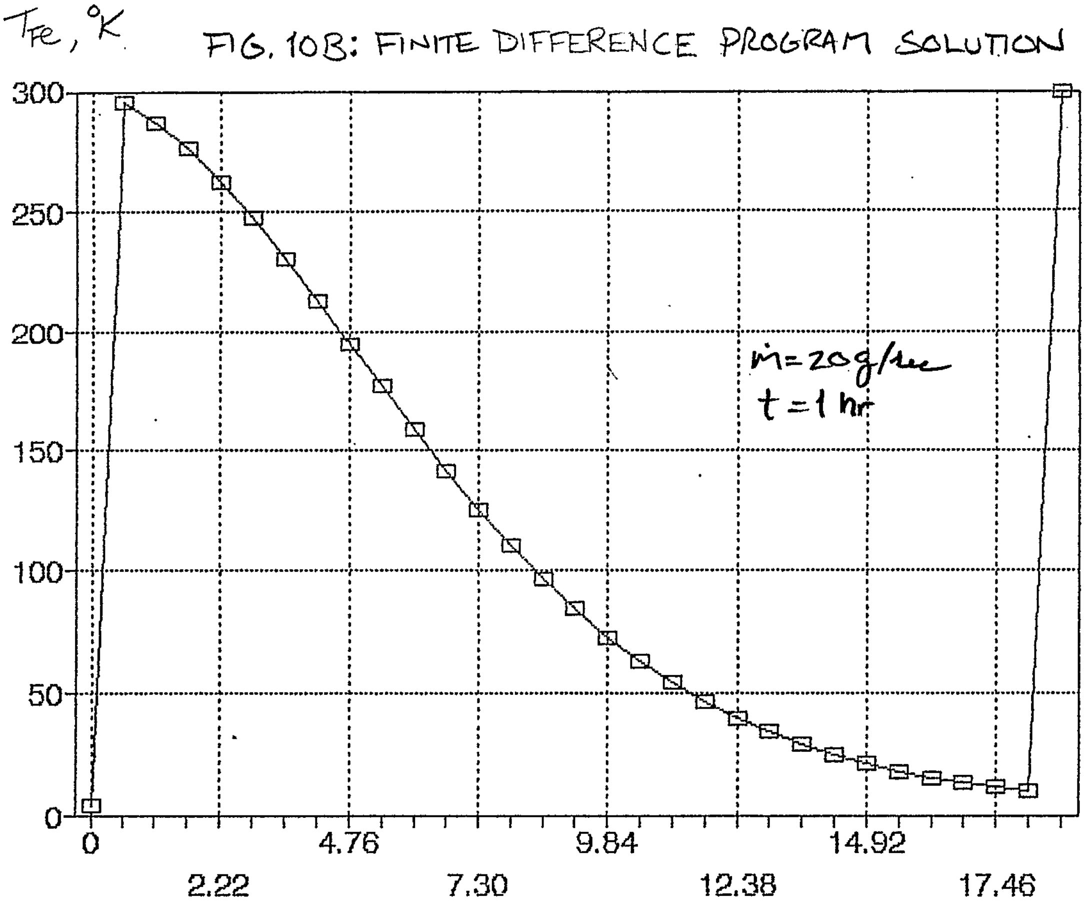


FIG. 10B: FINITE DIFFERENCE PROGRAM SOLUTION



APPENDIX 3

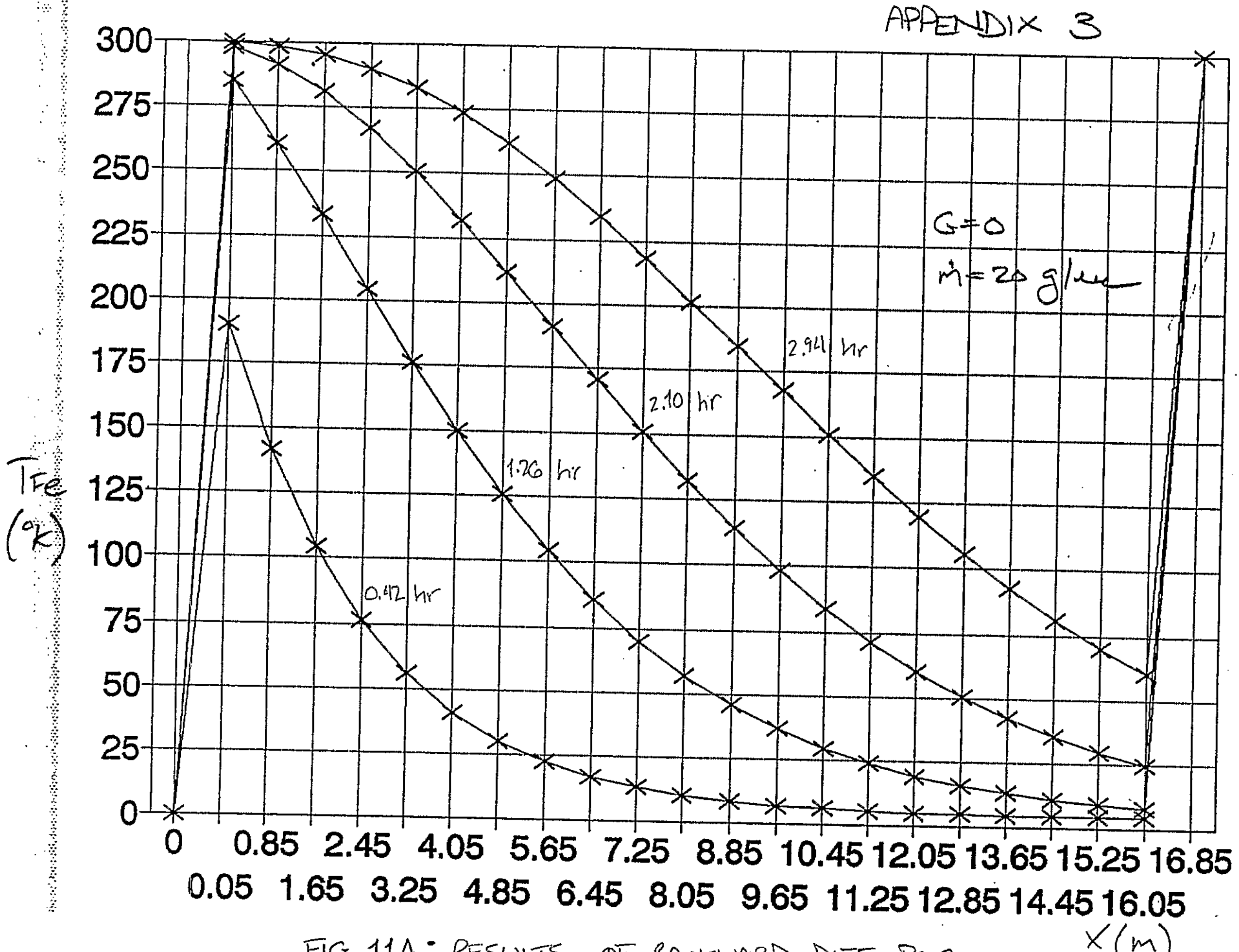


FIG. 11A: RESULTS OF BACKWARD DIFF. PGM.

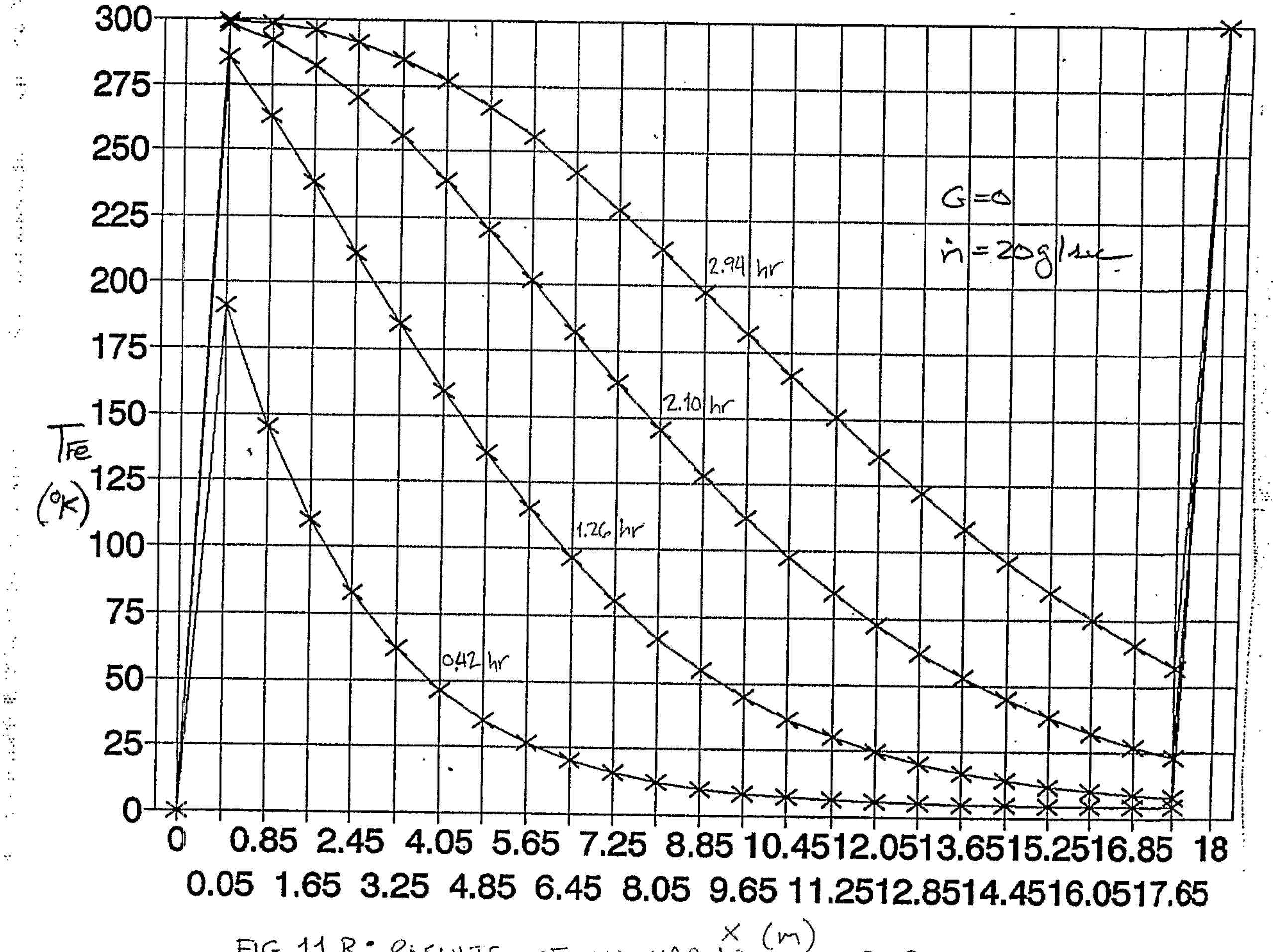
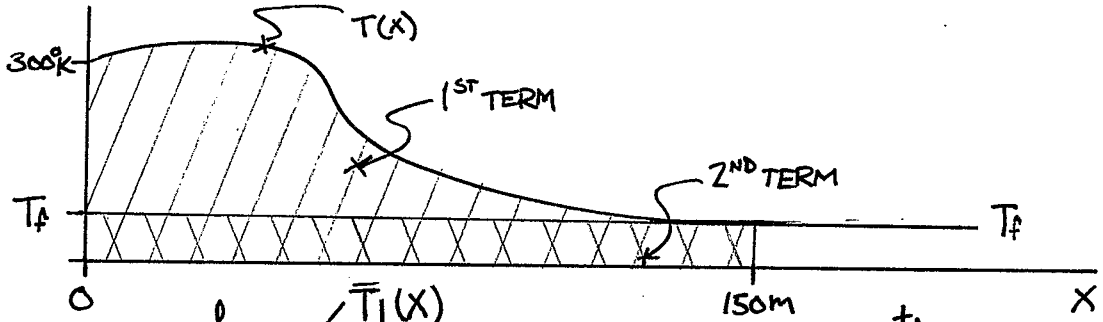


FIG 11B: RESULTS OF NO VARIABLE PROP. RUN

APPENDIX 4

A calculation was made to determine what the profile after the flat portion at 150 meters looks like. For a string of magnet warmed only by electric heat generation calculation shows that the uniform temperature after 1 hour of warming would be 78.3°K. The temperature profile after continuous flow for 1 hour per the conditions of figure 1 shows, at a position of 150 m from the inlet, a temperature of 78.6°K. Thus a difference of only 0.3°K is due to the heating from Helium. It is safe to assume then, that the profile is very flat (horizontal, uniform) in the downstream portion of fig.1B.

Thus the enthalpy lost by the Helium gas must have served to raise the magnet temperature in the first 150 meters. We may therefore write a heat balance for that portion of magnet.



$$M_L \sum_{0}^{\ell} \Delta X \int_{4^\circ K}^{\bar{T}|_{t_f}(X)} \bar{C}_v(T)\,dT - G_L \ell t_f = \dot{m} \int_{0}^{t_f} \left[h|_{T_o=300^\circ K} - h(t) \right] dt$$

where;

M_L =mass per unit length of magnet; 329 kg/m.

ΔX =incremental length of magnet; 0.1 m.

$\bar{T}|_{t_f}(X)$ =temperature as a function of position at time t_f , avg. over ΔX; °K.

$\bar{C}_v(T)$ =specific heat of iron as a function of temperature, avg. over ΔX; J/g·°K.

G_L =rate of electric heat generation; 334 W/m.

ℓ =length of magnet under consideration; 150 m.

t_f =time period after which temperature profile is frozen for analysis; 1 hr.

$\dot{m}$ =mass flow rate of Helium; 100g/sec.

$h|_{T_o=300^\circ K}$ =enthalpy of inlet Helium; 1574 J.

$h(t)$ =enthalpy of outlet Helium at the temperature $T_f(t)$; J.

$T_f(t)$ =temp. of downstream ($X \geq \ell$) magnet (and He) as a funct. of time; °K.

We integrate the known Cv(T) for iron over the solved profile after 1 hour to get the left side of the equation; then the known h(T) for Helium over the solved $T_f(t)$ to 1 hour to get the right. The result is that the left side is 95% of the right, well within allowable error for the finite difference program.