NATURAL CIRCULATION STABILITY

TMI-2

JUNE 29, 1979

by

S. H. Esleeck
J. E. Lemon

BABCOCK & WILCOX CO.

CONTENTS

1. INTRODUCTION

At 2:08 p.m. on April 27, 1979 at TMI-2 the single operating reactor coolant pump 2A was stopped and the natural circulation mode of reactor decay heat removal was initiated. Turbine bypass valves from the A-steam generator were opened and this was the predominant mode of heat removal. The B-steam generator valves were slightly opened with a small amount of heat removal. Approximately 11½ hours after the start of natural circulation, the B-steam generator turbine bypass valves were closed with only the A-steam generator steaming to the condenser -- a mode that continues to the present time.

An analysis was made by B&W during the week of April 30 (Reference 1) to provide a better understanding of the plant conditions during single loop natural circulation and to establish a basis for future decisions with regard to natural circulation. Reference 1 confirmed that the current operating mode is the most desirable and that "natural circulation will remain in a stable, well defined situation down to at least 0.5 MW." At the time Reference 1 was written, the decay heat level was approximately 2 MWt. Current estimates of decay heat show 0.5 MWt will occur about mid-September of this year. (See Figure 7).

Shortly after midnight on May 3, 1979 a perturbation occurred in the B-loop which was characterized by a rapid increase in the B-loop cold leg temperature of approximately 40^{o}F at which time it leveled off and proceeded to decrease to its original value over the next few days. At about 4:00 p.m. on May 7 the perturbation again occurred and has been repeated seven more times to date (May 10, 16, 18, and June 1, 8, 15, 24). Reference 2 was prepared on May 8 and explained the perturbation as brief circulation or "burping" of the B-loop due to cooldown of the B-steam generator. Prediction was made in Reference 2 that the B-loop perturbation would occur again and it did as noted above.

It is the purpose of this writeup to review the periodic circulation that occurs in the B-loop, to discuss its cause, and to review the expected long term characteristics of A-loop natural circulation with the objective of providing the operators with advance notice of significant changes that will be observed in the trend of reactor coolant system parameters compared to the trends observed since starting natural circulation.

2. DISCUSSION

Since April 27, 1979, removal of reactor decay heat has been achieved by natural circulation of the reactor coolant loop with heat transfer to the steam system primarily via the A-steam generator with final heat dump to the condenser. The A-steam generator is removing heat by boiling below atmospheric pressure with discharge to the condenser which is being held at approximately 1 psia vacuum. Feedwater is being supplied to the A-steam generator through the main feed nozzles by a main condensate pump which takes suction from the main condenser hotwell. Feedwater temperature ranges from 80 to 90F. The "A" loop is the primary heat transport loop with reactor coolant temperature being controlled via back pressure control from manual throttling of the turbine bypass valves.

When natural circulation was started on April 27, the reactor coolant temperatures were at approximately 225F (Thot Leg) and 222F (Tcold Leg). As shown in Figure 1 the reactor coolant temperature then decreased fairly rapidly over the next 4 to 5 days after which the trend was a more gradual decrease to 160F (Thot Leg) and 150F (Tcold Leg) on June 7. Since that time the reactor outlet temperature has been controlled at about 160F by adjusting the turbine bypass valves. The overall decrease in temperature since April 27 is due to a greater amount of heat being removed via the steam generator, insulation losses, leakage, etc. than the decay heat rate generated by the reactor.

Figure 1 shows an overall view of the pulsing that has occurred periodically since natural circulation was started. Figures 2, 3 and 4 provide more detail for each individual pulse while Figure 5, which is a plot from B&W reactimeter data shows very fine detail of the pulse that occurred on June 1. The pulsing is explained as follows:

> Just prior to the pulse, reactor coolant in the B-steam generator tubes has cooled via heat losses to the containment air so that it provides an adequate head for flow in the B-loop. The pulse is probably started by some perturbation (it would start more gradually on its own) and flow accelerates to a level several times the A-loop flow (See Item 3 in the Discussion). However,

this flow rapidly decreases due to hot reactor coolant water "siphoning" into the steam generator from the reactor outlet pipe making it a "light" downcomer and eliminating the natural circulation driving head.

The B-loop reactor coolant pump inlet leg risers are an important factor in the pulsing phenomena. These 28-inch pipes have a high surface to volume ratio (compared to the B-steam generator) which causes more rapid cooling in the pipes by heat losses. Also, a large portion of the pipes and the bottom of the steam generators (including their support structures) are submerged in reactor building water (See Figure 10). This submergence increases the total heat losses in this area by a factor of almost 70* compared to the pipe and support structure not being submerged. As a result of this additional cooling increasing the density in the cold leg riser, the B-steam generator acting as a downcomer must cool to a much lower temperature to overcome the weight of water in the cold leg riser. This "cooling" riser phenomenon makes the pulse more pronounced than would be expected with normal heat losses.

*Data from B&W's Alliance Research Center for Mirror Insulation indicates K (wet) = 13 $\frac{\text{BTU - IN}}{\text{HR - FT}^2 - {}^{0}\text{F}}$ K (dry) = 0.49 $\frac{\text{BTU - IN}}{\text{HR - FT}^2 - {}^{0}\text{F}}$ was scaled from full power operating can.

Figures 2, 3, and 4 were plotted to show detailed variations in important reactor coolant temperatures over the last two months to give a better insight to thermal behavior of the A and B-loops. By studying the temperature plots one can note certain interesting facts that not only highlight past behavior but provide indications of expected future trends:

(1) The difference between the A-loop hot and cold leg temperatures is decreasing with time. This is shown clearly in Figure 6 which contains a plot of temperature difference vs time. Using this plot of ΔT vs time and also the plot of decay heat vs time (Figure 7) one can calculate the A-loop natural circulation flow as a function of time (Figure 8). The decreasing natural circulation flow shown in Figure 8 will have a bearing on the future trend in reactor coolant system parameters as discussed later.

(2) Movement of water in the B-loop causes mixing of colder B-loop water with the A-loop water as evidenced by the reduction in both the cold and hot leg temperatures in the A-loops. Cycling of the A-loop temperatures typically continues for a few days following a pulse and then dampens out. Both the magnitude of the A-loop temperature change and the length of time of the cycling appear to be increasing with time. These factors are significant in estimating future natural circulation conditions as discussed later.

(3) After the onset of B-loop circulation, one B-loop cold leg temperature increases to a maximum value close to the temperature of the upper downcomer. This indicates that reactor coolant water in the steam generator at an elevation slightly below the upper downcomer thermocouple moves rapidly into the cold leg during the pulse. From this it can be concluded that the volume of reactor coolant displaced during the four* minute pulse is approximately 1200 cubic feet or an average flow of 2200 gpm, i.e. several times that of the A-loop.

(4) After onset of the pulse, one B-loop cold leg increases to a higher temperature than the other parallel leg. A reasonable explanation for this is that the resistance between the two parallel flow paths is not equal, possibly due to the pump impellers stopping at different positions, thus forcing unequal flow rates between the two flow paths.

(5) Both B-loop cold legs TC-B1 and TC-B2 (to a lesser degree) increase slightly just prior to the onset of B-loop circulation. This indicates that the B-loop circulates at a low rate prior to the onset of the pulse. Further indication of this is given by the steam generator downcomer temperatures which show increases reflecting the downward movement of the warmer reactor hot leg coolant into

*Determined from Figure 5.

the steam generator. It is believed that the increase in B-loop flow would be more gradual without the onset of a high flow rate except for perturbations which occur during system operation (See 6 below) and cause the onset.

(6) It is interesting to note the fact that most of the pulses start within an hour or so of shift change. No specific reasons for this have been found and, indeed, this could be purely coincidental. However, as discussed previously, it is probable that a perturbation occurs in the system to accelerate the pulse. It is possible that each shift operates the plant in a slightly different manner, such as batching in feedwater to the A-OTSG, batching makeup to the reactor coolant system when the pressurizer contained a steam bubble, or adjusting the turbine bypass valve position. Minor operating differences could provide the required initiating perturbation when the B-loop is at its maximum cooldown condition and already in an onset to pulsing.

(7) Initially, the pulses occurred in pairs with several days separating the pairs. However, more recently the pulses have occurred singly on a regular period of about a week apart. A logical basis for this may be that the plant is being operated in a more uniform manner between shifts, i.e. a systematic closing of turbine bypass valve, etc. Also, as noted in Figure 1 the overall containment temperature

has been increased within the past month which would tend to decrease the rate of heat loss from the B-steam generator. This means that a longer interval is required for the steam generator to cool sufficiently to provide the necessary driving head to cause the pulse. This forces the pulsing to be more regular with a longer interval between pulses.

(8) Figures 2, 3, and 4 show the increase of the B-loop steam generator shell thermocouples and downcomer temperatures during the pulse and the reduction due to cooling following the pulse. (See Figure 10 for the location of the thermocouples). These temperatures directly represent changes in the reactor coolant temperature in the steam generator tubes. Calculations have shown an approximate 7F to 8F difference between the steam generator shell temperature and the reactor coolant temperature.

As discussed earlier, the decrease with time of the A-loop hot leg to cold leg temperature difference will have a bearing on the future trend in reactor coolant system parameters. As this temperature difference decreases with time the density difference for driving the A-loop in the natural circulation mode also decreases. Calculation of the driving head for natural circulation in the A-loop has been made by B&W and is shown in Figure 9 as a function of time. Although the absolute values could vary depending on the analysis methods, the relative values would still show the decreasing trend (See Appendix A for the calculational method used in this study).

In an ideal natural circulation loop consisting of a single heated riser and a cooled downcomer one could predict with reasonable certainty that natural circulation would continue until the driving head becomes essentially zero. However, TMI-2 deviates from this ideal condition in two significant ways:

(1) The pump inlet leg is a cooling riser due to losses to the air and reactor building water. The impact of these losses tends to have a greater impact on A-loop cold leg temperature as the flow decreases with time.

(2) Pulsing in the B-loop causes temperature and flow cycling in the A-loop.

Because of these two factors it is difficult to estimate the exact time when significant changes will start occuring in the reactor coolant temperatures signifying a major deterioration in A-loop natural circulation flow. As an indicator of the margin that exists, the current driving head in the A-loop is about 0.023 psi (Figure 9) whereas the driving head in the B-loop between pulses when there is essentially zero flow is about 0.015 psi.

It is believed that certain cyclic behavior will be observed at TMI-2 before the A-loop natural circulation will actually stop. It is expected to be as follows:

- Following a pulse of the B-loop, the A-loop ΔT begins to cycle. In time, this cyclic behavior in the A-loop temperature should become more pronounced, i.e., of a greater magnitude and longer duration (as mentioned previously, early signs of this appear to be occurring now). Eventually the A-loop cyclic behavior will fail to converge to some steady state level before the next B-loop pulse and a continuous cyclic behavior will be established. An additional indication of deterioration in A-loop natural circulation flow is expected to be increasing separation of the A-loop cold leg temperatures following a B-loop pulse due to a difference in flow between the two A-loop cold legs. Indication that this is beginning can be seen on Figure 4 following the June 24 pulse. These two parallel legs in all likelihood have slightly different resistances (due to position of pump impellers, manufacturing tolerances, etc.) and as the overall driving head decreases with time, these different resistances become more significant. The difference in flows could become so great that the flow in one leg will stop due to the heat losses from this slower flowing leg increasing its density and causing it to lose its driving head.

There are several operational procedures that may extend the system stability and delay the onset of continuous cyclic behavior. However, it must be emphasized that this would only be a temporary measure. Some possible ways of extending system stability are:

(1) Increase the level of secondary water in the A-steam generator. This raises the thermal center and increases the natural circulation driving head. This advantage must be balanced against the possible problems associated with getting water into the main steam lines via instrument penetrations in the shroud.

(2) Open turbine bypass valves and allow average temperature to decrease. As the thermal level of the entire system approaches ambient temperature, the heat losses from the B-steam generator are reduced, therefore the time between the B-loop pulses will be increased. Also when a B-loop pulse does occur the water temperature from the B-loop cold leg will be closer to that of the A-loop and its effect will be reduced. In addition, as average temperature in the A-loop is reduced, the heat loss

through the submerged cold leg is reduced thus increasing the natural circulation driving head and making the A-loop less prone to cyclic behavior. (See the Recommendations section of this report for a more detailed discussion of cooling down the plant.

It should be emphasized that these are only temporary measures. The only certain way to avoid thermal instability over the long term is to switch from natural circulation to forced circulation of the reactor coolant system. This would involve the use of a decay heat removal system. B&W has recommended this via separate correspondence.

3. CONCLUSIONS

A. Natural circulation operation in the A-loop will deteriorate over the next few months, that is, the A-loop hot and cold leg temperature cycling which follows a pulse in the B-loop will increase in magnitude and duration. The A-loop parallel cold leg temperatures show increasing divergence following a B-loop pulse, which will eventually lead to actual flow stoppage or pulsing in one of the cold legs. The current temperature data indicates that these variations are already occurring and it is estimated that in a few weeks, by the end of August, they will have increased to the point where temperature cycling is well pronounced in both loops.

B. Certain changes in operation can delay the onset of severe temperature cycling, however, this is only temporary. Forced circulation through the reactor coolant system is the only certain way to avoid cycling.

C. Continued operation in the natural circulation mode with temperature cycling and pulsing in the A-loop should present no operating problems if the reactor coolant system pressure can be controlled within acceptable limits. Temperature cycling is not necessarily an indication of net thermal change in the system but rather a rapid transfer of large masses of water from one location to another.

4. RECOMMENDATIONS

To date B&W has been recommending maintaining hot leg temperature at or above 160°F by throttling the "A" side turbine bypass valves. This is based on the following considerations:

1) The density change per degree is larger between 160°F and 150°F than it is between, for example, 130°F and 120°F. Therefore the system can respond more quickly to thermal upsets (e.g. "B" loop pulses) at higher absolute temperatures. This is because at the lower temperatures larger ΔT's would have to develop to get the same driving head available at 160°F. Thus, larger swings in "A" loop temperature would result from "B" pulses.

2) Starting from 160°F provides a 60 ΔT down to saturation temperature at the existing condenser vacuum (2" Hg pressure). This has two benefical effects. First, this 60 degrees is available to cool the water in the B-OTSG and start natural circulation in that loop if it becomes necessary and, second, this large available ΔT improves the self regulating characteristics of the system. The logic is as follows: Any system upset which results in a reduction in primary flow through the A-OTSG will reduce the heat available at that time to be transferred to the steam. This will result in less steam generation (less steam flow), and correspondingly less pressure drop between the steam generator and the condenser. In the limit this means the steam generator could cool the primary fluid all the way down to saturation temperature for the existing condenser vacuum.

This colder primary water increases the driving head for natural circulation and this increases flow again.

3) Another reasons for maintaining hot leg temperature at about 160°F is to provide enough driving head for the main steam Bypass line drain traps to flow to the condenser.

These reasons are still valid; however, as a result of this study it has become apparent that there are also counter reasons for opening the turbine bypass valves and allowing average temperature to decrease.

1) As the thermal level of the entire system approaches ambient temperature, the heat transfer rate from the B-OTSG is reduced; therefore the time between B pulses will be increased. Also, when it does pulse the water temperature from the B cold leg will be closer to that of the "A" loop, and its effect will be correspondingly reduced.

2) As average temperature in the "A" loop is reduced the heat lost through the portion of the "A" loop cold legs and steam generator that is under the reactor building water level is reduced. As the influence of this competitive heat sink is reduced the heat available for transfer out the steam generator is increased. Therefore, smooth operation of "A" loop natural circulation is more probable.

The tradeoff here is this, at lower average temperatures the system response to thermal upsets is more sluggish, however, these upsets (i.e., B-loop pulses) are less likely to occur.

Also, the limited increase in smooth operation of natural circulation gained by lowering average temperature must be weighted against the increased risk of water hammer if the main steam Bypass traps fail to function at the lower driving heads. JDM

B&W recommends that hot leg temperature be maintained at $160^{o}F$ by throttling the turbine bypass valves as necessary. When control with the bypass valves is no longer effective, consider opening these valves as necessary to permit smooth operation of natural circulation. This will drop the average temperature in the "A" loop. Monitor for water hammer in the "A" main steam Bypass line~~s~~. If water hammer becomes unacceptable throttle down on the bypass valves and accept cyclic operation of natural circulation until the long term decay heat removal system is put in operation. JDM

Apparent meaning:
When the B pulses too frequently and the recovery of natural circulation in A loop becomes too sluggish ....

JDM

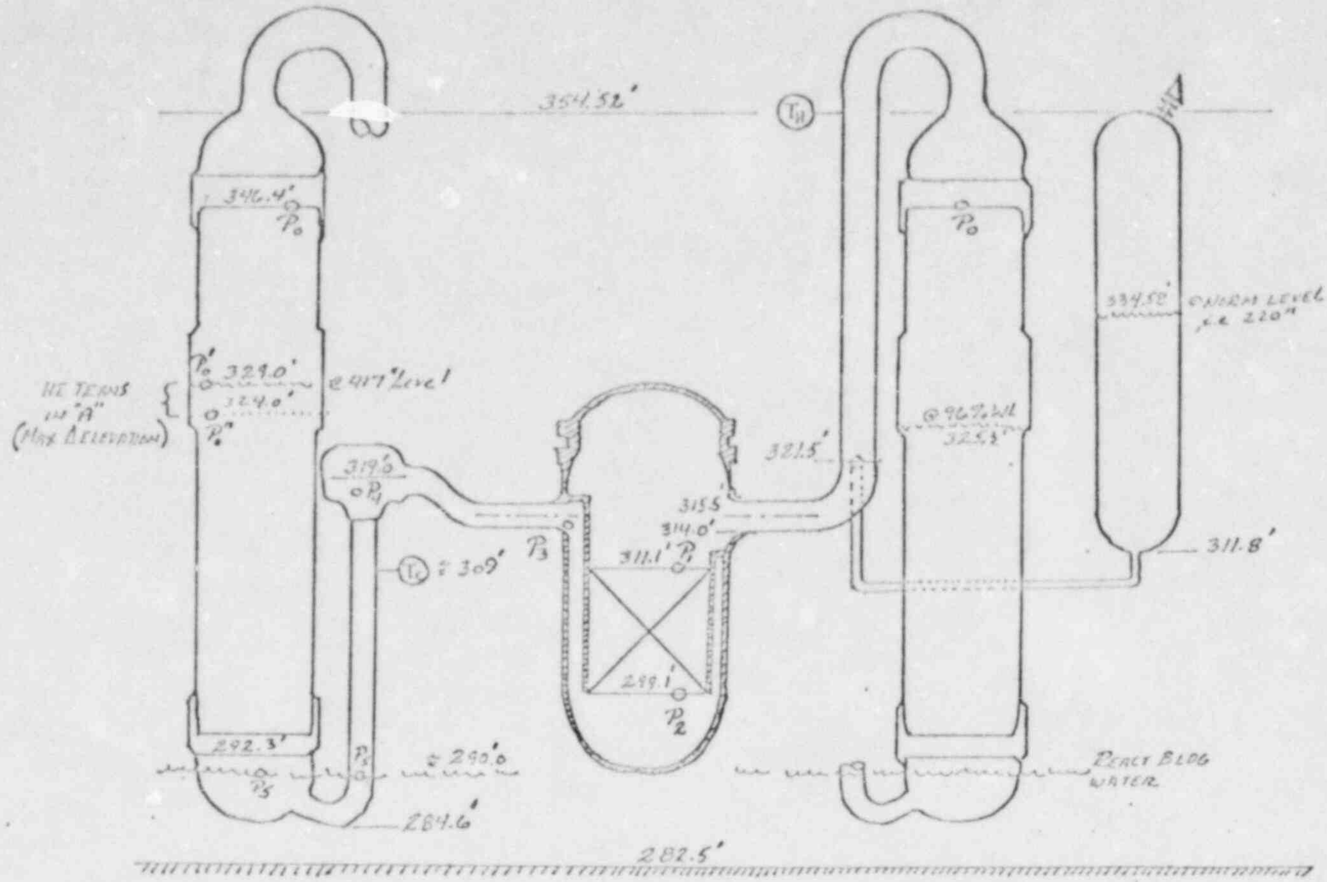
5. REFERENCES

1. "Transicion to Natural Circulation at TMI-2", B. A. Karrasch and J. J. Kelly, Babcock & Wilcox, May 3, 1979 (Forwarded to Mr. R. Wilson, GPU, in a letter dated May 3, 1979 from G. E. Kulynych).

2. Handwritten letter dated May 8, 1979 from J. E. Lemon, Babcock & Wilcox, to R. F. Wilson, GPU; Subject: Possible Cuase of "B" Loop Temperature Perturbations.

6. APPENDIX A

CALCULATIONAL METHOD FOR NATURAL CIRCULATION DRIVING HEAD



AVAILABLE HEAD FOR NAT. CIRC. = ΔP_{DYN} = Σ DOWNCOMERS − Σ RISERS = psi

RISERS:

$$P_2 - P_1 = \left(\frac{311.1 - 299.1}{v_{2-1}}\right)\frac{1}{144} = \frac{0.08333}{v_{2-1}}$$

$$P_1 - P_0 = \left(\frac{346.4 - 311.1}{v_{1-0}}\right)\frac{1}{144} = \frac{0.2451}{v_{1-0}}$$

$$P_5 - P_4 = \left(\frac{319.0 - 290.0}{v_{5-4}}\right)\frac{1}{144} = \frac{0.2014}{v_{5-4}}$$

DOWNCOMERS

OTSG:

$$P_5 - P_0'' = \left(\frac{324.0 - 290.0}{v_{5-0''}}\right)\frac{1}{144} = \frac{0.2361}{v_{5-0''}}$$

$$P_0'' - P_0' = \left(\frac{329.0 - 324.0}{v_{0''-0'}}\right)\frac{1}{144} = \frac{0.0347}{v_{0''-0'}}$$

$$P_0' - P_0 = \left(\frac{346.4 - 329.0}{v_{0'-0}}\right)\frac{1}{144} = \frac{0.1208}{v_{0'-0}}$$

$$P_3 - P_4 = \left(\frac{319.0 - 314.0}{v_{3-4}}\right)\frac{1}{144} = \frac{0.0347}{v_{3-4}}$$

$$P_2 - P_3 = \left(\frac{314.0 - 299.1}{v_{2-3}}\right)\frac{1}{144} = \frac{0.10353}{v_{2-3}}$$

FOR "A" LOOP, ASSUME ALL HT TRANS AT W.L. (ZERO HT LOSS)

$$\Delta P_{DYN} = \left(\frac{329.0 - 299.1}{v_{COLD}}\right)\frac{1}{144} - \left[\left(\frac{311.1 - 299.1}{v_{AVG}}\right)\frac{1}{144} + \left(\frac{329.0 - 311.1}{v_{HOT}}\right)\frac{1}{144}\right]$$

$$\Delta P_{DYN} = \frac{0.20764}{v_{COLD}} - \frac{0.08333}{v_{AVG}} - \frac{0.12431}{v_{HOT}}$$

with specific volumes @

v_{COLD} @ T_{COLD-A}

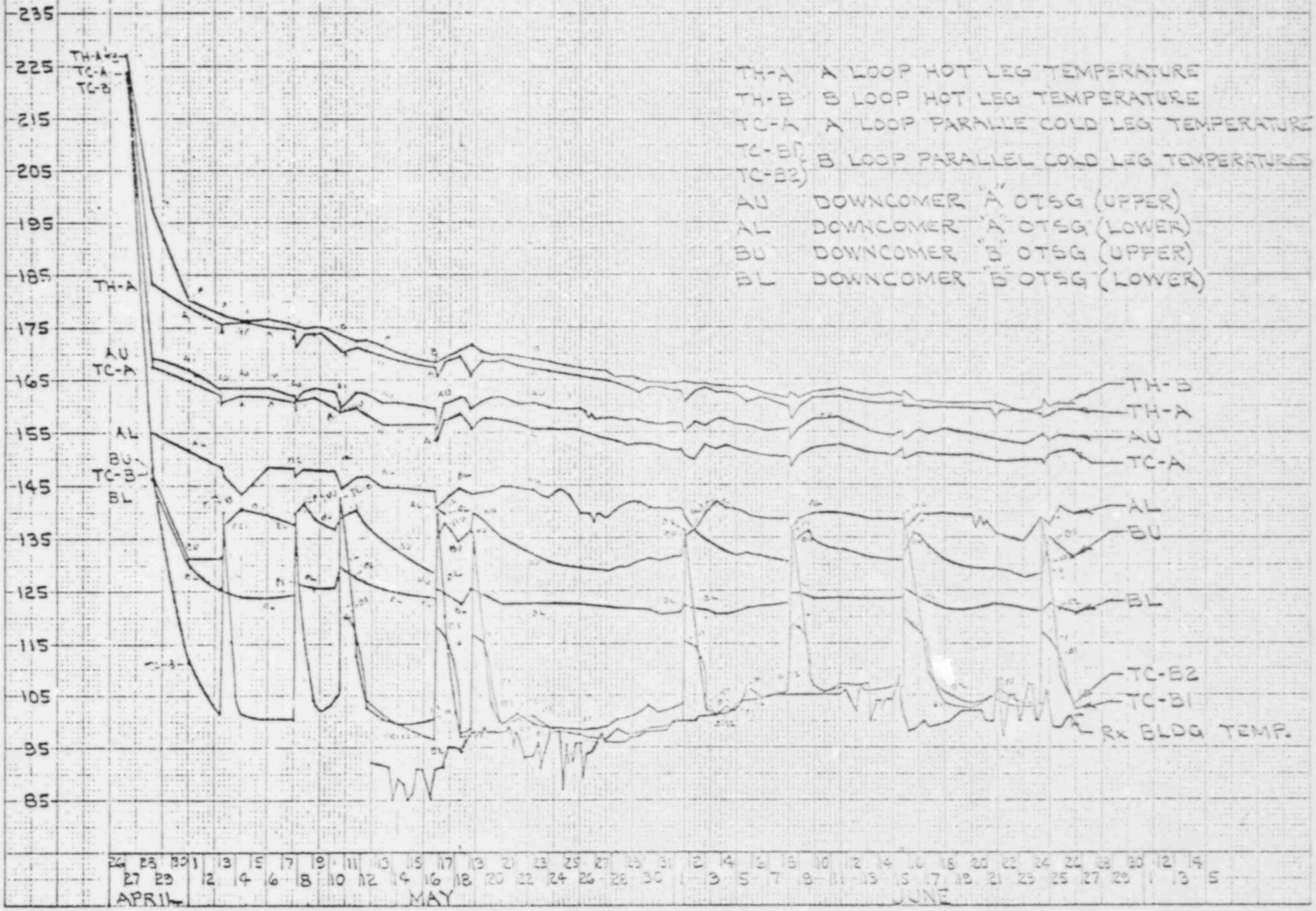
v_{HOT} @ T_{HOT-A}

v_{AVG} @ $\frac{T_{COLD-A} + T_{HOT-A}}{2}$

7. FIGURES

10 X 10 TO THE CENTIMETER 46 1510
18 X 25 CM. MADE IN U.S.A.
KEUFFEL & ESSER CO.

FIGURE 1 OVERALL TMI-2 TEMPERATURE PROFILE



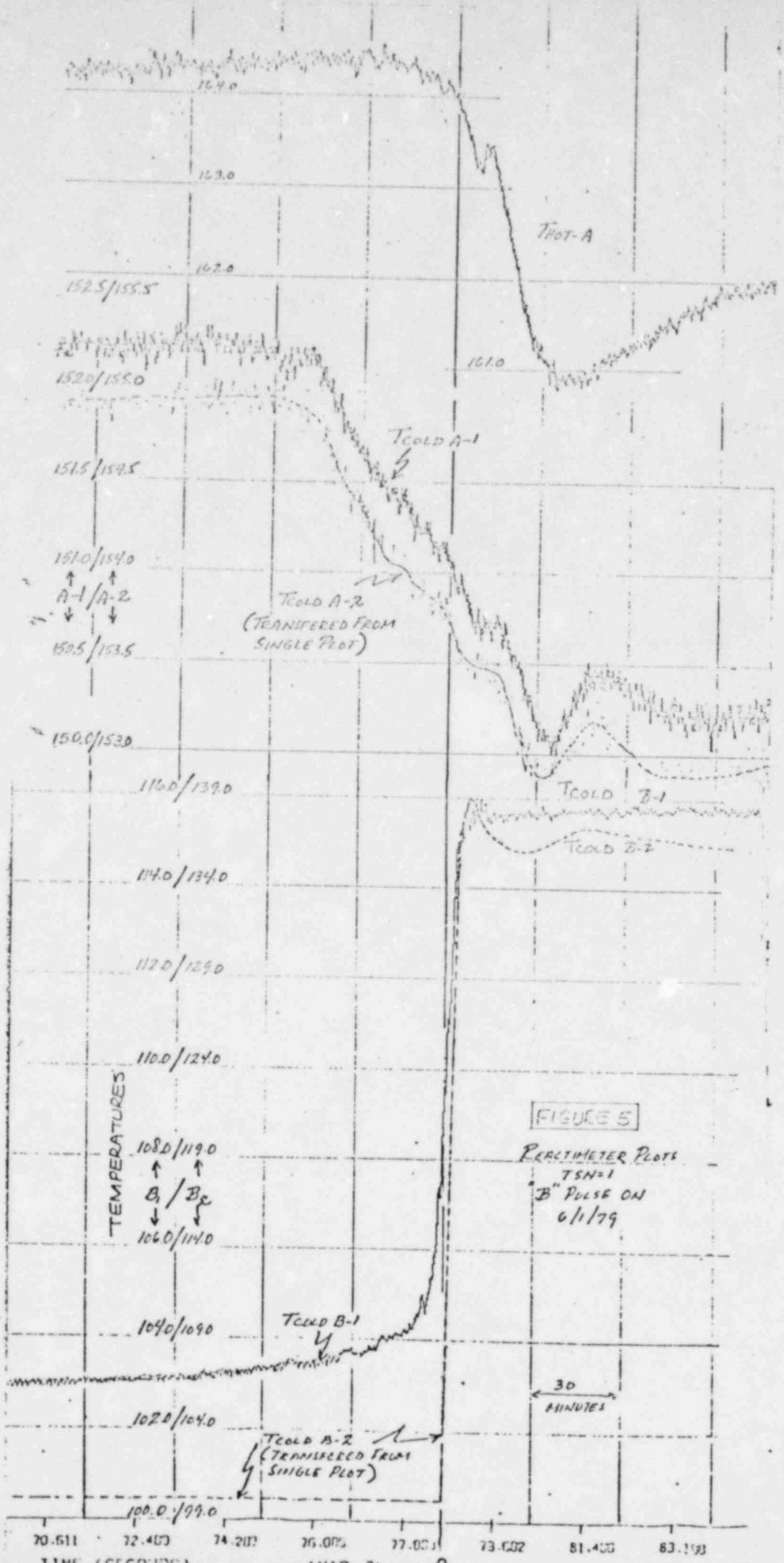
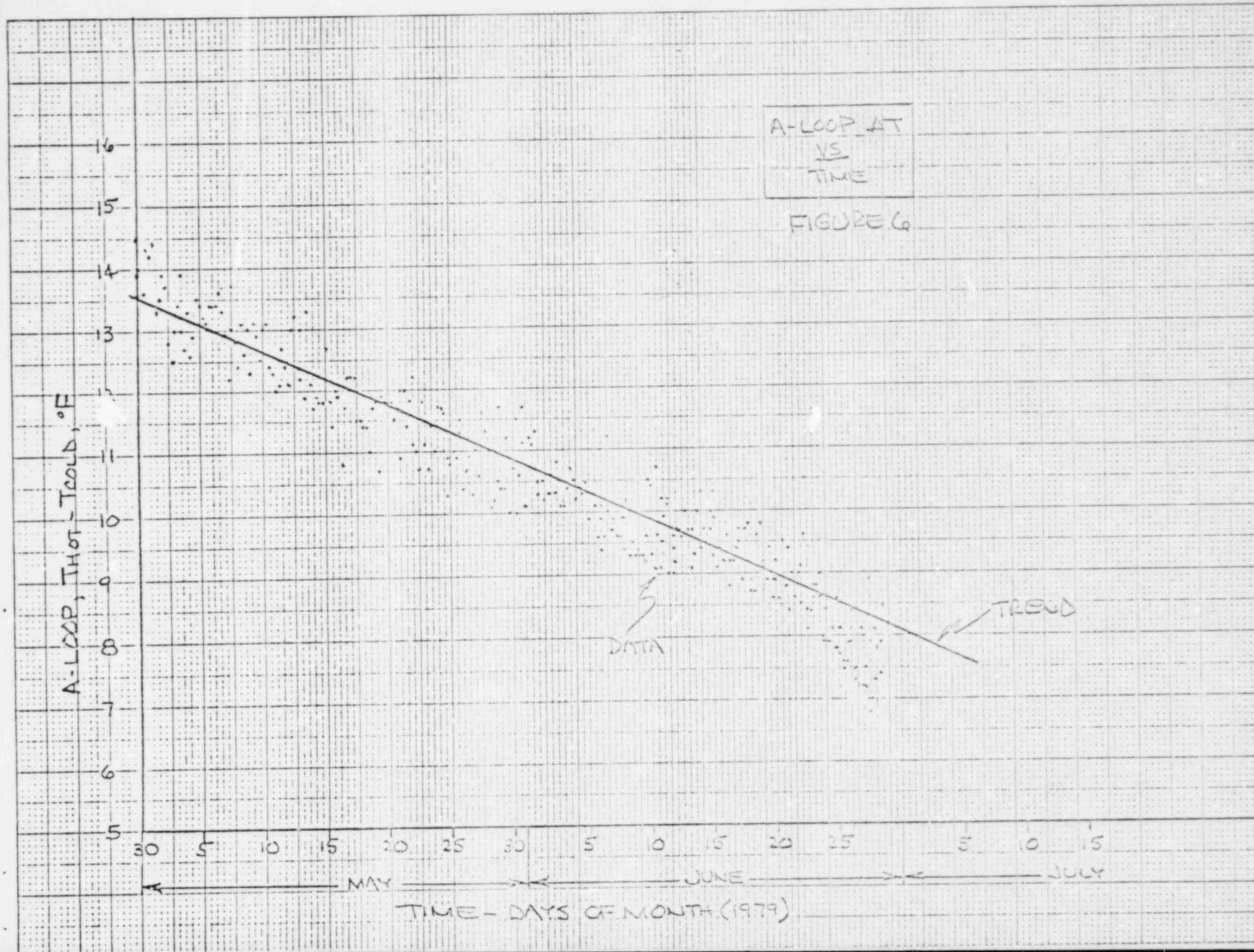


FIGURE 5

Reactimeter Plots
TSN=1
"B" Pulse ON
6/1/79

46 1470


A-LOOP ΔT
VS
TIME
FIGURE 6
A-LOOP, THOT - TCOLD, °F
16
15
14
13
12
11
10
9
8
7
6
5
30
5
10
15
20
25
30
5
10
15
20
25
5
10
15
MAY
JUNE
JULY
TIME - DAYS OF MONTH (1979)
DATA
TREND

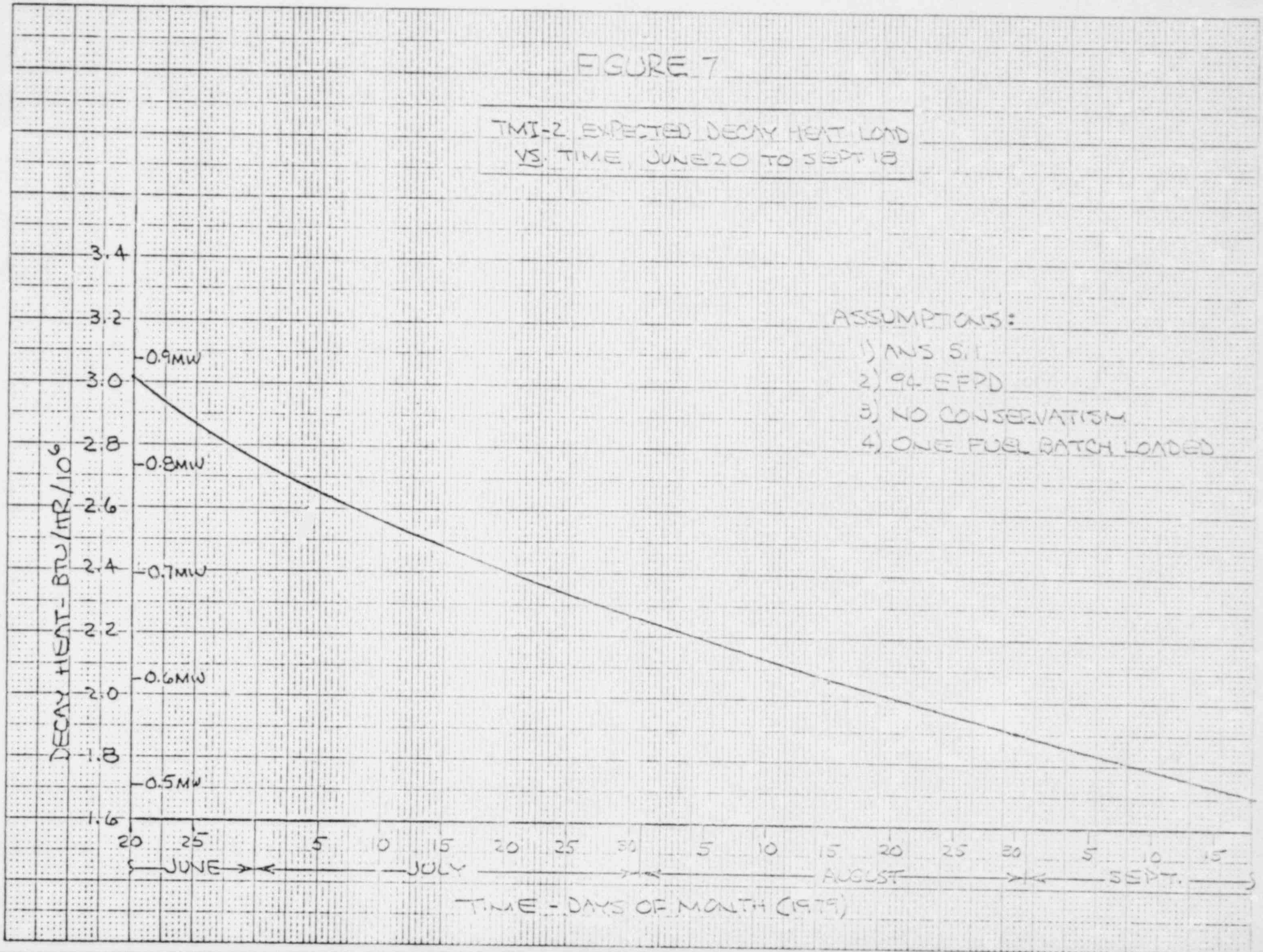
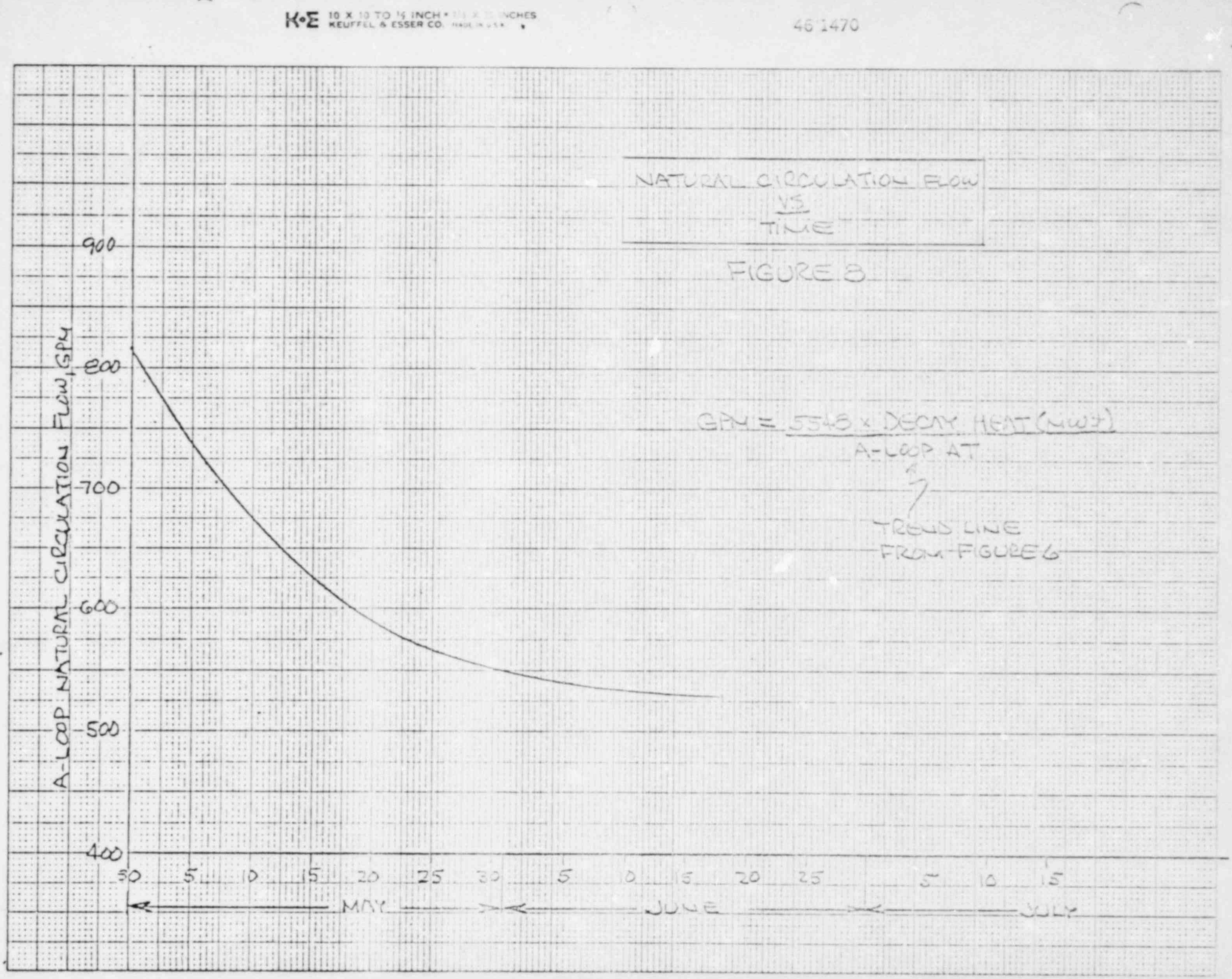
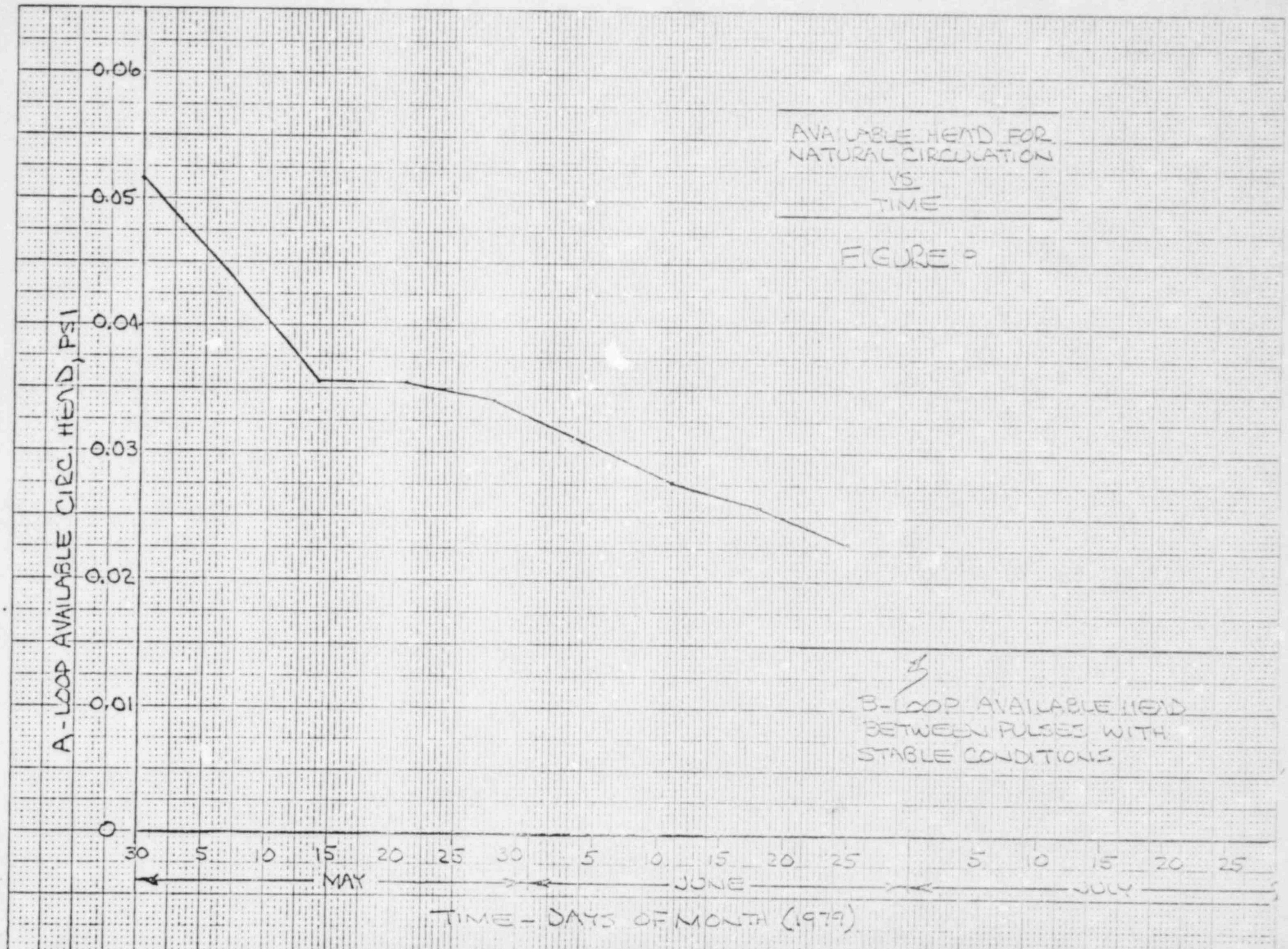


FIGURE 7
TMI-2 EXPECTED DECAY HEAT LOAD
VS. TIME JUNE 20 TO SEPT 18
ASSUMPTIONS:
1) ANS 5.1
2) 94 EFPD
3) NO CONSERVATISM
4) ONE FUEL BATCH LOADED
DECAY HEAT - BTU/HR/10^6
3.4
3.2
3.0
2.8
2.6
2.4
2.2
2.0
1.8
1.6
0.9MW
0.8MW
0.7MW
0.6MW
0.5MW
20 25 5 10 15 20 25 30 5 10 15 20 25 30 5 10 15
JUNE
JULY
AUGUST
SEPT.
TIME - DAYS OF MONTH (1979)


K•E 10 X 10 TO ½ INCH
KEUFFEL & ESSER CO.
46 1470
NATURAL CIRCULATION FLOW
VS
TIME
FIGURE 8
GPM = 5545 x DECAY HEAT (MWt)
A-LOOP AT
TREND LINE
FROM FIGURE 6
A-LOOP NATURAL CIRCULATION FLOW, GPM
900
800
700
600
500
400
30
5
10
15
20
25
30
5
10
15
20
25
5
10
15
MAY
JUNE
JULY

K•E 10 X 10 TO ½ INCH • 7½ X 10 INCHES KEUFFEL & ESSER CO. MADE IN U.S.A.

46 1470



ARRANGEMENT OF TMI-2 REACTOR COOLANT SYSTEM