American Nuclear Society,
Conference on Problems of
Operating Research and Power
Reactors
Ottawa, CANADA
October 21-23, 1963

Atomic Energy of Canada Limited
Chalk River Nuclear Laboratories

Operations Division

Extending Reactor Time-to-Poison and Reducing Poison Shutdown Time by Pre-Shutdown Power Alterations

Edward Kerr

Presented at the ANS Conference on Problems of Operating Research and Power Reactors, October 21-23, 1963 at Ottawa, Ontario.

DISCLAIMER

The cost of shutting down and poisoning-out of a high flux reactor, either a research or power reactor, is high. For example, the revenue from a 200 MW_e power reactor which produces electricity at cost at 5 mills/kWh is $1000/hr. Since only the fuelling costs of about 1 mill/kWh cease when this reactor is shut down, it follows that reactor down time costs about $800/hr. A poison-out for this reactor will last upwards of 30 hours and cost over $25,000.

Some reactor poison-outs, indeed most of them, are inevitable. They begin with a component failure which either trips the reactor or necessitates an immediate shutdown and which cannot be repaired before the increase of xenon-135 makes start-up impossible. There are, however, some faults which, while requiring early attention, do not require immediate attention. In such cases, it is worth considering manipulating the reactor power prior to shutting down and increasing the time-to-poison a sufficient amount to enable the required maintenance work to be completed and the reactor immediately re-started. This procedure, while eliminating the lost production resulting from the poison-out, will itself entail some lost production. The problem is therefore to gain the maximum time-to-poison with the least production loss.

There is, unfortunately, no direct mathematical solution to this problem. The method employed in NRU for achieving this result which is called "the maximum xenon method" is based on intuition. Because of its non mathematical nature it is described by means of an analogue of the iodine-xenon equations rather than the equations themselves.

(first slide)

Here we have the iodine and xenon equations written in terms of reactivity (in this case milli-k) and power (in MW) for the NRU reactor. This is the form most convenient for routine operational calculations. It should be mentioned that iodine is not a reactivity load although given in reactivity units -- but rather a potential reactivity load.

In the analogy we see that iodine production is proportional to power and decay is proportional to the static head, i.e. the amount of iodine in the tank. The decaying iodine provides the inlet to the xenon tank, while there are two outlets from the xenon tank -- one is the straight xenon decay, while the other represents the xenon burn off. The latter is the capture of a neutron by a xenon-135 atom to form xenon-136 and this is proportional to both reactor flux or power, and the head in the xenon tank or xenon concentration.

The equilibrium iodine level varies directly with reactor power -- if the flow into the iodine tank were increased, the head would increase until there was a porportional increase in flow from the iodine tank. This does not hold for the equilibrium xenon level, since the flow out of the tank is power dependent as well as the flow into the tank, and for high fluxes (greater than 10^{13}) the equilibrium xenon level is more or less independent of reactor power.

Now let us look at what happens when the reactor power is reduced to zero after equilibrium values of xenon and iodine have been reached. Initially, the flow from the iodine to the xenon tank remains the same as it was before the reactor shutdown, while the flow out is greatly reduced since the power modulated valve on the outlet has closed. Therefore, the xenon level begins to rise. If the reactor is not re-started in a fairly short time, the concentration of xenon is so great that it absorbs too many neutrons and a chain reaction is not possible. When this happens, the reactor is said to be poisoned out, and it is necessary to wait until the xenon level increases then decays back to the poison out level before the reactor can be re-started. The resulting transient for NRU when shutdown from equilibrium at 200 MW is shown on the second slide (fig. 2).

The two terms which we use, time-to-poison and poison shutdown time are shown. It will be noticed that poison shutdown time also includes the time-to-poison. For NRU the equilibrium xenon load is about 33 milli-k. The slides shows that for a xenon poison out level of sixty milli-k, the time-to-poison is about 0.9 hrs. and the poison shutdown time is 35 hrs.

(fig. 1 again)

Returning to the hydraulic analogy, we can see that the time-to-poison depends on the xenon level, and that the time-to-poison would be increased if we could reduce the xenon level before shutting down, because a larger rise in xenon could take place before poisoning out occurred. The time-to-poison would also be increased if we decreased the iodine level, because the speed at which the xenon level rises following a shutdown depends directly on this quantity.

Beginning with a reactor in equilibrium at full power, we see that we cannot alter power in a way to lower the xenon level, at least initially, because this can only be done by further opening the outlet valve which means running at some power greater than full power. It is therefore necessary to begin by lowering the iodine level which means lowering power. However, the amount of power decrease is limited by the xenon level which will rise when power is lowered, and therefore no power decrease can occur which raises the xenon above the poison out level. There are, however, advantages to having the xenon level high, since this increases the rate of flow out of the xenon tank. In other words, the maximum level means the maximum rate of removal from the two tank system. This was also felt to be that which would give the least loss in production, and it might be added that none of the other power patterns which we have attempted have as yet disproved this.

Suppose that, having operated at reduced power for some time, we have effected a considerable reduction in iodine but we still have xenon close to the poison-out level. If we are to have any increase in time-to-poison it will be necessary to lower the xenon level. This can be done if full power operation is resumed, since the effect of the fast burn off of xenon will at first more than offset the effect of the increase in iodine on the time-to-poison when the reactor is finally shut down.

It was consideration of the foregoing that led to the "maximum xenon method" of extending time-to-poison which appears to give the least production loss during the pre-shutdown power alterations. This method is as follows:

Figure 3 gives all the steps

1. The reactor is shutdown, and then restarted just before it poisons out.

2. It is run at a power which holds the xenon level at this high value. Initially for NRU this power will be about half power. The exact level will depend on the poison out level, i.e. the reactivity available for poison over ride. This power is gradually lowered as time goes on to keep the xenon at the maximum permissible level.

3. When calculations indicate that the iodine is lowered sufficiently, full power operation is resumed for a period of about two hours. The exact length of time again depends on the time-to-poison required and the reactivity available. At the end of this time the reactor is shutdown and the required maintenance work performed.

In the example given, the time-to-poison is increased from its equilibrium value of .9 hours to 1.9 hours. The total time to bring this about is 11.7 hours.

An investigation of the way in which the production lost in the pre-shutdown power alterations varied with the level at which xenon is maintained during the operation at reduced power showed that the lowest production losses were incurred when the xenon was kept within one or two milli-k of the poison out level. If this safety margin were increased to three or four milli-k, the increased loss in production is not serious (perhaps 50 to 100 MWH for NRU), but it is sufficient to indicate that the "maximum xenon method" may indeed be the optimum. As this margin is increased further the loss in production increases markedly.

As a guide for judging when it is advantageous to extend the time-to-poison of the NRU reactor, a computer program was prepared which simulates this maximum xenon power alteration. The results are shown on the next slide.

(fig. 4)

As an example of the use of these curves, suppose that the poison out level was at 60 milli-k (i.e. 27 milli-k available for poison over-ride and 33 milli-k of equilibrium xenon). Under these conditions, the reactor would poison out following a shutdown from equilibrium in .9 hours and the poison out production loss would be 6880 MWh. Suppose a time-to-poison of 2.0 hours were required. Using the maximum xenon method, the lost production (including the final shutdown) is about 1600 MWh. Since this represents a considerable saving, (over 5000 MWh), it might well be advantageous to alter power in this manner prior to shutting down.

The reason such a large range of xenon poison out levels are given on this graph is because large load changes frequently occur in NRU due to the demands of research and isotope production. The curve for a 40 milli-k poison out level is shown because it approximates the design value for poison over ride in NPD.

Of course, the xenon equations for NPD are different because of differing flux in the fuel.

The same pre-shutdown power alterations may be performed to reduce the poison shutdown time rather than extending the time-to-poison. Reducing the poison shutdown time is worth considering for jobs which require ten or twenty hours of reactor down time. The pre-shutdown power pattern is identical to that for extending time-to-poison except that the final period of full power operation is reduced from about two hours to about one quarter hour. This stems from the fact that the xenon level at the time of shutdown contributes less to the poison shutdown time than it does to the time-to-poison.

The results for reducing poison shutdown time for the same poison out levels as in the previous curves for extending time-to-poison are given in fig. 5.

The results are not as spectacular as for extending time-to-poison, but it may at times be possible to save the equivalent of five or six hours full power operation and at $800/hr. this is not insignificant.

Returning to the first part of the power pattern for both extending time-to-poison and decreasing poison shutdown time, the example shown was for a complete shutdown until xenon was up to its maximum level, followed by operation at a power which held the xenon at this level. In other words, the xenon was raised up to just below the poison out level as quickly as possible. This part of the power pattern was investigated by Amnon Einav of the Isreal A.E.C. during a one year assignment to NRU. He found that it was not necessary to shut the reactor down completely at this point in order to minimize the lost production, but merely to operate at some reduced power. The production loss was essentially independent of the power chosen until xenon was raised to its maximum level. However, the time from the beginning of power alterations until the final shutdown increased with an increase in the power chosen during this initial period.

The power which is initially chosen will therefore depend on the circumstances. If, for example, the reason for the shutdown is to repair a heavy water leak then it may be that the complete shutdown will be chosen initially to minimize the time until the leak can be repaired and thus minimize the loss of heavy water. On the other hand, if the leak is thought to be temperature dependent then the contraction which accompanies the reduction in temperature when the reactor is shut down could cause the leak rate to increase drastically. In such circumstances, some higher power would be chosen for the initial stage of the pre-shutdown power alterations.

In closing, I would like to say that the extensive investigation of a reactor's xenon transients and the preparation of curves such as those which I have shown for NRU involve considerable work, and yet the results are only applicable to a restricted range of conditions. However, if just one reactor poison out is avoided, the effort will be more than justified.

2976-E

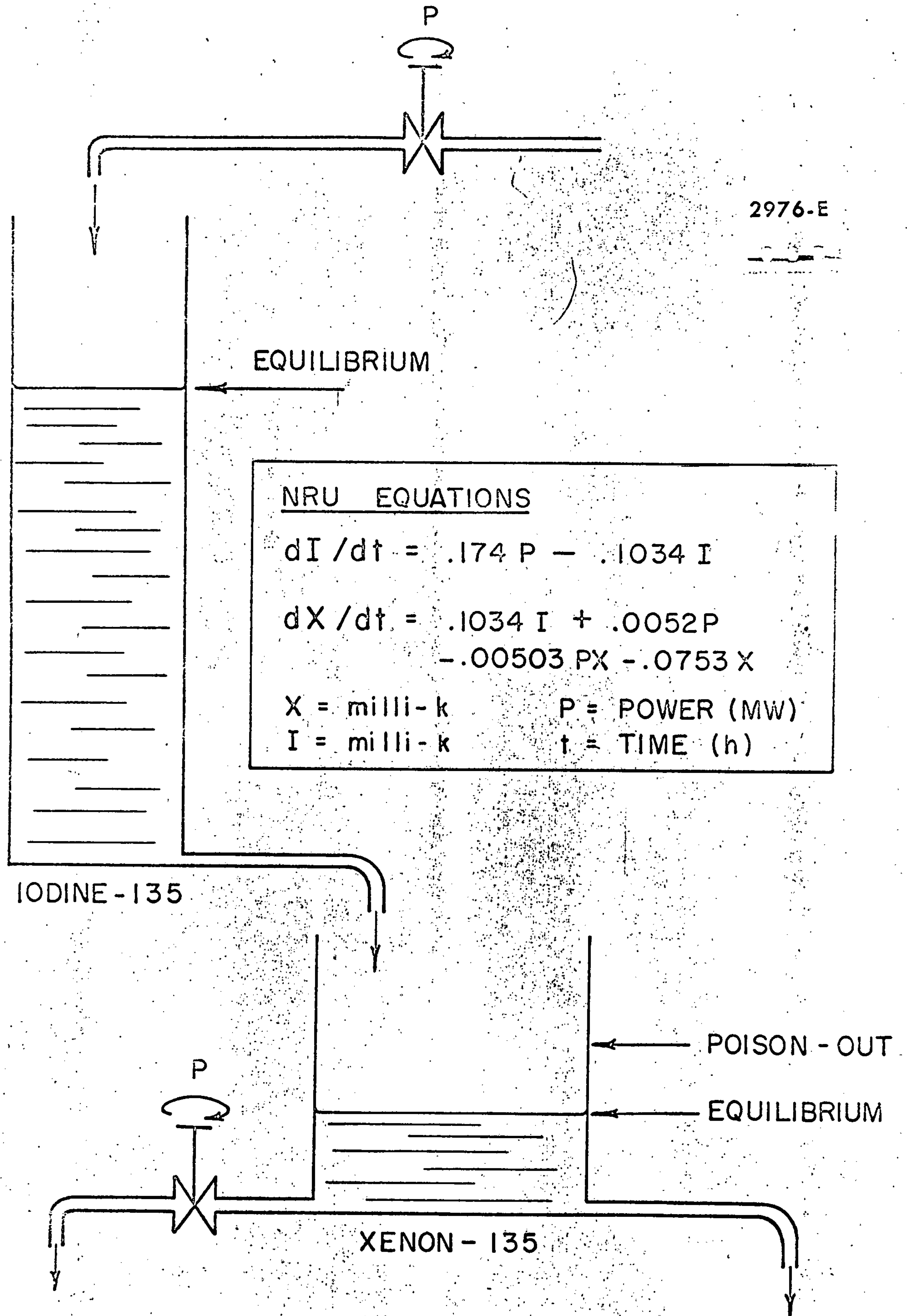


FIG. 1
HYDRAULIC ANALOGY

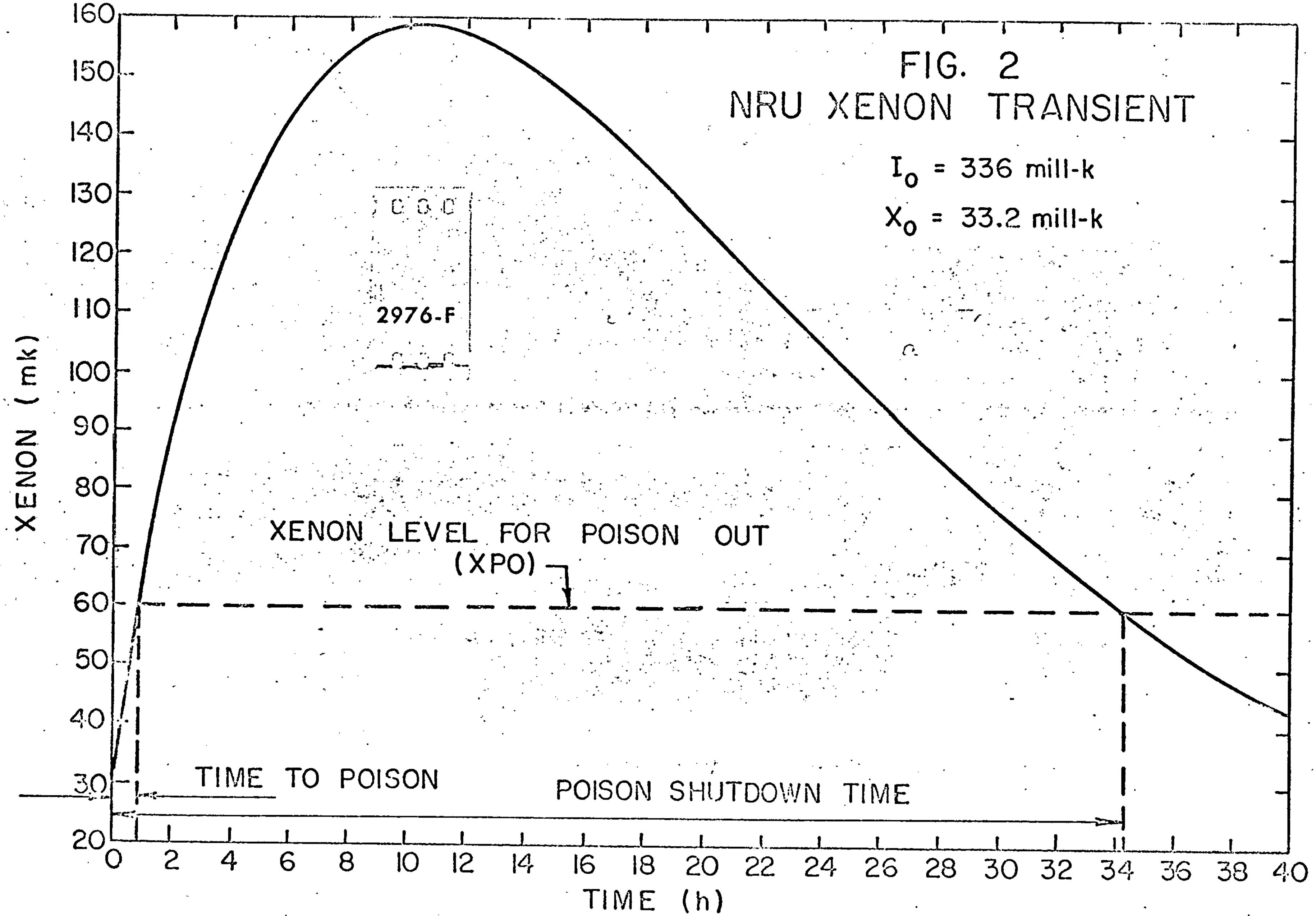
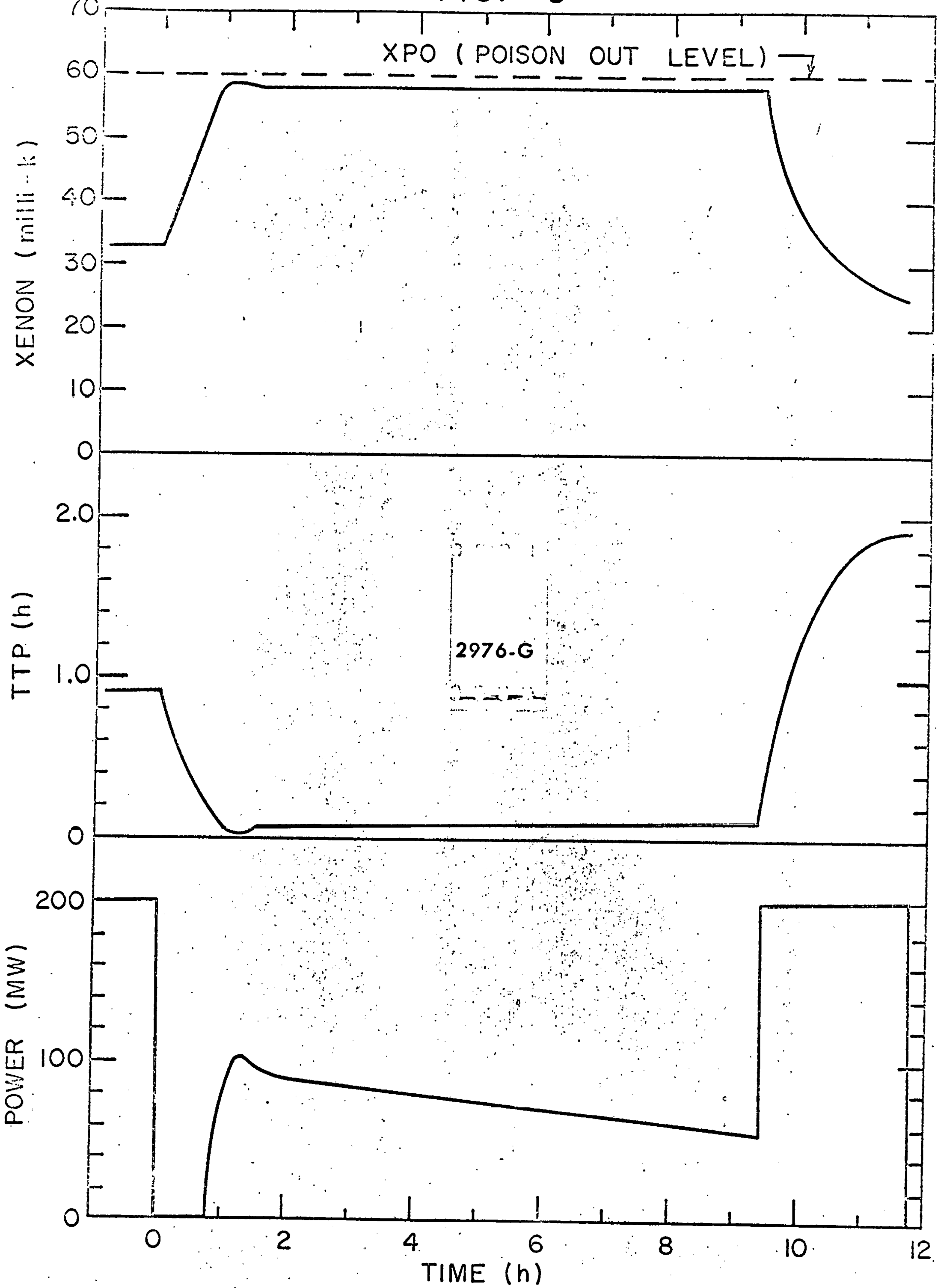


FIG. 2

NRU XENON TRANSIENT

FIG. 3



XPO (POISON OUT LEVEL)
XENON (milli - k)
70
60
50
40
30
20
10
0
TTP (h)
2.0
1.0
0
2976-G
POWER (MW)
200
100
0
0
2
4
6
8
10
12
TIME (h)

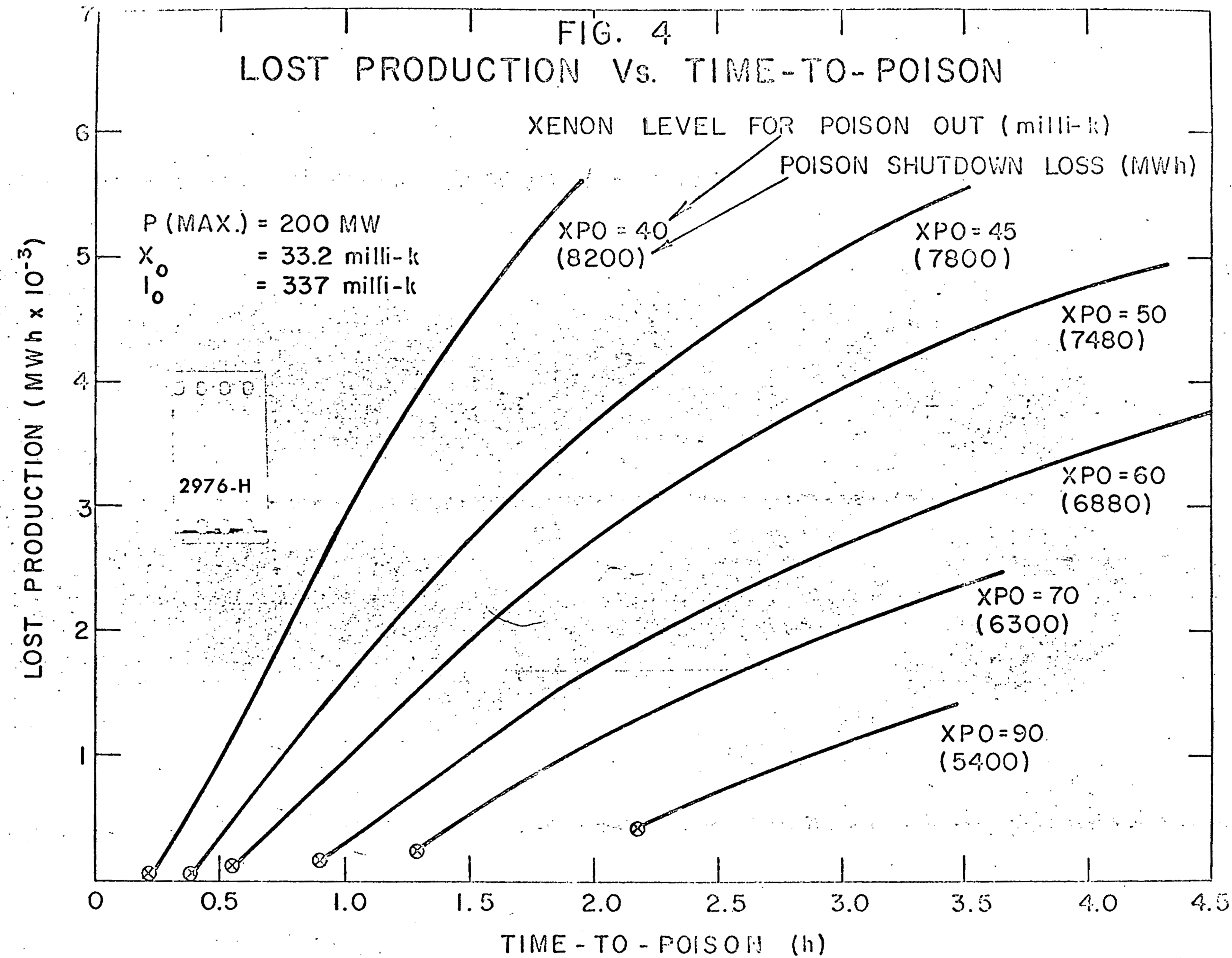


FIG. 4
LOST PRODUCTION Vs. TIME-TO-POISON
XENON LEVEL FOR POISON OUT (milli-k)
POISON SHUTDOWN LOSS (MWh)
P (MAX.) = 200 MW
X_o = 33.2 milli-k
I_o = 337 milli-k
XPO = 40
(8200)
XPO = 45
(7800)
XPO = 50
(7480)
XPO = 60
(6880)
XPO = 70
(6300)
XPO = 90
(5400)
2976-H
LOST PRODUCTION (MWh x 10^{-3})
TIME-TO-POISON (h)
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
1
2
3
4
5
6
7

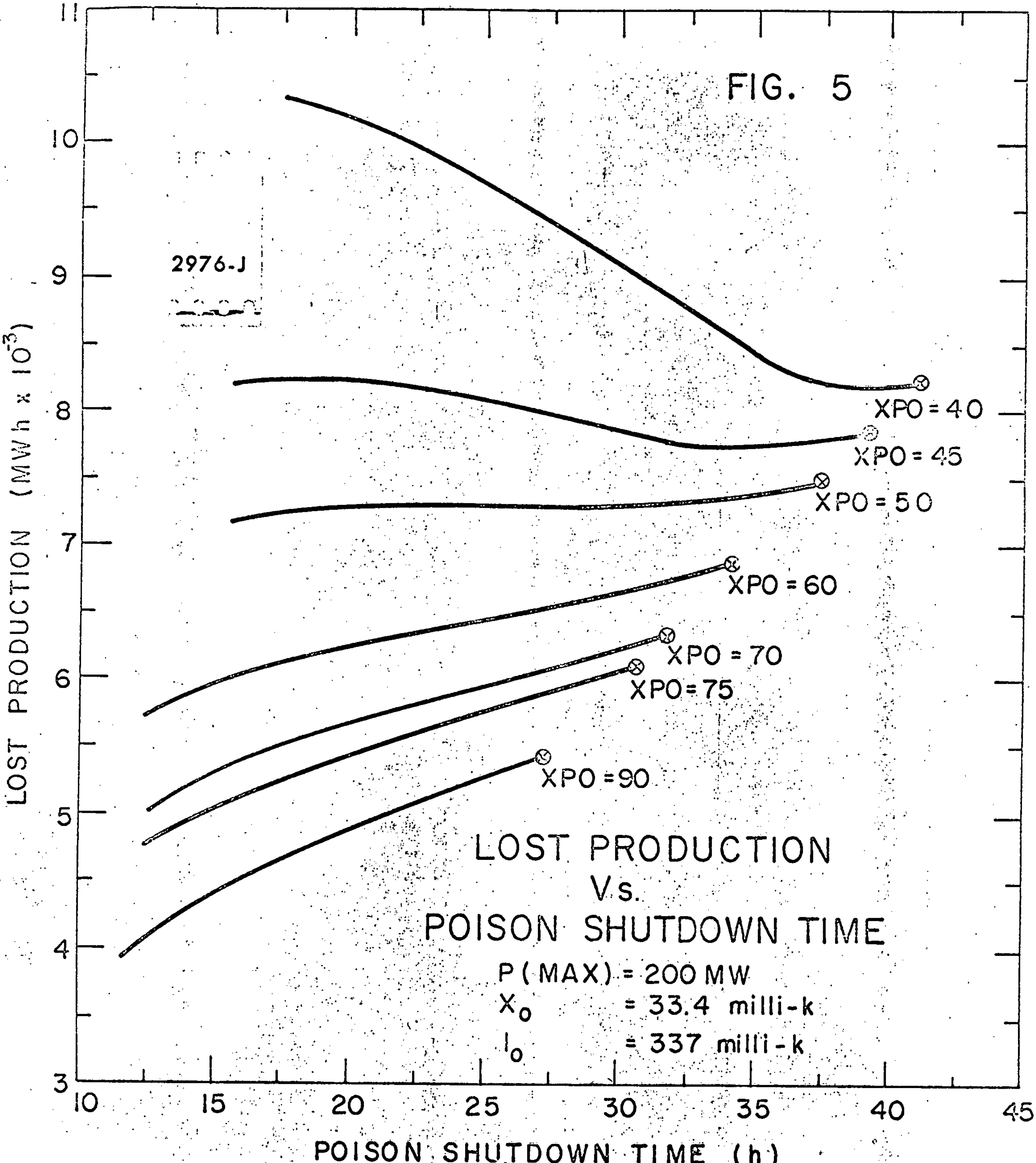


FIG. 5
2976-J
LOST PRODUCTION (MWh x 10^-3)
POISON SHUTDOWN TIME (h)
XPO = 40
XPO = 45
XPO = 50
XPO = 60
XPO = 70
XPO = 75
XPO = 90
LOST PRODUCTION
Vs.
POISON SHUTDOWN TIME
P (MAX) = 200 MW
Xo = 33.4 milli-k
Io = 337 milli-k
3
4
5
6
7
8
9
10
11
10
15
20
25
30
35
40
45