Reactor, Boiler & Auxiliaries - Course 233

MODERATOR LIQUID POISON SYSTEM *

I. PURPOSE OF SYSTEM

This system is used to control the reactivity worth of the moderator and hence the overall reactor reactivity, by the addition of soluble neutron poisons (neutron absorbers) to the moderator.

The moderator may be poisoned for any of the following purposes:

(a) To compensate for excess fuel reactivity for the first 200 full power days of operation in a reactor, loaded with a fresh fuel charge. This is sometimes called *fresh fuel burnup simulation*.

(b) To compensate for the lack of Xe negative reactivity (up to 28 mk worth) following a shutdown of about 30 hours or greater. This is sometimes called a *Xe simulation*, or a *Xe equilibrium load simulation* if the full 28 mk Xe loaded at full power is referred to.

(c) To overpoison (maintain highly sub-critical) the reactor during a shutdown. Overpoisoning is one of the operations necessary to obtain a guaranteed shutdown state on reactors without a dump tank.

(d) To compensate for reactivity due to overfuelling. This is sometimes called fuelling machine reactivity shim control or reactivity banking. (Overfuelling may be done deliberately in anticipation of a F/M outage. Without poison shim additions, the average zone level due to high excess reactivity may be higher than the normal control range).

* Do not confuse this system with the Liquid Poison Injection System. (SDS2)

II. ADVANTAGES AND DISADVANTAGES OF A POISON REACTIVITY CONTROL SYSTEM COMPARED TO A MECHANICAL ROD REACTIVITY CONTROL SYSTEM

(a) As the poison(s) used are soluble in the moderator D_2O, the reactivity effect is homogeneously distributed in the calandria. As a result there are no localized neutron flux distortions (which a rod system would produce) with the potential to cause fuel failures.

(b) The operating equipment can be located outside containment, where it is accessible even when the reactor is on power.

(c) The poison removal mechanisms (burnout by neutron flux and IX resin removal) are slow, in terms of reactivity addition rates, compared to the reactivity addition rates which could result from failures in mechanically driven reactivity mechanisms hence from this aspect the poison systems have a safety advantage.

A loss of poison due to a (poisoned) moderator system leak will also be inherently safe. If the loss of moderator leads to a drop in moderator level then the loss of Δk from this will always be larger than the increase in reactivity from the loss of poison in the lost moderator (1).

In particular the slow rate of resin removal by IX is made use of in the initial approach to critical and also in subsequent approaches to critical following reactor shutdowns.

(d) A disadvantage of the use of poison compared to rods is that loss of poison is possible if the poison comes out of solution (precipitates). This is more likely to occur in colder parts of the system (solubility is less at lower temperature), especially if high poison concentrations are present (as in the mixing tanks, see later). Providing this precipitation does not change the poison concentration in the calandria then no reactivity increase will result.

If poison precipitation occurred in the calandria, then the poison mk load would no longer be uniformly distributed but would likely become mainly distributed on the bottom of the calandria, thereby reducing the poison effectiveness. This would cause an (unsafe)

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(1) Note, this fact is not obvious but can be deduced by looking at the changes in the 6 factors of the 6 factor formula, see 227 notes.

increase in reactivity. Poison concentrations are however chosen to minimize this possible problem. (With gadolinium, one of the poisons discussed later, for example a moderator pH>7 is undesirable as this is more likely to make gadolinium precipitate).

(e) Another disadvantage of poison usage is the cost of resin required, the cost of resin deuterization and dedeuterization and the cost of waste resin storage.

III. CHOICE OF POISON

Two neutron absorbing poisons are available for use in this system - boron and gadolinium. There are a number of nuclear and chemical properties of each of these which dictate which one is used and when it is used. A comparison of relevent properties is summarized in Table 1 for convenience. Notes beneath the Table emphasize a few important points.

The properties in Table 1 determine the advantages and disadvantages of using either poison for the various reactivity control purposes. Table 2 summarizes these advantages and disadvantages.

The applications of these poisons in the stations are given in Table 3, with explanatory comments.

An Appendix at the end of this section gives details on the relative burnout rates of boron and gadolinium in a thermal neutron flux, the results of which are summarized in terms of a "burnout" half life in Table 1. The operator should not be concerned with the detailed mathematics, given for completeness, but should know the basic reasons for the higher burn out rate of gadolinium which is the higher gadolinium microscopic cross section. He should also understand the difference between chemical and isotopic sampling. The fundamental point here is that chemical sampling techniques measure the sum of the concentrations of all the isotopes of the particular element. If any neutron burn up has taken place then the isotopes will not be in their naturally occurring relative abundances. Isotopic sampling (in this context) is sampling which determines the concentrations of the neutron absorbing isotopes. As it is these isotopes alone which determine the mk worth of the poison, isotopic sampling is more useful than chemical sampling for assessing poison reactivity worth.

The mk worth may be difficult to calculate for the chemical poison concentration as this worth depends on the amounts of poison isotopes burned out. However none of our plants currently has the equipment required to do isotopic sampling of boron or gadolinium, so that samples must be sent to AECL for this purpose.

TABLE 1: Comparison of Boron and Gadolinium Poisons

PROPERTY	POISON	
	BORON	GADOLINIUM
Chemical Compound Used	boric acid B_2O_3	Gadolinium nitrate $Gd(NO_3)_3.6H_2O$ (1)
Physical Form of Chemicals	white crystals	white crystals
Neutron Absorbing Isotopes	B^{10}	Gd^{155}, Gd^{157}
Natural Abundance of Absorbing Isotope(s)	20%	15%, 16%
Neutron Absorbing Reaction (2)	$B^{10} + n \longrightarrow Li^7 + \alpha$	$Gd^{155} + n \longrightarrow Gd^{156} + \gamma$ $Gd^{157} + n \longrightarrow Gd^{158} + \gamma$
Reactivity Worth of one mg Poison (of natural element)/ kg D_2O in moderator	∿8 - 9 mk	∿30 - 37 mk
Burnout Time of Poison by Neutron Flux at Full Power (See Appendix)	slow, burnout half life ∿20 days	rapid, burnout half life ∿12 hours
Removal Time of 28 mk of Poison by IX, at Typical Maximum Flow	∿40 hours	∿6 hours
Quantity of IX resin Required for Poison Removal	high, 2 to 3 columns for 28 mk removal	low, ∿1 column for ∿ten x 28 mk removals
Solubility	low, tends to precipitate at low temperatures	high, but tends to precipitate at pH>7.
Conductivity in D_2O	low, 0.01 mS/m per mgB/kg D_2O	high, 0.2 ms/m per mg Gd/kg D_2O

(1) Downgrading produced by H_2O in this hydrated compound is negligible; therefore, deuteration is not required.

(2) Note that the reaction with boron produces Lithium not B^{11} and that all the products of absorption (for B and Gd) are non-active.

Table 2: Comparison of the Advantages and Disadvantages of B, Gd Poisons

POISON	ADVANTAGES	DISADVANTAGES
BORON	Preferred for longer term (days) operations due to slower burnout (little make up needed) and due to slower IX removal. Smaller mk/kg poison in case of inadvertant addition. Less likely to induce cover gas D_2 excursion due to lower conductivity than Gd.	Less soluble than Gd, could precipitate to block lines and reduce unsafely Δk worth in system. Uses more IX resin to remove than Gd, per mk worth.
GADOLINIUM	Preferred for short term operations (<2 days) due to more rapid burnout and more rapid IX removal. High solubility allows high mk to be achieved without poison precipitating out. Uses less IX resin to remove than B, per mk worth.	Conductivity higher than B which increases risk of D_2 excursion due to enhanced radiolysis. More rapid -ve reactivity insertion (per kg of poison) in case of inadvertent addition.

Table 3: Specific Applications of Moderator Poisons

APPLICATIONS	POISON USED	COMMENTS
(1) Fresh fuel burn up simulation	Boron	Slow neutron flux burn out rate reduces frequency of makeup additions. Slow IX column removal rate desirable for this long term control.
(2) Fuelling machine Δk shim	Boron	As above. If boron is maintained in moderator longer than necessary fuel costs will increase due to decrease in fuel burnup.
(3) Xe equilibrium Load simulation	Gadolinium	Burnout of Gd in mk matches closely the build up in mk of Xe to 28 mk with little use of IX Gd removal needed (1).
	Boron at PNGS-A	Requires the use of IX columns for B removal (2). Removal by neutron flux is negligible during 40 hours at full power. B system designed before Gd in use elsewhere. Less likely than Gd to cause a cover gas D_2 excursion.
(4) Overpoisoning during a shutdown. Overpoisoning for a guaranteed shutdown	Gd preferred	Preferred as subsequent start up uses less resin and is quicker than with B. Higher solubility is a safety advantage.
	B may be used	Slower to remove by neutron flux and IX, hence safer from a reactivity point of view. Lower solubility is a disadvantage.

Footnotes for Table 3:

1. (a) (i) Start Up Following a Shutdown of Longer ∿3 Days

A start up to full power 3 days (72 hours) after a shutdown begins with effectively no Xe in core Figure 1. The Xe will build up to ∿28 mk worth at almost the same rate as Gd in mk is burnt out by neutron flux removal alone.

The match will not be exact but any mismtach, as indicated by changes in the average zone level can be compensated by adding more gadolinium (zone levels rising) or by valving in Gd IX columns (zone levels falling).

(ii) Start Up Between 1-1/2 - 3 Days Following a Shutdown

If the start up to full power is between 1-1/2 - 3 days after a shutdown from full power then the Xe concentration will be typically as in Figure 2. Gd is required to be added as shown during the Xe burnout period. During the subsequent Xe build up the Gd burn out rate will approximately match this build up in mk, see Figure 2. Any mismatch again is controlled by more Gd addition or by Gd IX removal. Start up at 40 hours after shutdown is indicated in Figure 2.

(b) IX columns must be used to remove Gd after Xe has reached equilibrium to remove Gd^{156} and Gd^{158} in order to maintain a low conductivity.

(c) Normal purification must be valved out of service during flux removal of Gd or else Gd will be removed by the normal clean up IX column.

2. Use of boron is operationally less convenient than the use of gadolinium due to the more frequent boron IX resin changes required. This is because boron requires much more resin to remove than gadolinium requires, for the same mk worth of poison. In addition for a Xe simulation with boron the moderator purification system has to be available and in service. Any problems with insufficient flow, from say a clogged filter, strainer or malfunctioning valve, could interfere with the boron removal rate. As a consequence any lack of sufficient boron removal as seen by a fall in average zone level could result in a unit derating or even a forced shutdown because of lack of reactivity. With gadolinium, unavailability of the purification is not as important.

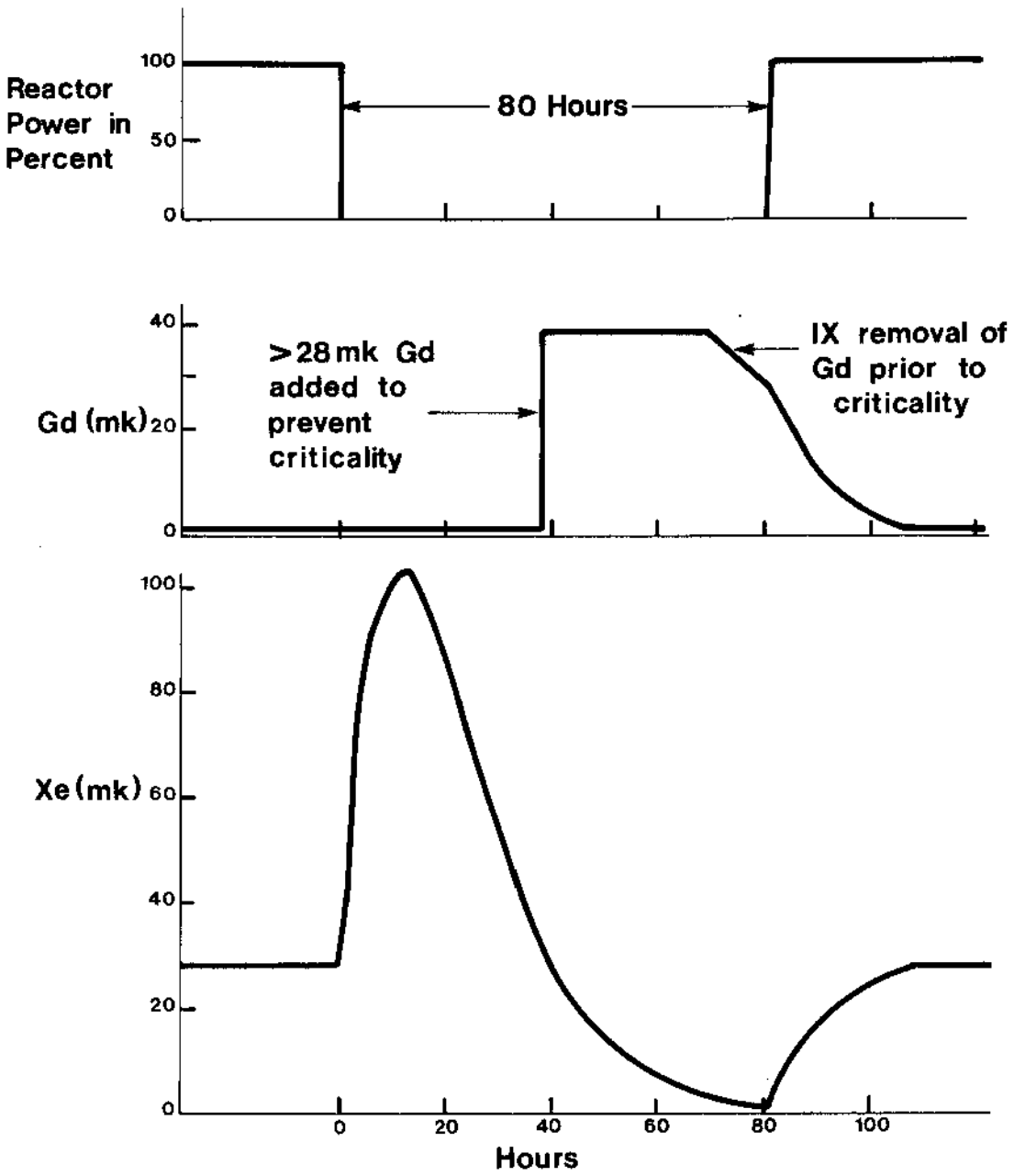

Figure 1: Gd Concentration in Moderator After a Shutdown Longer Than Three Days

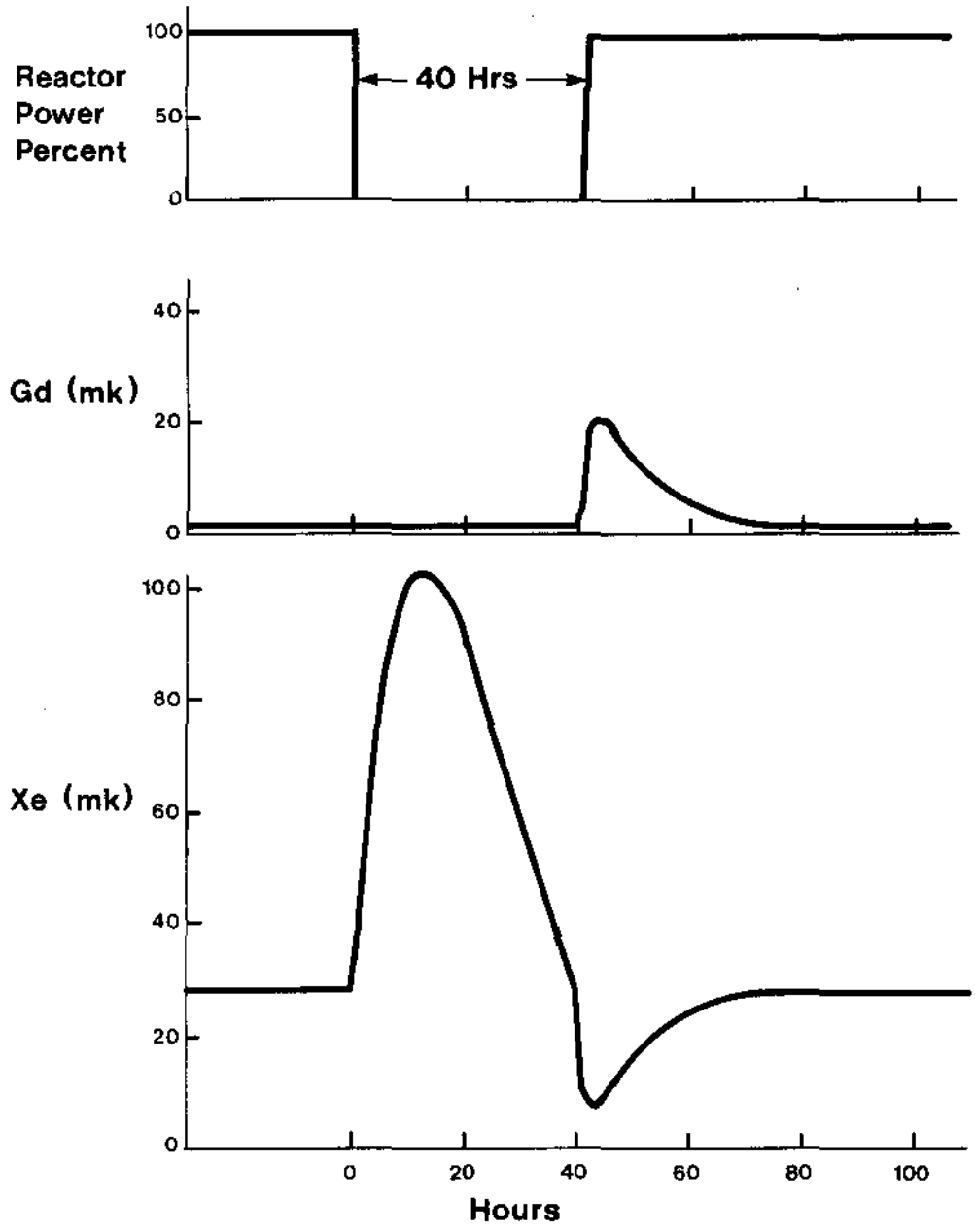

Figure 2: Gd Concentration in Moderator For a Start-Up 1-1/2 - 3 Days After a Shutdown

IV. EQUIPMENT DESCRIPTION

Typical system equipment is shown in Figure 3.

The system consists of a D_2O line supplying D_2O from the moderator system to the two poison mixing tanks - one for boron, one for gadolinium. Moderator system pressure (from heat exchanger outlet) provides the head for this supply line.

To allow the poison mixing tanks to be located in an accessible area on power, a decay tank is installed in the supply line. This allows the γ radiation fields from N-16 and O-19 isotopes to decay to acceptable levels when the mixing tanks are filled during reactor operation.

One line from each tank runs to the main moderator system, the tie-in point, being chosen so that good, rapid distribution of poisoned D_2O is achieved in the bulk moderator.

Poison addition may be done from the tanks to the moderator by gravity feed via motorized valves, or by small pumps, depending on the station. The poisons are added, in amounts weighed by the chemical lab, to the respective tanks via valves.

An agitator in the tanks provides good mixing and dissolving of the poisons. (Some plants are equipped with tank recirculation lines instead of agitators, for this purpose.) Good dissolving is particularly important with boron as its solubility is quite low. Line blockages due to solid boron could occur if dissolving is not complete. Precipitation of boron from solution, also causing line blockages, is also feasible particularly at low ambient temperatures. The solubility of gadolinium is high and problems with poor dissolving or precipitation are unlikely.

The mixing tanks are much smaller ($\sim$0.4 m^3) than the calandria and because of the subsequent poison dilution when addition is made to the moderator, the tanks contain higher poison concentrations than in the moderator. Actual concentrations in the tanks are determined by the reactivity addition rates required. Typically this would be $\sim$0.5 mk/minute for an addition flow rate $\sim$0.1ℓ/sec.

Venting the gas space of the mixing tanks is important to enable the tanks to be filled and emptied with no problems. Usually the vent lines are located so as to be serviced by the moderator vapour recovery system.

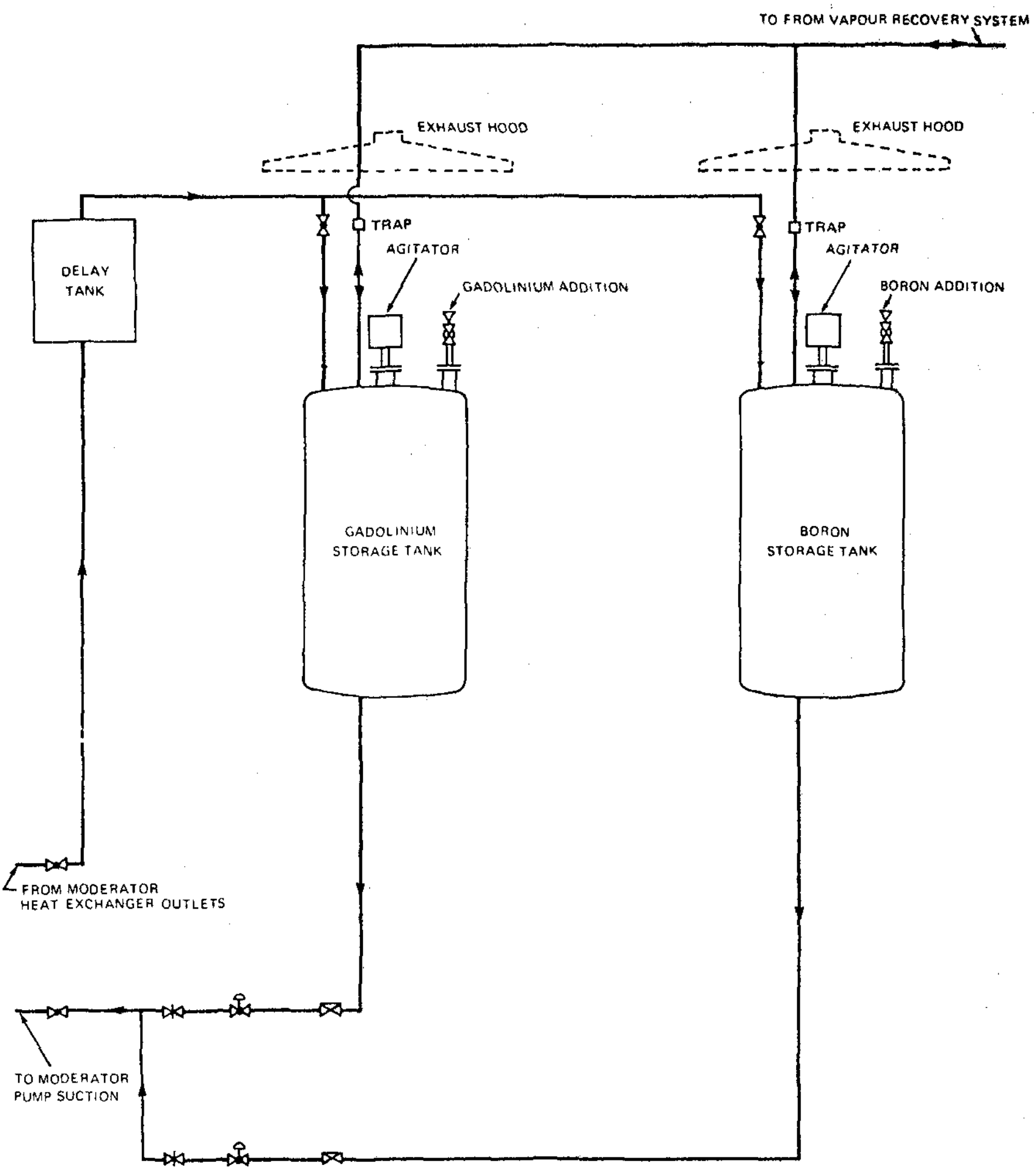

Figure 3: Typical Moderator Poison Addition System

V. OPERATING FEATURES OF SYSTEM

Radiation hazards associated with the system are from tritium during the D_2O filling of the mixing tanks and from residual γ radiation from N-16.

Addition of either poison to the moderator is usually done from the control room. From here the motorized addition valves on pumps can be operated and the addition flow rates monitored, and a watch kept on the average liquid zone level during the addition.

Whilst this system is basically very simple, it should be realized that it is normally a manually controlled reactivity mechanism (i). Inadvertent shutdown due to over-addition of poison is therefore a hazard. Examples of this have in fact caused Significant Events in our plants in the past. Any poison over-addition however, is a safe incident as far as reactivity is concerned, but undesirable from a production point of view.

Response to poison additions (sometimes called "shots") as seen by average zone level falling is not as simple as it may at first appear. There will be a delay of a few seconds in zone level response from the time of starting the addition due to the transit time for the poison to reach the calandria.

(i) Some plants provide for an auto addition feature of poison, (usually Gd) directed from the reactor regulating system program of the control computers, (see assignments).

ASSIGNMENT

1. Check in your own plant how:

   (a) poison is mixed in the mixing tanks.

   (b) the poison is added to the moderator system.

   (c) How long in (secs) B and Gd have to be added for to give a 10% decrease in average zone level, and what the delay time is for the addition process.

2. If the Gd^{3+} (chemical) concentration is 0.9 mg/kg D_2O at the beginning of a Xe 28 mk simulation, what will the chemical concentration be at the end of the simulation (48 hours), assuming no moderator IX columns have been in service. State why this is important in view of objective #2. Repeat the above question for boron, assuming a fresh charge of boron of 3.5 mg/kg D_2O is used initially, and that no IX columns have been in service.

3. Check in your own plant, if there is an auto addition feature available for poison and state the reasons it is available.

APPENDIX 1

I. Burnout Rates of Boron and Gadolinium in a Thermal Neutron Flux

There is a large difference in the relative burn out rates of these poisons (which is one of the reasons they are used for different applications). To show this we will first of all assume there is no poison removal by purification (the rates of removal by this process are discussed in the purification system section), and secondly we assume an average thermal neutron flux $\phi = 10^{14}$ neutrons/sq. cm/sec. This value is typical of a large reactor at full power. The final numbers quoted may then vary somewhat from station to station according to ϕ.

From nuclear theory level 2 we know that the absorption rate/cc/sec is given as $\Sigma_A \phi$ where Σ_A is the macroscopic absorption cross section of the absorbing isotope. This can also be written as $N\sigma\phi$ where N is the number of nuclei/cc at a given time and σ_A the microscopic absorption cross section. Mathematically we can then write that the burn out rate/second is:

$$\frac{dN}{dt} = N\sigma_A\phi$$

so that: $N = N_o e^{-\sigma_A \phi t}$

where: N_o is the number of nuclei at t= 0

This then shows that the isotope involved burns out exponentially with time so that we can define a burn out half life as:

$$t_{\frac{1}{2}} = \frac{0.693}{\sigma_A \phi}$$

For <u>boron</u> where the absorbing isotope is B^{10}, and σ_A=3840 barns we find that:

$$t_{\frac{1}{2}} = \frac{0.693}{3840 \times 10^{-24} \times 10^{14}}$$

$$= 18 \times 10^6 \text{ sec}$$

$$\sim 20 \text{ days}$$

For gadolinium where there are two main absorbing isotopes. Gd^{155} and Gd^{157}, there is no simple formula for burn out half life but we can approximate by finding the half life for the isotope with the largest cross section, which has the largest influence on the effective half life, at least for the first 12 hours or so.

As Gd^{157} has a cross section of 2.5×10^5b (larger than $\sigma(155) = 6.1 \times 10^4$b) the half life is:

$$t_{\frac{1}{2}} = \frac{0.693}{2.5 \times 10^{19} \times 10^{14}}$$

$$= 2.7 \times 10^4 \text{ secs}$$

$$\sim 8 \text{ hours}$$

(For times greater than 12 hours or so the new effective $t_{\frac{1}{2}}$ becomes ~30 hours as Gd^{155} predominates). A better value to use for an 'average' half life for mk changes is about 12 hours

II. Reactivity Change with Burn Out and Chemical Concentration Change with Burn Out

(i) Boron

With boron the concentration of B^{10} isotope is proportional to the mk worth of the poison. The B^{11} has negligible effect on reactivity as its σ_A is very small. Figure A1 shows then how the mk value of natural boron changes, as a percentage, with time, assuming we have 100% natural boron at t = 0 and no boron removal by purification. Every 20 days the mk drops by 50%, assuming a ϕ of 10^{14} neutrons/sq cm/sec.

This is contrasted to the mk value which would be calculated if we use the conversion 1 mgB/kg D_2O = 8 mk where the boron is taken to be the chemically (ie, no isotopic distinction) measured concentration. Figure A1 shows the chemical measurement will vary from 100% at t = 0 to a minimum of 80% of the original concentration, when all the B^{10} has burnt out, as B^{11} is 80% of natural boron. Hence after about a week of irradiation the difference between the true mk worth and the mk worth calculated from a chemical measurement of boron becomes very significant.

(N.B. Figure assumes no purification and a flux of 10^{14})

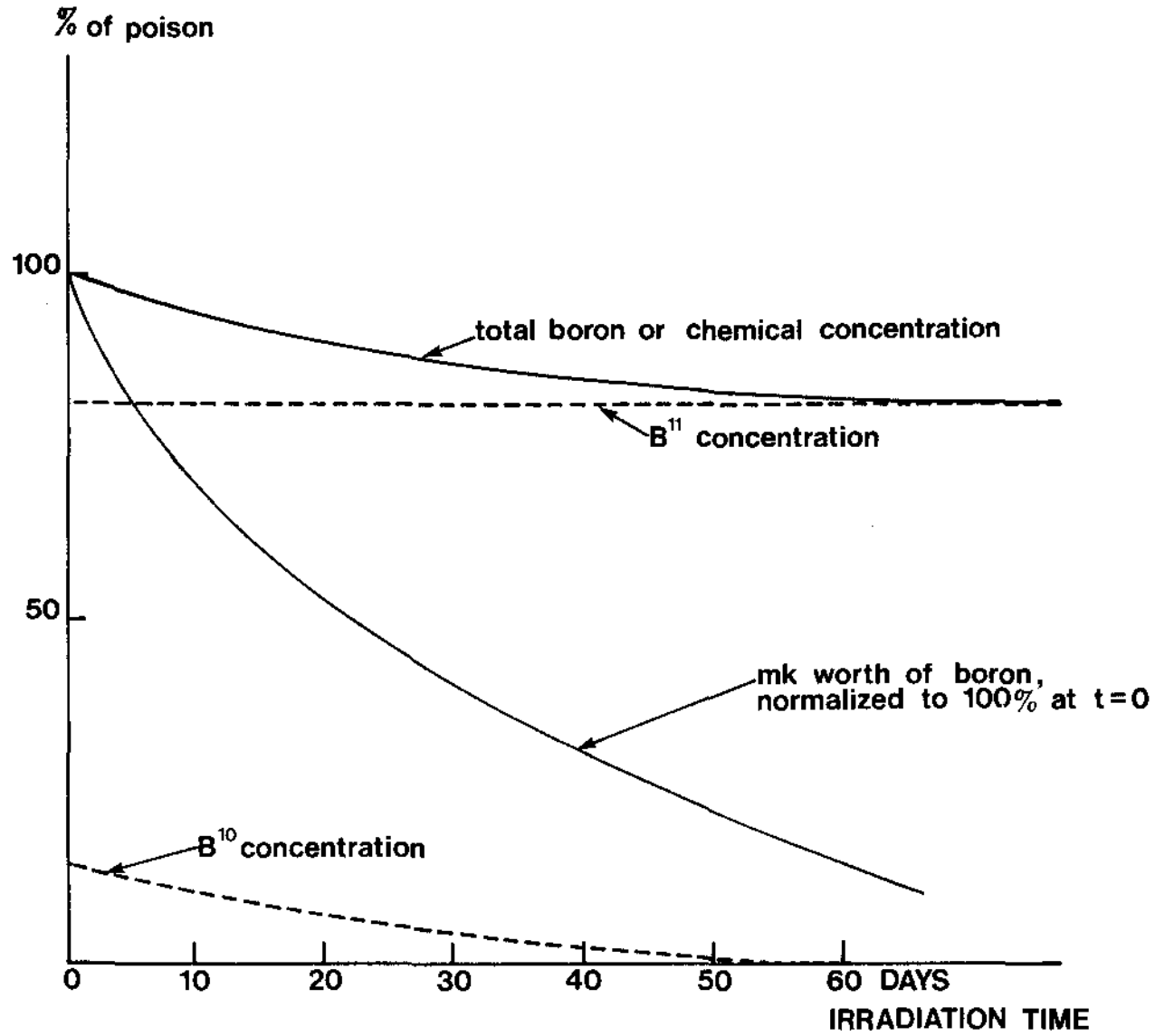

Figure A1: Variation of Boron mk Worth and Boron Chemical Concentration with Irradiation Time.

(ii) Gadolinium

A similar problem in interpreting gadolinium concentration measurements and converting them into mk values also occurs except the differences here are even more significant than the boron. Figure A2 illustrate this.

As Gd^{155} and Gd^{157} both undergo an n, γ reaction to form stable Gd isotopes then a chemical measurement of concentration will remain unchanged as burnout proceeds and after a few hours any use of the conversion factor 1 mg Gd/kg D_2O = 37 mk will give a significantly wrong value.

The actual mk worth of the Gd^{155} and Gd^{157} is shown for comparison as burnout proceeds to illustrate this. Hence it should be realized that only and isotopic concentration measurement for Gd (and B) will enable a true mk value to be established. Unfortunately equipment required to do this (a mass spectrometer) is not available in the plants and samples must be sent to CRNL for analysis.

D.J. Winfield

(N.B. Figure assumes no purification and a flux of 10^{14})

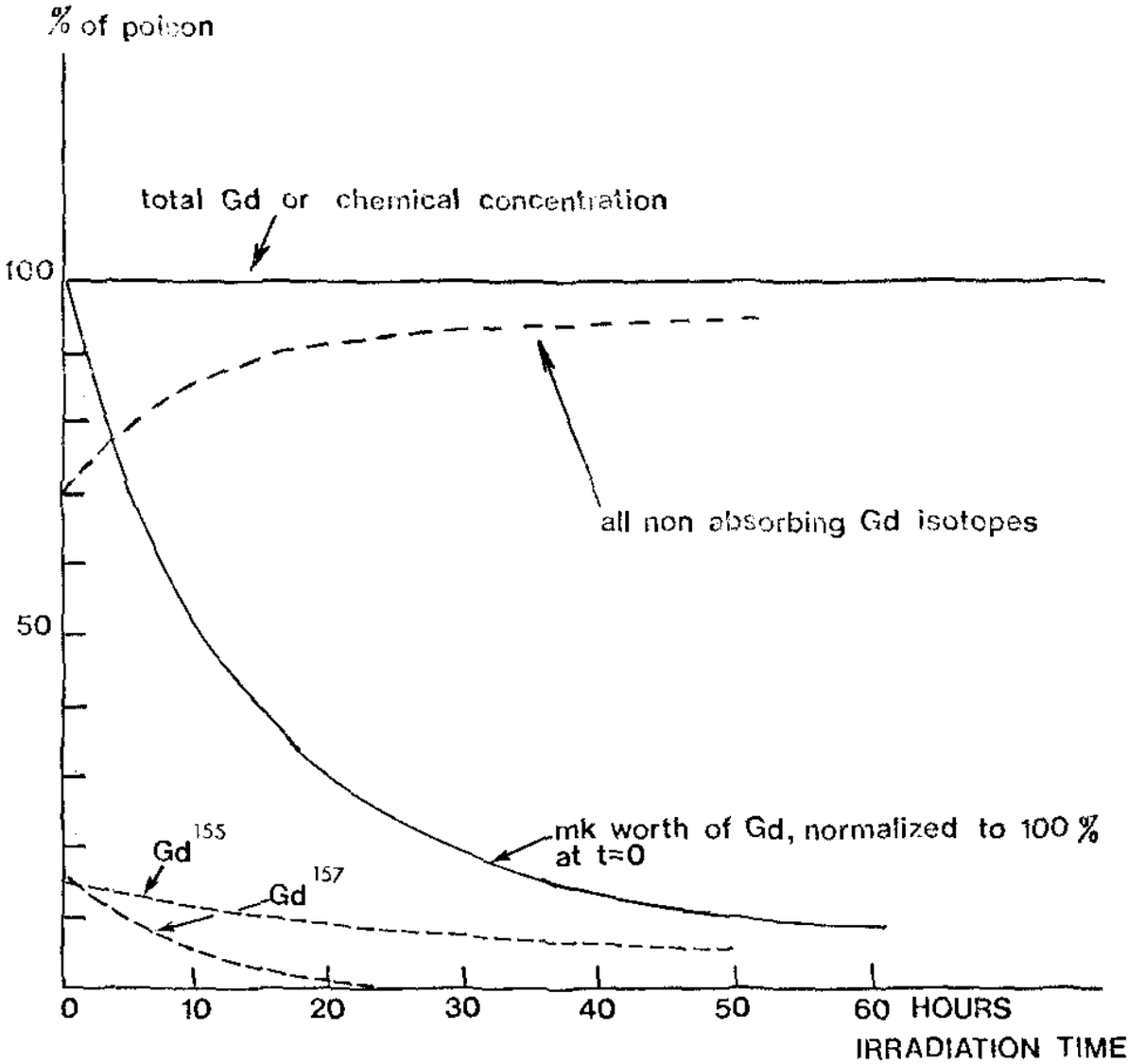

Figure A2: Variation of Gadolinium mk Worth and Chemical Concentration with Irradiation Time