Nuclear Theory - Course 227

REACTIVITY CONTROL

Reactivity mechanisms represent the final control elements which cause changes in the neutron multiplication constant k (or reactivity Δk) hence, reactor power. There are two separate requirements of the reactivity mechanisms which are preferably fulfilled by two independent systems. These requirements are:

1. Reactor Regulation. The three basis functions of the reactor regulation systems are:

   a) Maintain $k = 1$ for steady power operation.

   b) Provide small changes +ve or -ve in Δk to change reactor power.

   c) Prevent the development of flux oscillations.

2. Reactor Protection. The principal purpose of the protective system is to rapidly insert a large amount of negative reactivity to shutdown the reactor (TRIP).

From a reactor safety viewpoint it is desirable to have reactor regulation and protection performed by separate systems. From a practical viewpoint no single system can adequately fulfill all the requirements for reactor regulation let alone regulation and protection together.

Requirements of Reactivity Mechanisms

As well as independence between (1) and (2) the complex physical and nuclear changes occurring in core during reactor operation mean that an effective regulating system will have to consist of more than one type of reactivity mechanism. A convenient breakdown of the various in core reactivity changes which require compensating/regulating controls is listed in Table 1 and grouped in terms of the most important parameters of any reactivity mechanism namely:

(i) reactivity worth (or depth) Δk (mk).

This must be somewhat larger than the reactivity change for which the mechanism must compensate or control, and

(ii) operational time interval.

This is the time period during which the mechanism has to be able to supply or remove reactivity and this will hence determine the reactivity insertion rate (sometimes called the ramp reactivity rate), Δk per unit time (mk/s).

Each of the tabulated reactivity changes is now briefly described and typical Δk worths necessary to adequately control these changes as they occur in our stations are shown for comparison in Table 2. Where these values change from fresh fuel to equilibrium fuel load conditions then the difference is noted.

In Core Reactivity Changes

(a) Power Changes (Ref. Lesson 227.00-12)

Because the temperatures of the fuel and coolant increase as power increases from a hot shutdown condition to a hot full power condition, reactivity changes. Under normal (ie, non excursion) type conditions there will be a negative reactivity worth change called the *power coefficient of reactivity*. These are tabulated in Table 2. In order to maintain criticulity an equal but opposite reactivity worth must be supplied by some other means, (eg, by removing an equivalent reactivity worth from the Zone Control System).

(b) Fuel and Coolant Temperature Changes (Ref. Lesson 227.00-12)

As the fuel and coolant are heated from a cold shutdown condition (~25° C) to a hot shutdown condition (~276°C) reactivity decreases, Table 2.

(c) Moderator Temperature Changes (Ref. Lesson 227.00-12)

Normally moderator temperature is kept fairly constant (typically 70°C maximum in the calandria and 40°C at the heat exchanger outlets) but variation could be obtained by changing the rate of heat removal from the heat exchangers. The accompanying reactivity change is usually negative with increasing temperature for a freshly loaded core but changes to a small positive value at equilibrium fuel burn up as shown in Table 2.

(d) Fresh Fuel Burn Up (Ref. Lesson 227.00-7)

From an initial fresh fuel charge to equilibrium fuel burn up there is a large increase in negative reactivity load over a period of 6 - 7 months as a result of build up of long lived neutron absorbing fission products (not including Xe^{135}) and depletion of fissile material. Figures for our reactors are quoted in Table 2. This is a slow but continuous reactivity change.

(e) Equilibrium Fuel Burn Up

At equilibrium fuel burn up, when the operating target excess reactivity has been reached, fission products continue to be built up and fissile material continues to be depleted. Continuous on power refuelling is of course the most important method of compensating for this continual depletion of fissile material at equilibrium burn up. The rate of reactivity loss for our reactors without refuelling is shown in Table 2 and for comparison the reactivity increases due to the refuelling of a single typical central channel are also listed.

(f) Equilibrium Xe Load Build Up (Ref. Lesson 227.00-11)

Following a long reactor shutdown (>2 - 3 days) an equilibrium reactivity load (up to 28 mk see Table 2) will be built up due to Xe^{135} accumulating in the fuel after start up.

(g) Xe Transient Build Up (Ref. Lesson 227.00-11)

Within 12 hours of a reactor shutdown (or large derating due to operational problems, or a load following situation) there is a very large transient rise in Xe poison concentration (up to -80 mk above the equilibrium level at Pickering, Table 1). To enable us to restart the unit, Xe OVERRIDE or BOOSTING CAPABILITY is provided to compensate for this reactivity loading providing an override time, measured after shutdown, which gives reactivity capability of restarting a unit within this time. Actual reactivities available and the override times thus obtained are listed in Table 2 for all our stations.

(h) Flux Oscillations (Ref. Lesson 227.00-11)

As localized flux/power changes occur in the core (from, for example, refuelling part of a channel or movement of a localized control rod) these can result in quite large undamped power swings (Xenon oscillations) being set up with periods between 15 - 30 hours.

To counterbalance these oscillating unbalanced reactivity loads in various regions (called ZONES) of the core, the ZONE CONTROL system is used. Total reactivity worth of these systems are shown in Table 2, and are actually larger than required to control only the flux oscillations as these systems are also used for bulk power control.

(i) Plutonium and Samarium Build Up (Ref. Lessons 227.00-7&11)

After shutdown plutonium builds up from the decay of neptunium adding positive reactivity and samarium builds up from the decay of Promethium adding negative reactivity. The overall effect is positive as shown in Table 1.

TABLE 1

In core reactivity changes

	Source of in-core reactivity changes.	Δk depth	time interval
(a)	Power changes, hut shutdown to hot full power.	medium (+ve, -ve)	seconds, minutes
(b)	Fuel and Coolant temperature changes.	medium (+ve, -ve)	seconds, minutes
(c)	Moderator temperature change.	small (+ve, -ve)	minutes
(d)	Fresh fuel burn up.	large (-ve)	6 - 7 months
(e)	Equilibrium Xe load build up.	large (-ve)	40 hours
(f)	Xe transient build up.	large (-ve)	<12 hours
(g)	Flux Oscillations.	medium (+ve, -ve)	15 - 30 hours
(h)	Equilibrium fuel burn up.	small (-ve)	days (continuous)
(i)	Plutonium and Samarium build up.	medium (+ve)	300 hours

TABLE 2: COMPARISON OF STATION REACTIVITY LOADS

REACTIVITY WORTH CHANGE		NPD	DOUGLAS POINT	PICKERING A & B	BRUCE A & B
(a) Power Coefficient	fresh fuel	-3.3 mk	-6 mk	-7 mk	-9 mk
hot shutdown - hot full power	equilibrium fuel	-1.2 mk	-5 mk	-3 mk	-3.5 mk
(b) Fuel and Coolant	fresh fuel	-3 mk	-6 mk	-8 mk	-9 mk
temperature 25°C to 275°C	equilibrium fuel	-1 mk	-4.5 mk	-2.5 mk	-3 mk
(c) Moderator Temperature	fresh fuel	-0.08 mk/ C	-0.06 mk/ C	-0.06 mk/ C	-0.07 mk/ C
Coefficient	equilibrium fuel	+0.01 mk/ C	+0.03 mk/ C	+0.08 mk/ C	+0.09 mk/ C
(d) Fresh Fuel Burn Up		-9 mk	-20 mk	-26 mk	-22 mk
(e) Xe Equilibrium Load		-24 mk	-28 mk	-28 mk	-28 mk
(f) Xe Peak Load		-46 mk	-107 mk	-98 mk	-105 mk
Xe Override Capability*		+2.4 mk	+10 mk	+18 mk	+15 mk
Xe Override Time		35 min	30 min	45 min	40 min
(g) Zone Control Reactivity Worth		NONE	3 mk	5.4 mk	6 mk
(h) Reactivity Loss (Equilibrium Fuel)		-0.15 mk/day	-0.3 mk/day	-0.3 mk/day	-0.5 mk/day
Reactivity Gain/Refuelled Central Channel		+0.1 mk	+0.2 mk	+0.2 mk	+0.5 mk
(i) Plutonium and Samarium Build Up		+2.5 mk	+6 mk	+6 mk	+6 mk

* New elements only, will decrease by ~30% at end of life burn up.

As you can see the range of reactivity depths and insertion rates make it impractical to try to design a single control mechanism.

Methods of Reactivity Control

Before we can discuss actual control mechanisms we must look at the theoretical methods of reactivity control. Recalling that:

$$k = \varepsilon p \eta f \Lambda_f \Lambda_t$$

we will examine which of the six factors we can use to change/control reactivity (remember $\Delta k = \frac{k - 1}{k}$)

First neither the fast *fission* factor (ε) nor the resonance escape *probability* (p) are easily varied. They depend on the amount of U-238 present and the lattice spacing in the reactor. Therefore, we make no attempt to control reactivity by controlling ε or p.

Next is the *reproduction factor* (η).

Recall that:

$$\eta = \nu \frac{\Sigma_f^{fuel}}{\Sigma_a^{fuel}}$$

If we increase the amount of fissile material present (Σ_f^{fuel}) we will increase η. That is, more neutrons will be produced per neutron absorbed by the fuel.

Thermal utilization (f) is the fraction of neutrons absorbed by the fuel to those absorbed in the whole core:

$$f = \frac{\Sigma_a^{fuel}}{\Sigma_a^{fuel} + \Sigma_a^{non\text{-}fuel}}$$

If we increase or decrease the amount of non-fuel absorption, we vary f, hence reactivity. Variation of neutron absorption is by far the most common method of control.

Finally we have the *fast and thermal non-leakage* probabilities (Λ_f & Λ_t). If we vary the leakage of neutrons from the reactor we will vary reactivity.

Reactivity Mechanisms

In order to discuss the reactivity mechanisms presently in use we shall divide them into five groups based on their basic function in the reactor. The five functional groups are:

1) Automatic Reactor Regulation - (includes bulk power and zone control)

2) Xenon Override.

3) Long Term Reactivity Control - (includes fresh fuel burn up, the build up of equilibrium xenon and the build up of plutonium and samarium after shutdown).

4) Equilibrium Fuel Burn up.

5) Shutdown Systems

For each of these catagories we will discuss the methods used and the significant advantages and disadvantages of those methods (See 433.50-1 for a discussion of the mechanics of the systems). Table 3 indicates which systems are used at each station and the reactivity depth of each system.

Automatic Reactor Regulation

a) Moderator Level Control.
Small changes in moderator level change the thickness of the reflector on top of the reactor thus varying leakage (Λ_f & Λ_t).

Advantages:

1) Easily incorporated into a system using moderator dump for protection.

Disadvantages:

1) Zone control is not possible.

2) Lowering the moderator level distorts the overall flux distribution.

b) Control Absorbers.
Solid rods of a mildly absorbing material (typically stainless steel) which can be operated vertically in the core. Because they are parasitic absorbers the control absorbers change the thermal ulitization (f).

Advantages:

1) Provide additional reactivity at minimal cost.

Disadvantages:

1) In core guide tubes represent, permanent, reactivity loss (fuel burn up loss).

c) Liquid Zone Control (LZC)
Zone Control Compartments inside reactor which contain a variable amount of light water (a mild neutron absorber). Varying the amount of light water in the LZC, varies parasitic absorption hence thermal utilization (f).

Advantages:

1) Individual zone levels can be independently varried for zone control.

2) Operating equipment is mainly outside containment, therefore, accessible during reactor operation.

3) Cooling easily accomplished.

4) Only slight distortion of the overall flux pattern.

Disadvantages:

1) Requires special design to insure that the zones fail safe (ie, fill).

2) In core structure represents a reactivity (or fuel burn up) loss.

Xenon Override

a) Booster Rods.
Solid rods of highly enriched (~90%) U-235. Insertion of booster rods increases the amount of fissile material in the reactor hence the reproduction factor (η). It also increases f.

Advantages:

1) Can provide large override capability.

Disadvantages:

1) Enriched Uranium is a very expensive, non-Canadian product.

2) Require highly reliable source of cooling (loss of cooling to an inserted booster at high power could cause the rod to melt down in about 5 seconds).

3) Because of cooling requirements additional trips are required thus complicating the reactor protection systems.

4) Limited lifetime as the reactivity worth decreases with each use.

5) A criticality hazard exists in the storage of both new and irradiated booster rods.

6) Because of all of the above reasons, the AECB requires special licenses, which, at this writing (June 1979) BNGS A does not have.

b) Adjuster Rods

Solid rods of a neutron absorbing material (Cobalt or Stainless Steel). Normally fully inserted in the reactor thus increasing parasitic absorption (decreasing f). Positive reactivity is provided by withdrawing the adjuster rods.

Advantages:

1) Provide flux flattening which must be provided by some other method if booster rods are used for xenon override.

2) No significant decrease in reactivity worth over normal lifetime.

Disadvantages:

1) Presence of adjusters results in a fuel burnup penalty of ~8%. (The adjusters reduce f, therefore, we must increase one of the other factors. Thus η is increased by not allowing the fuel to burn out as much.

Long Term Reactivity Control

The method of long term reactivity control presently in use is the addition of soluble poison to the moderator. While solid rods could be used for this purpose, soluble poison systems are cheaper and cause no flux distortions. However, the addition of poison to the moderator does reduce the flux reaching the ion chambers sufficiently to require that the power reading from out of core ion chambers be corrected for the presence of the poison. Boron in the form of boric acid D_3BO_3 or gadolinium in the form of gadolinium nitrate $Gd(NO_3)_3 \cdot 6H_2O$ are the poisons presently in use. Gadolinium has the advantage over boron for Xe load simulation because the neutron burn up rate of the neutron absorbing gadolinium isotopes (Gd155 and Gd157) and the Xe build up are sufficiently complementary that little adjustment of the gadolinium concentration by IX control is necessary during start up. The IX columns are, however, used to remove the reactivity build up of low cross section gadolinium absorption products to limit their accumulation in the moderator.

Using boron to simulate Xe load needs a closely monitored operation of the cleanup circuit to obtain the rapid reduction of boron required (3.5 ppm = 28 mk), boron removal being essentially only dependent on the IX removal rate rather than neutron burn up rate. Much more IX column capacity is also needed for B removal than for the Gd system. Gadolinium is not used at Pickering A as there is some concern that it may lead to high deuterium gas levels in the cover gas system due to increased radiolysis of the moderator.

Equilibrium Fuel Burn Up

On power refueling is used in all of Ontario Hydro's reactors. This essentially keeps the amount of fissile material constant by replacing irradiated fuel with fresh fuel more or less continually. This system of refueling has several distinct advantages:

1) No downtime for refueling

2) Better average fuel burnup

3) Better flux shaping.

4) Failed fuel can be removed easily without a shutdown.

There are of course some disadvantages mainly the high capital cost of the fueling machines and the maintenance which is required for them.

If the fueling machines are unavailable for some reason, there is a limited time the reactor can continue to operate. A Bruce 'A' reactor normally consumes 0.5 mk/day. (That is the reactivity worth of the fuel diminishes at that rate). If the LZC were at 50% at full power in an equilibrium fuel condition, about 3 mk of excess positive reactivity would be available. That gives approximately 6 days of operation before we must start inserting the boosters (actually undesirable for this purpose) or reduce the operating power (called derating) or shutdown the reactor.

On the other hand, if you overfuel the reactor you may have to derate the reactor due to the high flux in the area of the new fuel, (called regional overpower).

Shutdown Systems

Early Candu designs had a single shutdown system. As the design of the reactor became more sophisticated, the requirement for extremely high reliability dictated that two independent shutdown system be provided. There are presently three types of shutdown systems in use.

1) Moderator Dump

As the moderator level decreases, the physical size of the active portion of the core decreases. As the core gets smaller, leakage increases (Λ_f and Λ_t go down).

Advantages:

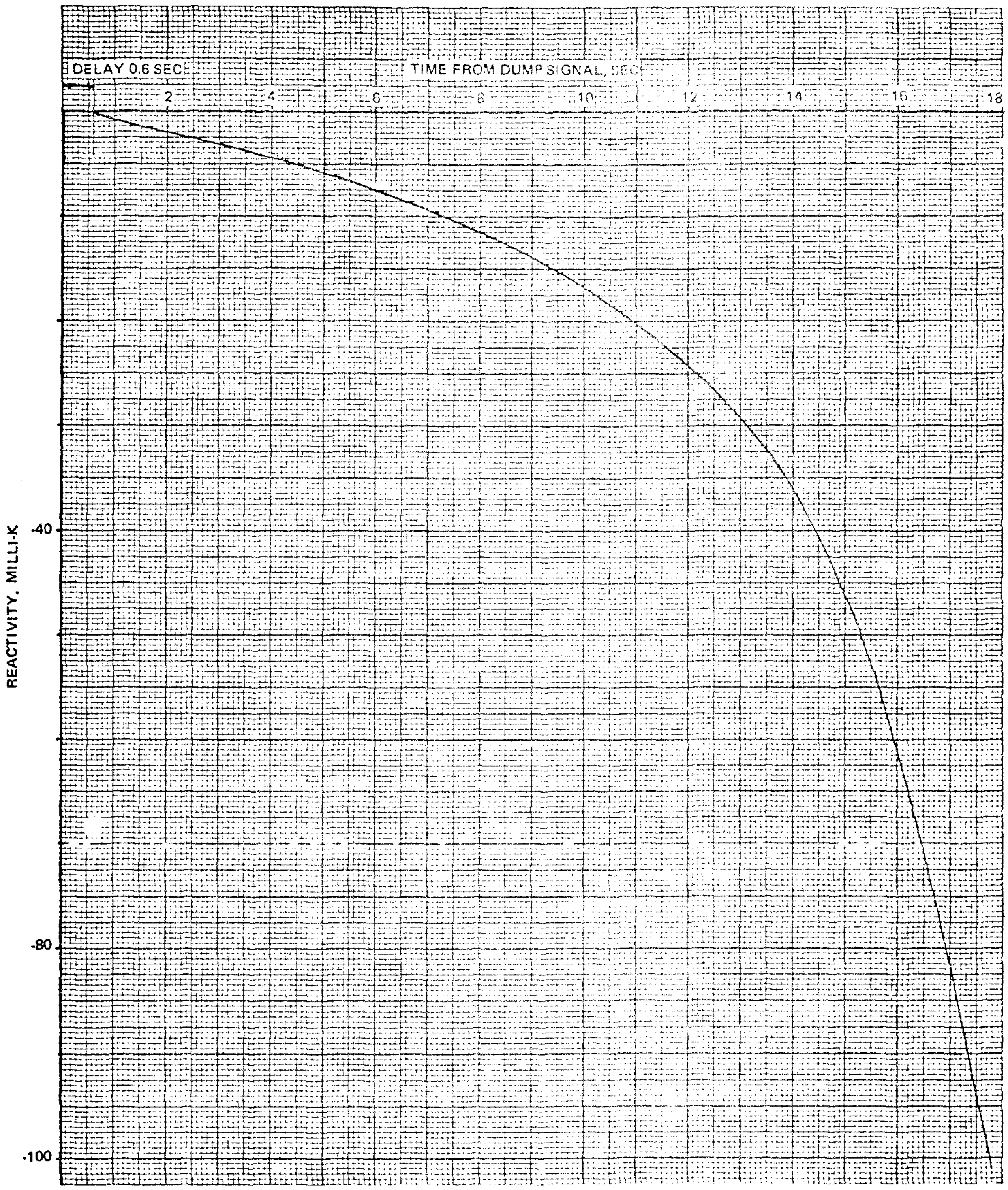
1) Simple, fail safe with gravity system.

2) Absolute shutdown, with the moderator dumped the core cannot be made critical.

Disadvantages:

1) Slow for a large reactor. The initial reactivity insertion rate may not be adequate to protect the reactor from certain types of accidents. Figure 1 shows reactivity vs time for moderator dump at PNGSA. Note that in the first two seconds only -2mk of reactivity has been inserted.

2) Time required to pump the moderator back into the calandria is so long (~50 min. at PNGSA) in a larger reactor that a poison out is quite possible.



REACTIVITY VERSUS TIME FROM INITIAL MODERATOR DUMP SIGNAL
(100 PERCENT MODERATOR LEVEL, EQUILIBRIUM FUEL CONDITIONS)

44.01100-46

FIGURE 1

2) <u>Shutoff Rods</u>

Hollow cylinders of neutron absorbing material (normally stainless steel sheathed cadmium) which can be gravity dropped into the reactor. Their presence greatly increases parasitic absorption thus reducing the thermal utilization (f).

<u>Advantages:</u>

1) Rapid reactivity insertion as required for protection in certain worst case accidents. Figure 2 shows reactivity <u>vs</u> time for PNGSA shutoff rods. Note that in 2 seconds the rods have inserted -22 mk.

2) Rapid recovery from a trip is possible. (~3 minutes to withdraw the rods).

<u>Disadvantages:</u>

1) Limited reactivity depth. As presently designed shutoff rods do not provide enough reactivity for a guaranteed long term shutdown.

2) Complex system (relative to dump) subject to mechanical failure. Safety analysis normally assumes that the two most reactive rods don't drop on a trip.

3) <u>Poison Injection</u>

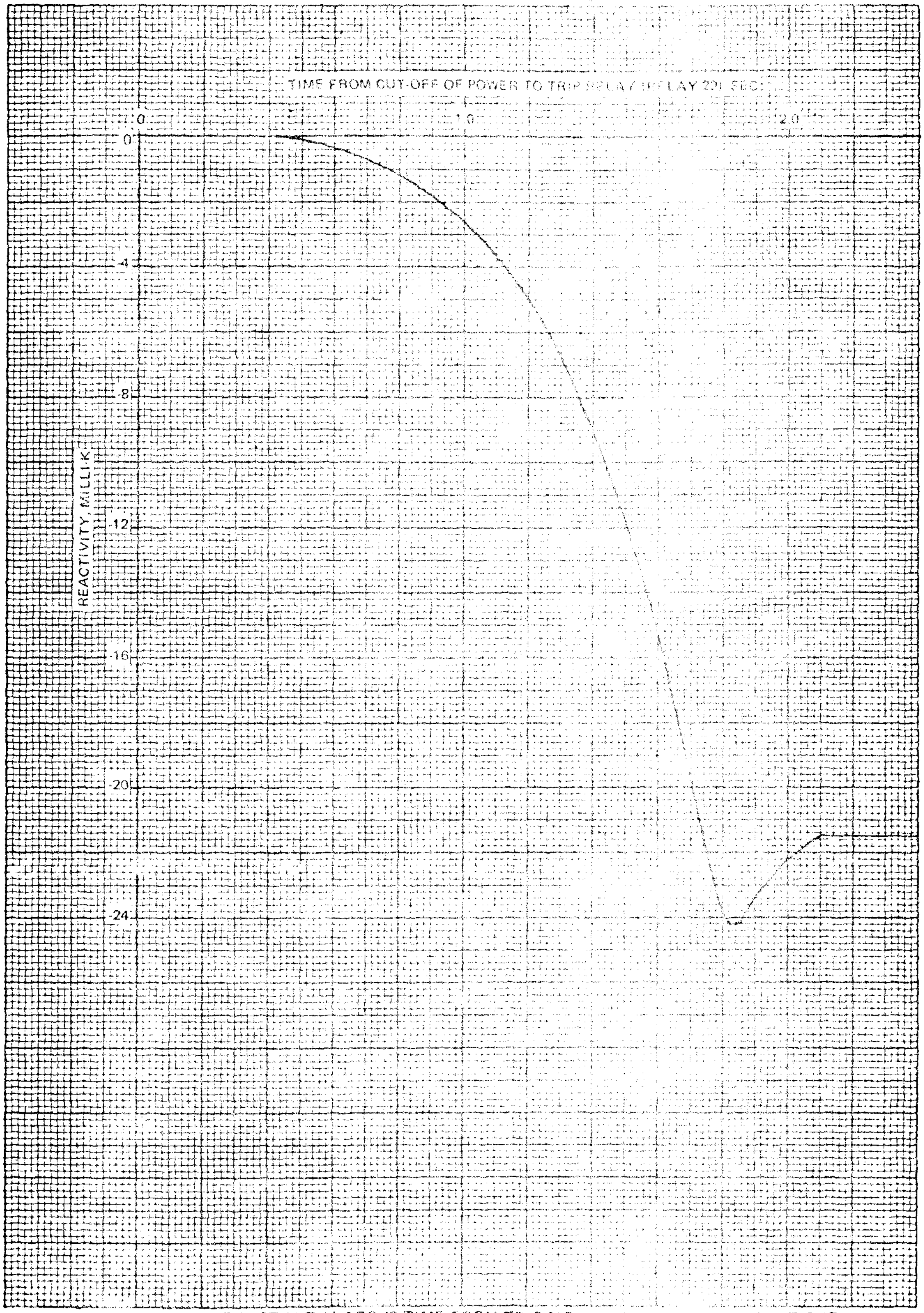
Poison (Gadolinium) is injected into the moderator under high pressure. This causes a large reduction in the thermal utilization (f).

<u>Advantages:</u>

1) Rapid insertion of reactivity. Figure 3 shows reactivity <u>vs</u> time for BNGSA poison injection system. Note that -33 mk is inserted in 1.5 seconds. Total worth is approximately -675 mk.

<u>Disadvantages:</u>

1) Poison must be removed from the moderator by ion exchange which is costly and slow (~12 hours). If poison injection shuts down the reactor, a Xenon poison out will occur before the moderator poison can be removed.

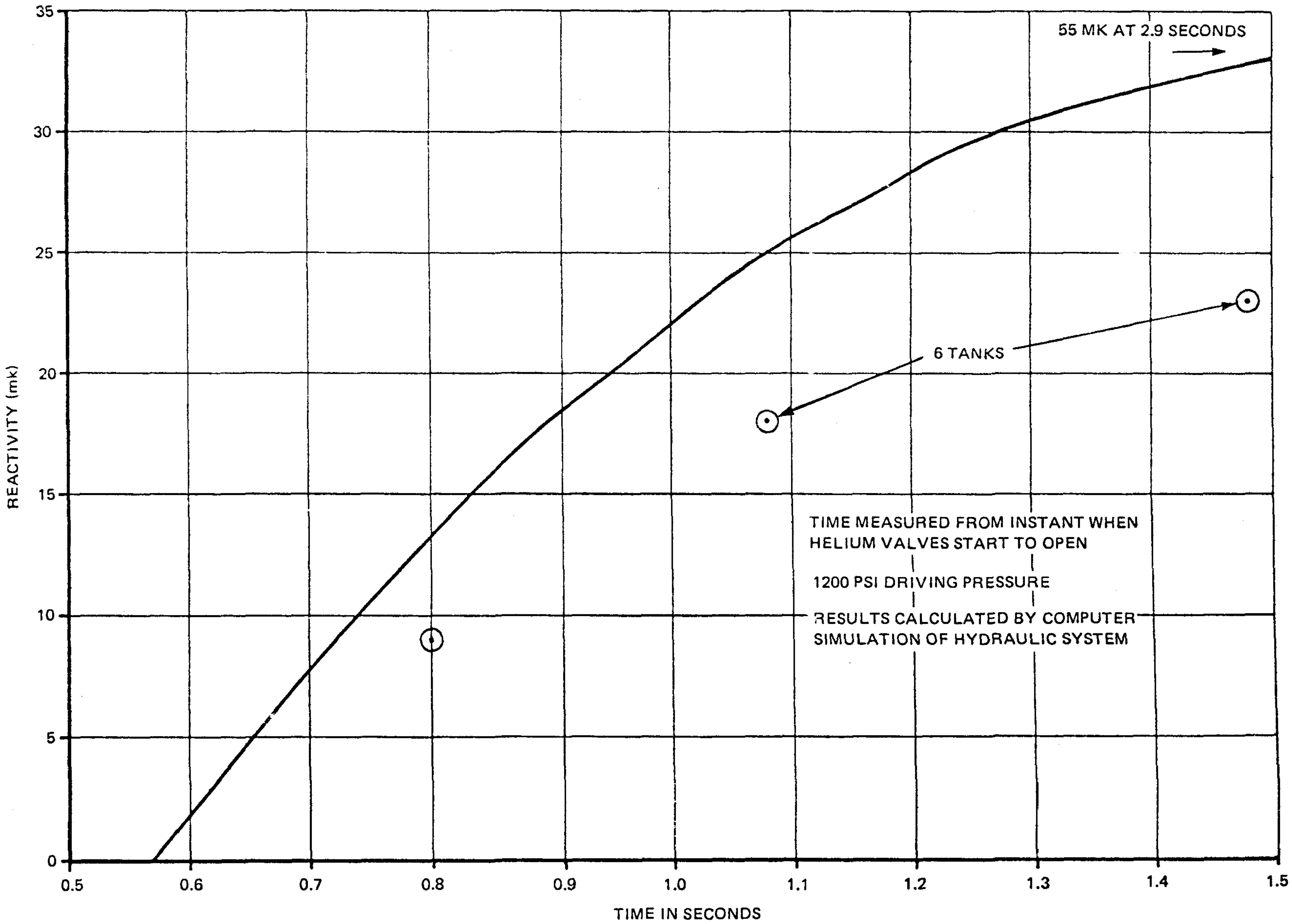


REACTIVITY VERSUS TIME FROM TRIP SIGNAL [illegible] [illegible] SHUT-OFF ROD DROP AT FULL MODERATOR LEVEL, EQUILIBRIUM FUEL CONDITIONS

44 01100-

FIGURE 2

FIGURE 3



Reactivity Vs Time, For Poison Injection.

227.00-13

		NPD	Douglas Pt.	Pickering A	Bruce A	Pickering B	Bruce B
Automatic Reactor Regulation (1)	Primary	Moderator Level Control	4 Control Absorbers (3mk)	14 Liquid Control Zones (5.4mk)	14 Liquid Control Zones (6mk)	14 Liquid Control Zones (6mk)	14 Liquid Control Zones (6mk)
	Secondary	NONE	Moderator Level Control	Moderator Level Control	4 Control Absorbers (7mk)	4 Control Absorbers (10mk)	4 Control Absorbers (9.5mk)
Xenon Override		1 Booster Rod (2.4mk)	8 Booster Rods (10mk)	18 Adjuster Rods (18mk)	16 Booster Rods (15mk)	21 Adjuster Rods (18mk)	24 Adjuster Rods (18mk)
Long Term Reactivity Control		Moderator Level Control	Moderator Poison Addition (Variable reactivity depending on poison Concentration)				
Equilibrium Fuel Burn up		All Stations use on power refueling					
Shutdown Systems	SDS 1	Moderator Dump	Moderator Dump	11 Shutoff Rods (24mk)	30 Shutoff Rods (40mk)	28 Shutoff Rods (48mk)	32 Shutoff Rods (69mk)
	SDS 2	NONE	NONE	Moderator Dump (2)	Poison Injection (55mk in 2.9s)	Poison Injection (N/A)	Poison Injection (55mk in 2.9s)

NOTES:

(1) The primary system is normally used for reactor regulation. If the primary system is unavailable or has insufficient reactivity depth, the secondary system will act automatically.

(2) Operation of the dump system at Pickering A is not entirely independent of the shutoff rods.

TABLE 3

Reactivity Control Systems

ASSIGNMENT

1. A Bruce reactor trips inserting - 40mk due to the shutoff rods. Using the information in Table 2 and assuming an equilibrium fuel condition, would you expect the reactor to remain shutdown (subcritical) if the heat transport system was kept at normal operating temperature? If the heat transport system was cooled down? Justify your answers.

2. Both methods of Xenon Override require derating when used. Explain why.

3. Simple chemical analysis for boron or gadolinium is not considered sufficient to determine the reactivity worth of moderator poison, explain why.

J.E. Crist
A. Broughton