REACTIVITY ACCIDENTS ANALYSIS DURING NATURAL CORE COOLING OPERATION OF ETRR-2

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One of the main features of Egypt Test and Research Reactor Number 2 'ETRR-2', MTR type, is a continuous steady state operation at low power level, <= 400 kW, with core cooling by natural water circulation. Two flapper valves mounted on the return core cooling pipe lines and long chimney encloses the reactor core assure natural convection phenomena through the reactor core and rector pool. Many tests and experiments are carried out during this state of operation. A possible occurrences of reactivity insertion accidents RIA may be expected over this operation. The present work studies two types of possible RIA: 1-fast reactivity insertion accident FRIA with rate 1.04$/s and 2-slow reactivity insertion accident SRIA with rate 0.023$/s which may occur due to fast/slow withdrawal of a control rod or sudden cooling of the core inlet water temperature. Failure or success of the reactor scram system during the transient operation is considered. A computer code TRAP22 is developed for such analysis. It is verified against CONVEC code and commissioning tests for steady state operation. The results of verification show good agreement. The study demonstrates that the reactor can be scrammed safely due to either FRIA or SRIA, whenever the maximum expected hot channel HC clad temperature lies within the range 70.73°C - 71.85°C. While, in case of failure of scram system the maximum HC clad temperature reaches the burn out value at time 1.175s for FRIA and at 46.36s for SRIA. At the burn out point the clad surface heat flux exceeds its design critical value which results in partial fuel melt.

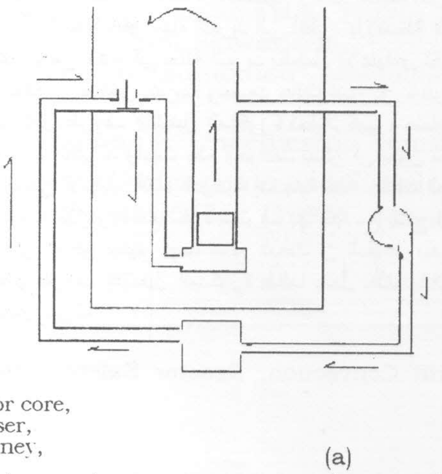
من أهم خواص مفاعل مصر البحثى الثانى (وهو من نوع مفاعلات البحث وإختبار المواد)، هى تشغيله فى حالة إستقرار بقدرة صغيرة ٤٠٠ كيلو وات أو أقل مع تبريده بالحمل العادى، لإجراء بعض الأبحاث والإختبارات. ويرجع ذلك لخواص التصميم حيث تود قلب المفاعل بمدخنة مستطيلة وعالية تحيطه من أربعة جوانب ويبلغ إرتفاعها فوق قلب المفاعل ٢و٣ متر تقريبا، حيث تعمل على توجيه تدفق مياه التبريد إلى أعلى. بالإضافة إلى وجود صمام فى كل خط من خطى أنابيب رجوع مياه التبريد إلى المفاعل، وهى تنفتح فى حالة التبريد بالحمل الإعتيادى لكى تنساب فيها مياه المفاعل الباردة هابطة الى أسفل قلب المفاعل ثم تمو بقلب المفاعل الساخن لتبريده وتصعد عاليتا لتبدأ دورة تبريد جديدة. تتناول الدراسة الحالية تحليل حوادث الفاعلية التى يمكن أن تحدث خلال ظروف التشغيل المذكورة تحليلا كميا وحسابيا. صنفت هذه الحوادث من حيث معدل إضافة الفاعلية إلى صنفين: أ- سريع ، ب-بطيء. وسبب هذه الحوادث يمكن أن يكون سحب مفاجئ لأعمدة التحكم أو تبريد مفاجئ لمياه مدخل قلب المفاعل. وقد أخذ فى الاعتبار أثناء الدراسة إستجابة نظام إيقاف المفاعل من عدمه. أستحدثت شفرة كمبيوتر جديدة لتمثيل المفاعل أثناء الحادثة وتم إختبارها مع شفرة معترف بها كذا مع نتائج إختبارات ما قبل التشغيل التى تمت حديثا ، أظهرت نتائج التحقق مدى واسع من التوافق بينهم. بينت نتائج البحث أن المفاعل يقف عن التشغيل أتوماتيكيا فى حالة وقوع أى من حوادث الفاعلية السابقة وفى ظل ظروف التشغيل المذكورة طالما يعمل نظام إغلاق المفاعل بصورة جيدة ، أما فى حالة إعطاله فإن قلب المفاعل يتعرض للانصهار جزئيا.

Keywords: Accident Analysis, Reactivity, Natural Convection, Reactor Safety, Safety Review.

INTRODUCTION

ETRR-2 design specifications implies two engineering aspects to facilitate core natural circulation [1]: 1- long core chimney (3.2 meter height) over reactor core(0.8 meter height); 2-two flapper valves, each is placed on a return pipe line of the primary cooling circuit. When the flapper valves open, the pool water(cold) enters the return pipe line and moves downward up to the core inlet and then moves upward through the core (Figure 1-a). The cold water removes the heat generated in the fuel elements and rises upward due to bouncy forces via the chimney. It mixes with the large amount of cold pool water and cools down then return again to the openings of the flapper valves to start a new cycle. A RIA could happen during tests or experiments that are executed at this state of operations; they are categorized into:

1. FRIA; that occurs as a result of fast withdrawal 4.5s of a control rod CR with maximum worth 3300pcm (4.714$), which may be due to failure of CR mechanisms. This results in a fast reactivity insertion rate 1.04$/s.
2. SRIA; Any erroneous withdrawal of CR resulting from spurious operation or incorrect power indication could cause slow reactivity insertion accident. The expected rate is 0.023$/s. In addition, a sudden cool of the core inlet temperature, due to a change in the secondary cooling water temperature by a sudden variation of the atmospheric temperature , may cause a slow reactivity insertion with small rate 0.00024$/s. All the above insertions are considered a ramp function.



C: Reactor core,
DF: Diffuser,
CH: Chimney,
P: Pump,
HE: Heat exchanger,
RT: Reactor tank,
RP: Primary coolant return pipe,
OP: Primary coolant outlet pipe.

(a)

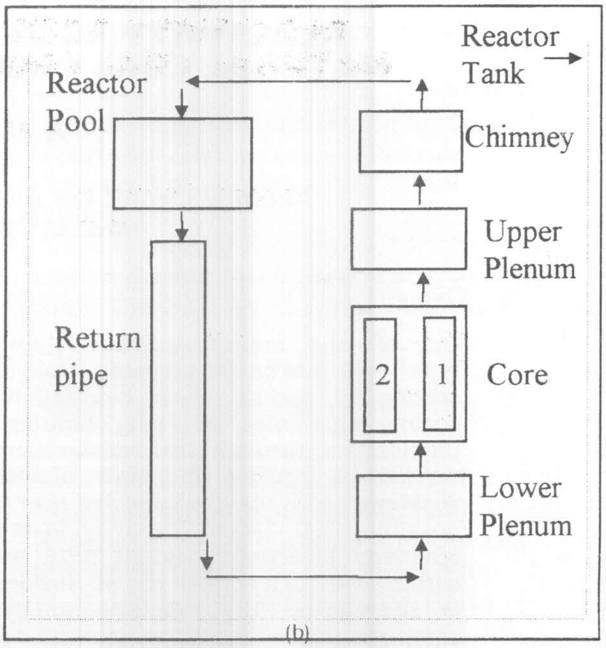


Figure 1 (a) Schematic diagram of ETRR-2 core and Chimney; (b) ETRR-2 natural circulation model

MODELING

The computer code TRAP22 is developed for the analysis. It simulates the core by two or more channels, every channel is divided into sections with maximum number of 25 sections, the core power distribution is assumed cosine and averaged over each section. Figure 1-b shows the natural circulation model of ETRR-2, while Figure 2 shows a channel grid subdivisions (i=1,...ich; j=1,...izch;) where ich stands for the total number of channels; and izch for the total number of axial divisions per channel. The present study considers two channels(ich=2) and four similar subdivisions for each channel(izch=4). The free convection heat transfer coefficient correlation's including boiling state are extracted from Reference 2. The Point kinetic model [3] is used for simulating the neutronic part and the Runge-Kutta technique is utilized to solve the time dependent system of equations in the transient case. The physical and thermalhydraulic equations, besides the method of solution using finite difference technique in space are stated below.

(a) Physical Equations

$$dP_o(t)/dt=[(R-B)P_o(t)+\sum_{i=1}^{6} B_iD_i]/L \quad (1)$$

$$dD_i(t)/dt=\lambda_i\,[N(t)-D_i(t)]i=1......6 \quad (2)$$

$$R=R_f+R_c+R_v+R_{ex}+R_c \quad (3)$$

where:

$P_o(t)$: Reactor power at time t

R: total reactivity

B: total delayed neutron fraction

B_i: delayed neutron fraction of group i

D_i: concentration of emitter of delayed neutron i

λ_i: delayed neutron decay constant of group=i

R_f: fuel reactivity feedback

R_c: coolant reactivity feedback

R_v: void reactivity feedback

R_{ex}: external reactivity insertion

R_{cr}: control rod reactivity insertion

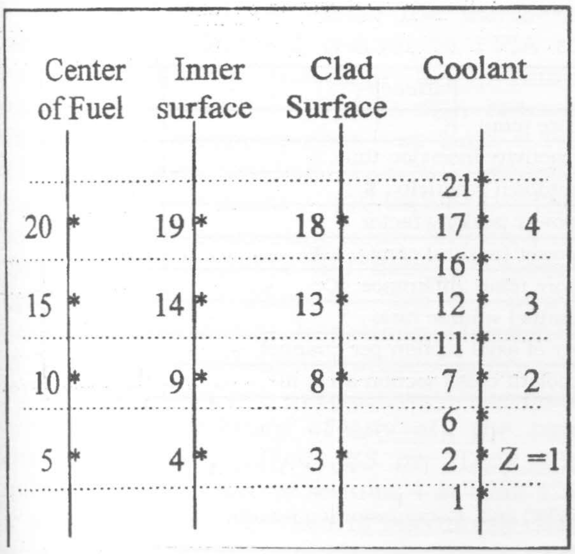


Figure 2 Channel grid Nodelization

(b)Thermalhydraulic Equations

$$Pd_{av}=\frac{P_o}{V_{fc}} \quad (4)$$

$$Pd_{hc}=Pd_{av}\,P_f \quad (5)$$

$$P_{av}(i,j)=\frac{P_oH}{2\Delta z}\left(\sin\left(\frac{\pi z_2}{H}\right)-\sin\left(\frac{\pi z_1}{H}\right)\right) \quad (6)$$

$$\frac{dT_f(i,j)}{dt}=\frac{P_{av}(i,j)-U_{al}(i,j)A(i,j)(T_f(i,j)-T_c(i,j)^{av})}{M_f(i,j)C_{pf}} \quad (7)$$

$$\frac{dT_c(i,j)}{dt}=\frac{U_a(i,j)A(i,j)(T_f(i,j)-T_c(i,j)^{av})}{M_c(i,j)C_{pw}}+\frac{W(i)(T_c(i,j)^{in}-T_c(i,j)^{out})}{M_c(i,j)} \quad (8)$$

$$U=\frac{N_uK_w}{H} \quad (9)$$

$$N_u=0.59\,(R_a)^{0.25},R_a<10^9 \quad (10\text{-a})$$

$$N_u=0.1(R_a)^{0.33},10^9<R_a<10^{13} \quad (10\text{-b})$$

$$R_a=G_rP_r \quad (11)$$

$$G_r=\frac{g\beta(T_w-T)H^3}{(\mu/\rho)^2} \quad (12)$$

$$P_{hc}= \quad (13)$$

$$P_{av}=P_o(1-P_fr \quad (14)$$

$$E_n=t\sum P_{av}(i,j) \quad (15)$$

where:

t: transient time;

P_o : total reactor power;

V_{fc}: total fuel volume in the core;

Pd_{av}: core average power density;

P_f: total power peaking factor;

Pd_{hc}: hot channel power density;

H: fuel element length;

z_1, z_2: channel section ends ;

$\Delta z = z_2 - z_1$;

A(i,j): heat transfer surface area of channel section i,j(shown in Figure 2);

U_a(i,j): over all heat transfer coefficient of channel i,j;

M_c(i,j): coolant mass of channel section i,j;

M_f(i,j): fuel mass of channel section i,j;

C_{pw}: water specific heat;

C_{pf} : fuel specific heat';

W(i): coolant flow of channel i,

P_{av}(i,j): average power of channel section i,j;

T_f(i,j): fuel center line temperature of channel section i,j;

T_c(i,j): coolant outlet temperature of channel section i,j;

$T_c(i,j)^{av}$: average coolant temperature of channel section i,j;

P_r, G_r, R_a, N_u: Prandtl, Grashof, Rayleigh, Nusselt Numbers;

T, T_w: water bulk and surface wall temperatures;

β, μ, ρ, k_w: volume expansion coefficient, viscosity, density, thermal conductivity of water;

g,U: acceleration of gravity, natural heat transfer coefficient

P_{hc}: total power generated in HC;

r: volume ratio of HC to core;

P_{av}: total power generated in average channel;

E_n: total energy released from the core.

CALCULATIONS AND RESULT ANALYSES

The main input data [4] are listed in Table 1:

The TRAP22 code is verified against results from CONVEC code[1,5] and commissioning tests[6,7], for ETRR-2 operation at 400 KW steady state natural circulation. Table 2 summarizes the results.

The main output results obtained for the studied cases are arranged in Table 3. where: R_o: Total reactivity \$; P_o: Reactor power Mw; En: Generated Energy MJ; TC2O1: Outlet temp. of channel 1 °C; TCD1_S3, TCD1_S4: Surface clad temp. of channel 1 section 3 and 4; TC2O2: Outlet temp. of channel 2 °C; TCD2_S3, TCD2_S4: Surface clad temp. of channel 2 section 3 and 4. Channel 2 refers to HC and channel 1 represents the remainder of core channels(it can be considered approximately the average channel). The critical point occurs at time 1.175s for FRIA and 46.36s for SRIA.

Table 1 Main input data

Parameter	Value	Parameter	Value
Operating power, KW	400.0	Inlet core temp., °C	40.0
Max. reactivity Insertion, \$	4.714	Fast reactivity insertion time, s	4.5
Slow reactivity insertion time, s	204.0	CR shutdown reactivity, \$	-11.928
Shutdown time, s	0.7	Total power peaking factor	2.36
Core total flow, kg/s	9.722	Max. power (natural conv.), KW	>440
Max. outlet core temp. , °C	53	Max. core temp. difference, °C	10
Shutdown system delay time, ms	25.0	Hot channel volume ratio	0.03
Number of channels per core	2	Number of axial section per channel	4
Number of fuel element	29	Core coolant cross section area; m^2	0.1122

Table 2 TRAP22 verification against CONVEC and Commissioning results

Inlet Plenum temp.,°C	40		24	
Code / Test	CONVEC	TRAP22	Commissioning	TRAP22
Outlet coolant temp. of HC	54	54.6799		-----
Max. wall temp. of HC	69.6	70.58		-----
Outlet coolant temp. of AC	-----	49.78662	33.5	33.78662

Table 3 Main results for ETRR-2 reactivity transients for low power operation. The numbers in parenthesis indicate the transient time in second

Case	**Fast**		**Slow**	
Parameter	**With scram**	**Without scram**	**With scram**	**Without scram**
$R_o ; \$$	0.0 (0.0) 0.08857 (0.08)[b] -9.73 (2.0)	0.0 (0.0) 0.895 (1.08)[b] 0.8728 (1.175)	0.0 (0.0) 0.05 (2.2)[b] -11.67 (5.0)	0.0 (0.0) 0.1957(20)[b] 0.1628(46.36)
P_o ; Mw	0.400 (0.0) 0.4498(0.12)[b] 0.014 (2.0)	0.400 (0.0) 8.817 (1.175)	0.400 (0.0) 0.4387 (2.2)[b] 0.01379 (5.0)	0.400 (0.0) 1.7414(46.36)
En; MJ	0.0 (0.0) 0.1278 (2.0)	0.0 (0.0) 2.585(1.175)	0.0 (0.0) 1.047 (5.0)	0.0 (0.0) 46.58(46.36)
TC2O1; °C	49.64 (0.0) 49.29 (2.0)	49.64 (0.0) 49.79(1.175)	49.64 (0.0) 48.83 (5.0)	49.64 (0.0) 77.316(46.36)
TCD1_S3 ; °C	60.07 (0.0) 60.17 (0.12)[b] 48.87 (2.0)	60.07 (0.0) 118.331(1.175)	60.07 (0.0) 60.91 (2.3)[b] 46.81 (5.0)	60.07 (0.0) 123.771(46.36)
TCD1_S4 ; °C	54.54 (0.0) 54.58 (0.12)[b] 49.82 (2.0)		54.54 (0.0) 54.89 (2.3)[b] 48.81 (5.0)	
TC2O2 ; °C	54.68 (0.0) 54.15 (2.0)	54.68 (0.0) 54.915(1.175)	54.68 (0.0) 53.46 (5.0)	54.68 (0.0) 96.35(46.36)
TCD2_S3 ; °C	70.58 (0.0) 70.73 (.12)[b] 53.51 (2.0)	70.58 (0.0) 159.343(1.175)	70.58 (0.0) 71.85 (2.3)[b] 50.38 (5.0)	70.58 (0.0) 167.627(46.36)
TCD2_S4 ; °C	62.16 (0.0) 62.22 (.12)[b] 54.96 (2.0)		62.16 (0.0) 62.69 (2.3)[b] 53.42 (5.0)	

b: maximum value

Figures 3 and 4 show the transient response of ETRR-2 reactor to FRIA of external reactivity insertion R_{ex} , ramp function, of rate 4.714\$/4.5s with reactor scram. The scram occurs at time 0.1s; where the power reaches 442.67KW(exceeds the safety set point 440.0KW)[1]. The power goes to maximum value 449.8KW at time 0.12s, due to the delay in rector protection signal 25ms[4]. On the other hand, the maximum hot channel (channel 2) clad and fuel temperatures approach 70.73°C and 70.96°C respectively. The clad section 3 temperature of any of the two channels 1 or 2 (Tcd1_S3 or Tcd2_S3) intersects with that of section 4 at time 1.5 s, which means movement of maximum clad temperature to the fuel element upper end following reactor scram.

Figures 5 and 6 illustrate FRIA without scram; the reactivity reaches a maximum value of 0.894\$ at time 1.08s and then decrease steadily due to the effect of temperature feedback reactivity. The HC maximum surface clad temperature (Tcd2_S3) reaches the burn out value at time 1.175s prior to water saturated boiling, at which the clad surface heat flux exceeds its design critical value(400W/cm^2). This indicates occurrences of fuel melt at that point(partial fuel melt). The core and channel parameters at the critical point are declared in Table 3

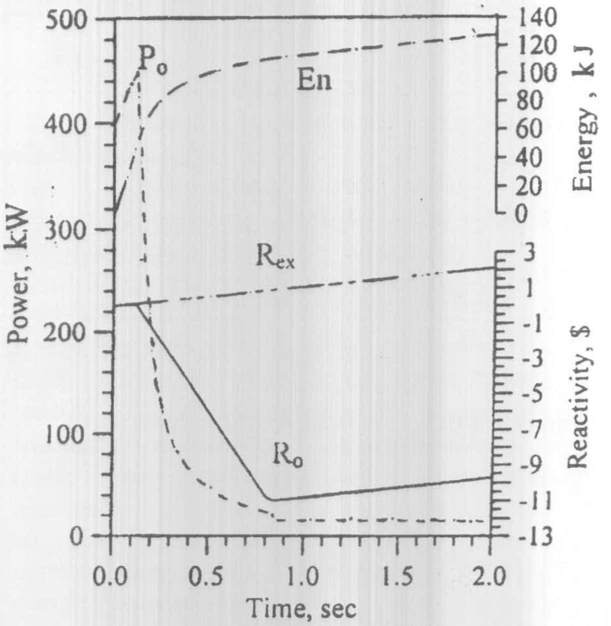


Figure 3 ETRR-2 response to FRIA with scram (power, energy, Reactivity)

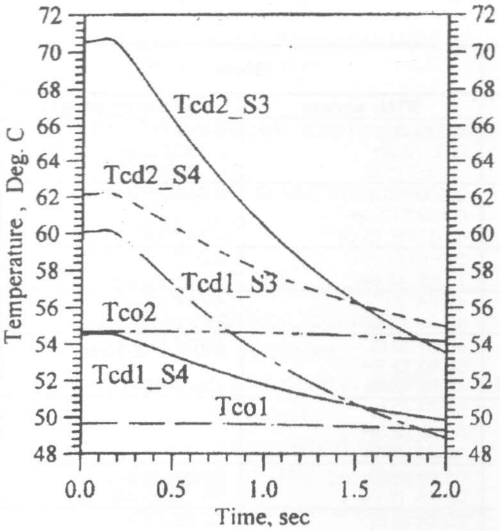


Figure 4 ETRR-2 response to FRIA with scram (channel temperatures)

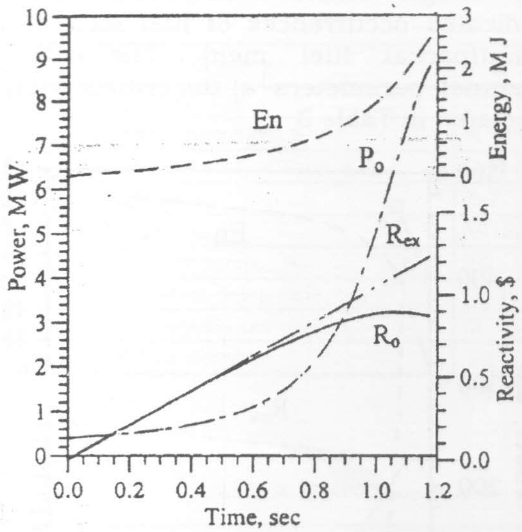


Figure 5 ETRR-2 response to FRIA without scram (power, energy, Reactivity)

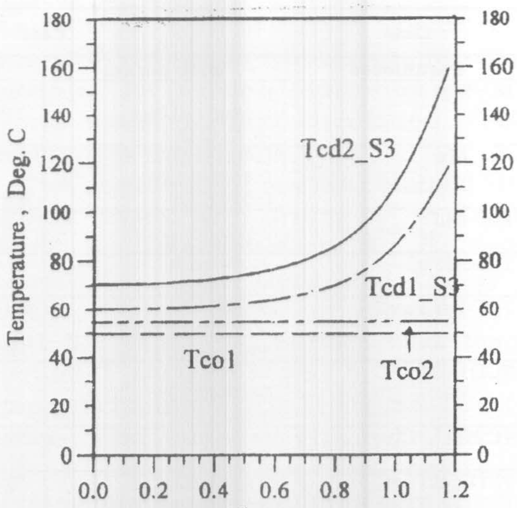


Figure 6 ETRR-2 response to FRIA without scram (channel temperatures)

Figures 7 and 8 represent the reactor transient response to SRIA of rate 4.714 $/204s with scram. No violation of safety limits are observed and the reactor shutdowns safely. The maximum values of temperatures are approximately the same as FRIA, but the maximum power of SRIA 1.047MW is very low compared with that of FRIA 11.12 Mw; this is due to the lower value of maximum total reactivity 0.05 $ of SRIA than that of FRIA 0.834$. The same comment for movement of maximum clad temperature after shutdown (as fast insertion) is applicable here, the intersection point occurs at time 3.8s.

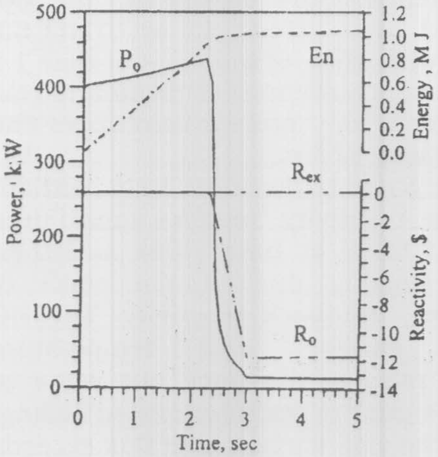


Figure 7 ETRR-2 response to SRIA with scram (power, energy, Reactivity)

In projection for Figure 9 and 10 for SRIA without scram, the Tcd2_S3 temperature reaches the burn out value at time 46.36s before saturated boiling, where fuel melt occurs. Table 3 listed parameters values at the critical point. However, it appears that the clad and consequently the fuel melt could be prevented by operator intervention(manual scram) within ~ 40s from alarm signal

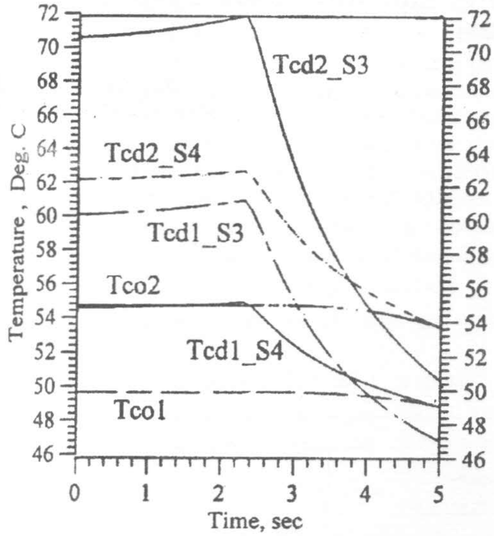


Figure 8 ETRR-2 response to SRIA with scram (power, energy, Reactivity)

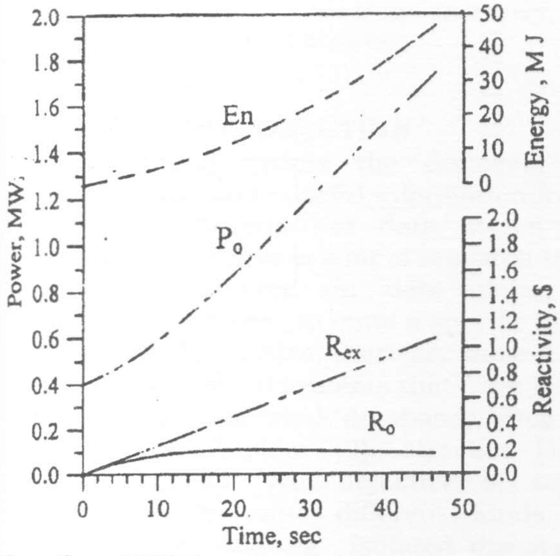


Figure 9 ETRR-2 response to SRIA with scram (power, energy, Reactivity)

In projection for Figure 9 and 10 for SRIA without scram, the Tcd2_S3 temperature reaches the burn out value at time 46.36s before saturated boiling, where fuel melt occurs. Table 3 listed parameters values at the critical point. However, it appears that the clad and consequently the fuel melt could be prevented by operator intervention(manual scram) within ~ 40s from alarm signal.

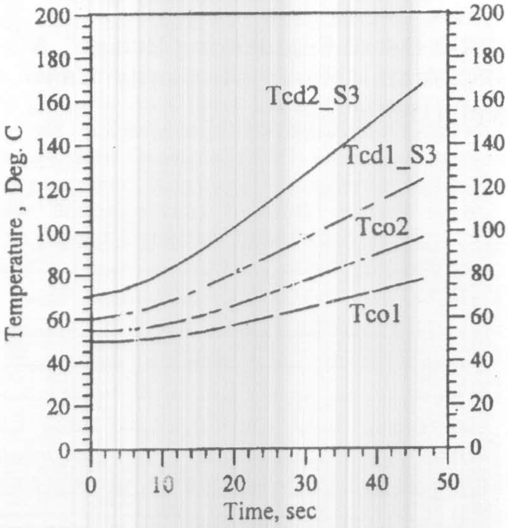


Figure 10 ETRR-2 response to SRIA without scram (channel temperature)

CONCLUSIONS

The following concluding remarks are reached:

1. The ETRR-2 shuts down safely after reactivity insertion accident (fast or slow); in condition that the scram system is available; which indicates stability of MTR type of reactors.
2. If the scram system fails on demand the clad rupture and partial fuel damage would be expected, at a different instants, prior to water saturation for both fast and slow reactivity insertion accident .
3. No enough time is available for operator intervention to mitigate accident consequences due to fast reactivity insertion accident with failure of scram system,
4. For slow transients without scram, the clad ruptures and consequently fuel melt

down could be prevented by operator action (manual shutdown) within a period less than ~40s from alarming signal.

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Received July 29. 1999
Accepted December 18. 1999