

MODELING OF A TOTAL LOSS OF POOL WATER ACCIDENT IN MTR REACTOR*

A.A. Fahmy**, M.S. EL- Koliel**, A.M.Abdullah** and A.S. Hanafi¹

ABSTRACT

In this study, it is intended to analyze early phases of a protected loss of coolant accident (LOCA) for MTR reactor. And to show the applicability of the presented model to the other similar types of research reactors. The transient situation since the time when coolant is beginning to be lost throughout one or more of the main coolant pipes which were supposed to be broken guillotine-like to the time when the core is totally uncovered is investigated. The modeling of the problem was separated into two phases; in the first phase when the water level of the pool is being decreased in a pre-estimated time-dependent way calculated by using modified Bernoulli Equation, the conservation equation are solved by using shooting method. The later phase, when water level reaches the top level of fuel plates and begins to decrease until the bottom of the core, and the fuel plates are being cooled by air.

Key Words: Thermal-hydraulic Modeling / Material test Research Reactor / Loca.

INTRODUCTION

The loss of coolant accident (LOCA) is considered to be beyond design accident. The former studies on LOCA were direct accident experiments during the years when first research reactors had been built. It was reported that partial LOCA analysis could be important for high flux and power of MTR-type reactors when the reactor core is partially covered with water. It has been a safety concern for the MTR research reactor if a fuel failure occurs during loss of pool water due to a severe earthquake which is expected to happen⁽¹⁾ with extremely small probability. Although the total loss of coolant is very much unlikely in MTR reactors because the different engineering safety features like (siphon effect breaker, flapper valve and chimney injection system) But this study is aimed at predicting fuel plate temperature during such a transient taking into account that the different engineering safety features not actuated during the accident.

MODELING

1- Loss of Pool Water

The MTR reactor under study is a pool-type reactor with an open water surface and variable core arrangement. The core nominal power was planned to be 22 MW_{th}, cooled by light water, moderated by water and with beryllium reflectors.

Its main usage is cobalt (Co⁶⁰) and other isotopes production, research and training. It has plate-type fuel elements (MTR type, 19.7% enriched uranium) with Aluminium clad. The main primary system shield is built of heavy concrete, and its thickness is such that the operational exposure doses of the operating staff are below prescribed limits. The reactor protection system commands two diverse and independent reactor shutdown systems that extinguish the nuclear reaction.

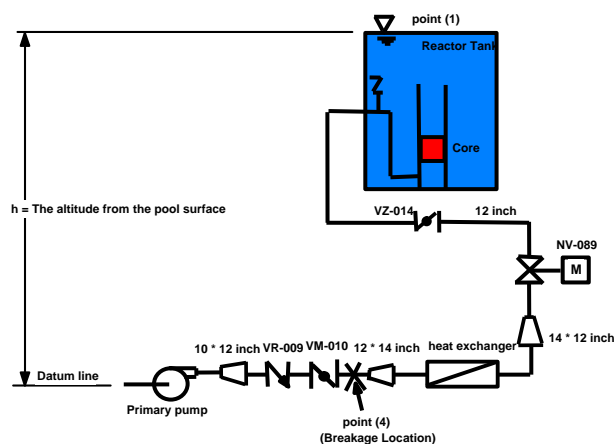


Fig. 1- Schematic of Total Loss of Pool Water Path.

One or more of the cooling pipes is supposed to be broken guillotine-like at the outside of the pool wall (as a result of expected earthquake or a terrorist bombing, etc.)⁽¹⁾. For the pipe under consideration, extended Bernoulli Equation could

*ندوة دور المهندس العربي في توفير الطاقة البديلة والاستخدام السلمي للطاقة النووية - اتحاد المهندسين العرب - الغريفة ١٧-١٩ مارس ٢٠٠٩

**Reactors Department, Nuclear Research Center, AEA, Cairo, Egypt
¹Faculty of Engineering, Cairo University, Cairo, Egypt

be written throughout the streamline, which is from pool surface to the point where the pipe is broken outside the pool as

$$\frac{P_1}{\rho_1} + \frac{v_1^2}{2} + g \cdot Z_1 - \frac{\Delta P_t}{\rho_1} = \int_1^4 \frac{\partial v}{\partial t} ds + \frac{P_4}{\rho_4} + \frac{v_4^2}{2} + g \cdot Z_4 \quad (1)$$

$$\int_1^4 \frac{\partial v}{\partial t} ds = \int_1^2 \frac{\partial v}{\partial t} ds + \int_2^3 \frac{\partial v}{\partial t} ds + \int_3^4 \frac{\partial v}{\partial t} ds \cong \int_1^2 \frac{\partial v}{\partial t} ds + \int_3^4 \frac{\partial v}{\partial t} ds \dots (2)$$

$$L_c \cdot \frac{dv_c}{dt} + L \cdot \frac{dv_4}{dt} \dots \dots \dots (3)$$

Where subscripts 1 and 4 denote pool surface and break point respectively, t is time, v is the coolant velocity, P is the pressure, ρ is the density, g is the gravity acceleration, z is the altitude from the pool base. The last term on the left hand side of the Eq. (1) is the total pressure drop along the stream line consisting of core pressure drop and pipe pressure drop.

Where subscripts 2 and 3 denote respectively core inlet, core outlet, L_c is the height of the core, v_c is the mean water velocity in the core, L is the total length of the broken pipe, v₄ is the mean water velocity in the pipe.

$$\frac{\Delta P_t}{\gamma} = \frac{\Delta P_c}{\gamma} + \frac{\Delta P_{pipe}}{\gamma} \dots \dots \dots (4)$$

$$\frac{\Delta P_c}{\gamma} = \frac{v_c^2}{2 \cdot g} \left\{ K_{en} + \frac{f \cdot L_c}{D_e} + \left(1 - \frac{A_c}{A_o} \right)^2 \right\} \dots \dots \dots (5)$$

Where

K_{en} = is a conservative value of the entrance loss coefficient for turbulent flow in smooth channels = 0.5

A_c = is the total water channel cross-sectional area in the fuel element.

A_o = is the cross section area of the end box immediately beyond the channel exit.

$$D_h = \frac{4 \cdot A_c}{p_{rem}} \dots \dots \dots (6)$$

From the continuity equation we get:

$$A_{pipe} \cdot v_4 = A_c \cdot v_c \dots \dots \dots (7)$$

$$v_c(t) = \frac{A_{pipe}}{A_c} \cdot v_4(t) \dots \dots \dots (8)$$

Substitute from Eq. (8) in Eq. (5) result

$$\frac{\Delta P_c}{\gamma} = \frac{\left(\frac{A_{pipe}}{A_c} \right)^2 \cdot v_4^2(t)}{2 \cdot g} \left\{ K_{en} + \frac{f \cdot L_c}{D_e} + \left(1 - \frac{A_c}{A_o} \right)^2 \right\} \dots (9)$$

$$\frac{\Delta P_{pipe}}{\gamma} = \frac{\Delta P_{fitting}}{\gamma} + \frac{\Delta P_{line}}{\gamma} + \frac{\Delta P_{H.X}}{\gamma} \dots \dots \dots (10)$$

$$\frac{\Delta P_{fitting}}{\gamma} = 0.138 \cdot v_4^2 \dots \dots \dots (11)$$

Calculations ΔP_{line}

$$\frac{\Delta P_{line}}{\gamma} = \frac{f_l \cdot L}{D} \cdot \frac{(v_4)^2}{2 \cdot g} \quad (m) \dots \dots \dots (12)$$

Total pipes length (L) = 17.92 (m),

ρ = 990 (kg/m³),

μ = 6*10⁻⁴

D = 12 inch = 0.3048 (m)

Assume turbulent flow,

$$Re = \frac{\rho \cdot v_4 \cdot D}{\mu} = 502920 \cdot v_4 \dots \dots \dots (13)$$

$$f_l = 0.316 \cdot (502920 \cdot v_4)^{-0.25} = 0.012 \cdot (v_4)^{-0.25}$$

$$\frac{\Delta P_{line}}{\gamma} = \frac{0.012 \cdot (v_4)^{-0.25} \cdot 17.92}{0.3048} \cdot \frac{(v_4)^2}{2 \cdot 9.81} = 0.035x(v_4)^{1.75} \dots \dots \dots (14)$$

$$\frac{\Delta P_{h.x}}{\gamma} = 0.777 \times v_4^{1.75} \dots \dots \dots (15)$$

$$\frac{\Delta P_c}{\gamma} = 0.0142 \times v_4^2 + 0.16 \times v_4^{1.75} \dots \dots \dots (16)$$

So to get the total pressure drop along the LOCA path substitute from equations (11),(14),(15) and (16) into equation (4), so

$$\frac{\Delta P_t}{\gamma} = 0.138.v_4^2 + 0.035x(v_4)^{1.75} + 0.777xv_4^{1.75} + 0.0142xv_4^2 + 0.16xv_4^{1.75} \dots\dots\dots(17)$$

$$\frac{\Delta P_t}{\gamma} = 0.1522xv_4^2 + 0.972xv_4^{1.75} (m) \dots\dots\dots(18)$$

From equation (1) noticing that,

$$P_4 = P_1 = P_{atm}, \rho_1 = \rho_4, v_1 = 0$$

And putting $h = (Z_1 - Z_4)$ into equation and substitute from equation (8) into equation (3) after that substitute from equation (3) into equation (1) we get,

$$h(t) = \frac{v_4^2(t)}{2 \cdot g} + \frac{\Delta P_t}{\gamma} + \frac{1}{g} \cdot \left(L_c \cdot \frac{A_4}{A_c} + L \right) \cdot \frac{dv_4}{dt} \dots(19)$$

So to get the variation of the height of water level h , equation (19) must be differentiating w.r.t time so, we get, then

$$\frac{dh}{dt} = 0.1xv_4 \cdot \frac{dv_4}{dt} \left(0.3044xv_4 \cdot \frac{dv_4}{dt} + 1.701xv_4^{0.75} \cdot \frac{dv_4}{dt} \right) + \frac{1}{g} \cdot \left(L_c \cdot \frac{A_4}{A_c} + L \right) \cdot \frac{d^2v_4}{dt^2} \dots\dots\dots(20)$$

Where,

$$L_c = 0.8 (m) , L = 17.92 (m) ,$$

$$A_c = 0.0001917 \times 18 \times 29 = 0.1 (m^2) ,$$

$$A_4 = A_{pipe} = \frac{\pi}{4} \cdot D^2 = \frac{\pi}{4} \cdot (0.3048)^2 = 0.073m^2$$

$$\frac{dh}{dt} \times A_{pool} = -v_4 \times A_{break} \dots\dots\dots(21)$$

Where

A_{pool} is the area of the reactor pool and

A_{break} is the cross-sectional area of the broken pipe.

Equation (32) could be arranged for v_4 using Eq. (34).

$$A_{pool} = \frac{\pi}{4} \times D^2_{pool} = \frac{\pi}{4} \times (4.5)^2 = 15.9(m^2)$$

$$A_{break} = \frac{\pi}{4} \times d^2 = \frac{\pi}{4} \times (0.3048)^2 = 0.073(m^2)$$

$$\frac{dh}{dt} = -4.4 \times 10^{-3} \cdot v_4(t) \dots\dots\dots(22)$$

So substitute from equation (21) into equation (20) and equating with zero we get,

$$0 = 4.4 \times 10^{-3} \cdot v_4(t) + \left(0.1v_4(t) + 0.3044xv_4(t) + 1.701xv_4^{0.75}(t) \right) \frac{dv_4}{dt} + \frac{1}{g} \left(L_c \frac{A_4}{A_c} + L \right) \cdot \frac{d^2v_4}{dt^2} \dots\dots\dots(23)$$

In order to calculate the mean water velocity in the core v_c and the height of the water level h , non linear equation (23) was solved together with equation (18) using shooting method [1]. So

dividing equation (23) by $\frac{1}{g} \cdot \left(L_c \cdot \frac{A_4}{A_c} + L \right)$ we get

$$\frac{d^2v(t)}{dt^2} + (0.2158xv + 0.948xv^{5.75}) \cdot \frac{dv}{dt} + 2.456 \times 10^{-3} \cdot v \dots(24)$$

$$\text{Let } \frac{dv}{dt} = w \dots\dots\dots(25)$$

$$\therefore \frac{dw}{dt} + (0.2158xv + 0.948xv^{0.75}) \cdot w + 2.456 \times 10^{-3} = 0 \dots(26)$$

Giving us two first order differential equations as

$$\frac{dv}{dt} = w \dots\dots\dots(27)$$

At $t = 0$ (sec),

v_o (initial) break water velocity = 3.6115 (m/s)

$$\frac{dw}{dt} = -(0.2158xv + 0.948xv^{0.75}) \cdot w + 2.456 \times 10^{-3} \cdot v \dots\dots\dots(28)$$

$$W(0) = v(1800) - v(0) / (1800-0) = -2.0166 \times 10^{-3} \dots\dots\dots(29)$$

So by using Runge-Kutta method we can get the variation of water level with time and velocity of water through the core v_c .

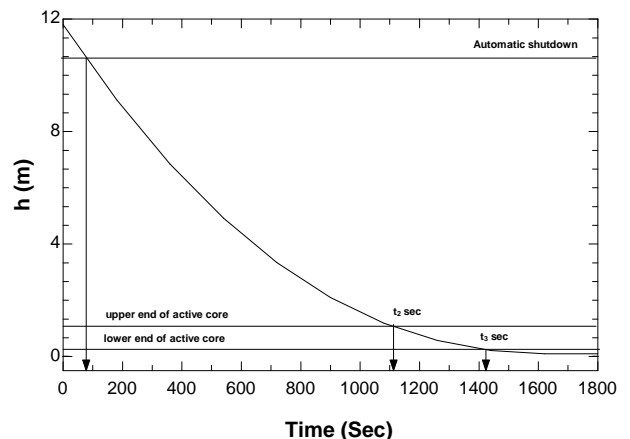


Fig. 2 - Variation of Pool Water Level With Time For Break Diameter = 12 Inches

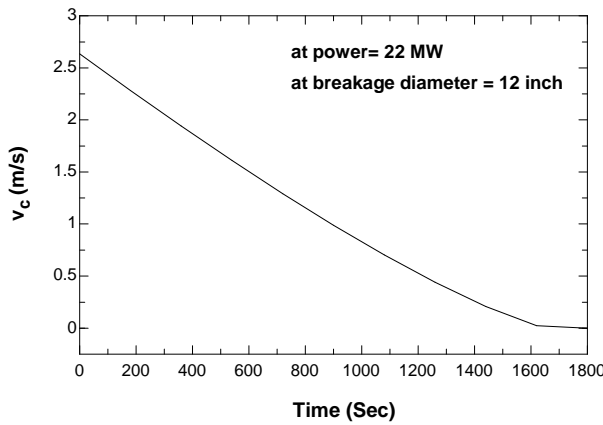


Fig 3 - Variation of Mean Core Water Velocity With Time for Break Diameter = 12 Inches

Where,

$t_1 = 75$ sec, $t_2 = 1113.9$ sec,
 $t_3 = 1422.3$ sec $t_4 = 1800$ sec

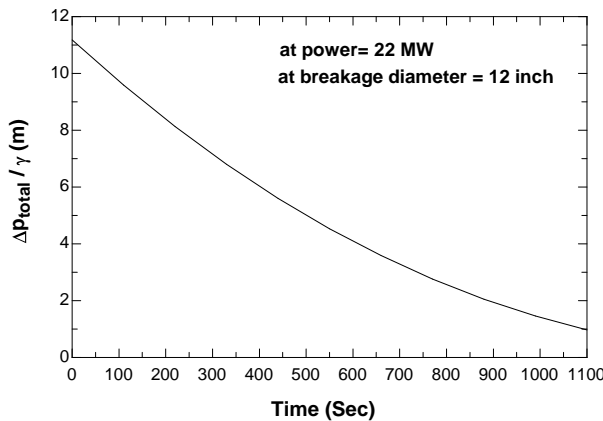


Fig. 4 - Variation of Total Pressure Drop Through The LOCA Path With Time

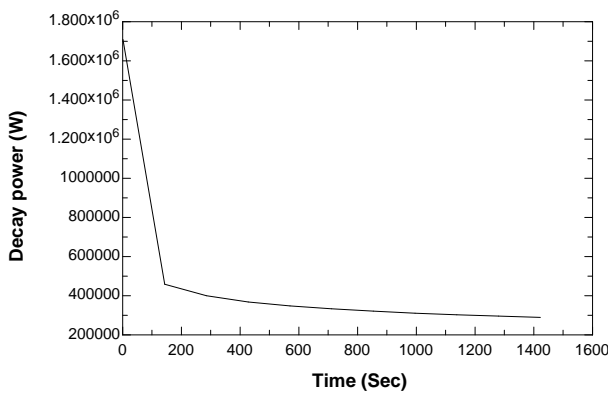


Fig.5 - Variation of Decay Power During LOCA With Time

1-1- Thermal-hydraulic Model

Considering a typical pool type research reactor with MTR type fuel elements of rectangular geometry, cooled with light water, and one-

dimensional core ⁽²⁾. The transient heat conduction equation is solved in the fuel and the clad. The general form of the time-dependent heat transfer equation from the fuel to the adjacent cladding is,

$$\frac{\partial T_f}{\partial t} = \frac{q''_f \cdot A_f}{M_f \cdot C_{pf}} - \frac{(T_f - T_{cl})}{\tau_f} \dots\dots\dots (30)$$

$$\tau_f = \frac{M_f \cdot C_{pf}}{U_f \cdot A_f} \dots\dots\dots (31)$$

$$U_f = \frac{K_f}{\delta_f} \dots\dots\dots (32)$$

$$\frac{\partial T_{cl}}{\partial t} = \frac{q''_{cl} \cdot A_{cl}}{M_{cl} \cdot C_{pcl}} - \frac{(T_{cl} - T_{co})}{\tau_{cl}} \dots\dots\dots (33)$$

$$\tau_{cl} = \frac{M_{cl} \cdot C_{pcl}}{U_{cl} \cdot A_{cl}} \dots\dots\dots (34)$$

$$\frac{\partial T_{co}}{\partial t} = \frac{q''_{co} \cdot A_{co}}{M_{co} \cdot C_{pco}} - \frac{(T_{cl} - T_{co})}{\tau_{co}} \dots\dots\dots (35)$$

$$\tau_{co} = \frac{M_{co} \cdot C_{pco}}{U_{co} \cdot A_{co}} \dots\dots\dots (36)$$

$$P(t) = P_0 \cdot (0.023178 \cdot x e^{-0.078t} + 0.05625 \cdot x t^{-0.2}) \dots\dots\dots (37)$$

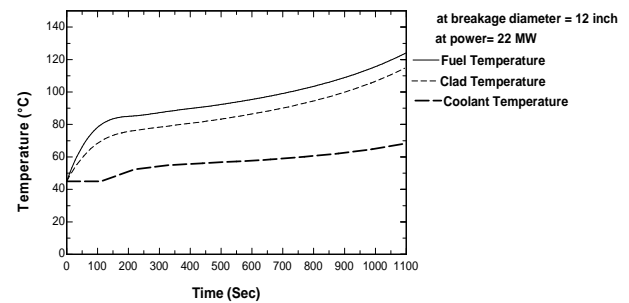


Fig. 6 - Variation of Fuel, Clad and Coolant Temperatures in Average Channel During LOCA Accident With Time

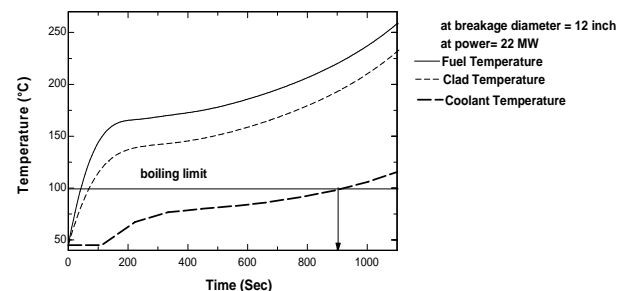


Fig. 7 - Variation of Fuel, Clad and Coolant Temperatures in Hot Channel During LOCA Accident With Time

2- UNCOVERED CORE MODEL

The reactor core is surrounded by water, which acts as moderator, reflector, coolant and biological shield in an open pool research reactor. An accident that could lead to water loss in the pool, and consequently, to direct exposure of the fuel elements in the reactor core to the air, will be followed by substantial fuel element temperature increase due to fuel element residual decay heat⁽³⁾. In this study, lumped parameter model is used to evaluate fuel element temperature, which respects to time for MTR reactor fuel elements following total loss of pool water. A single channel system, as shown in Fig. (7) is considered. No conductive or radiative heat transfer is allowed in the model analysis. Convective heat loss is constrained by the width of the coolant channel within the fuel element. Therefore, convection is allowed to occur only from inside the channel and not from plate edges, which are taken as adiabatic surfaces.

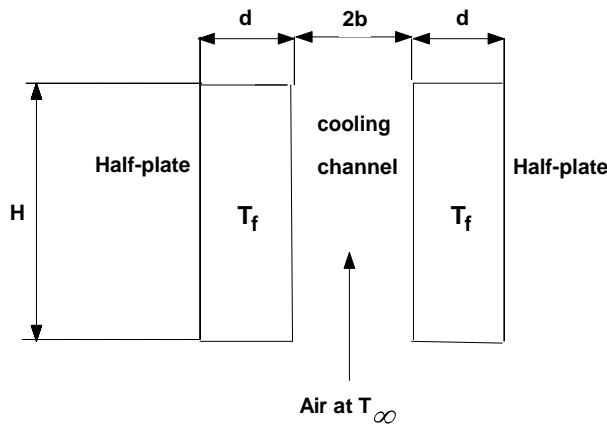


Fig. 8 - Schematic of Heat Transfer Model for Cooling of Reactor Fuel Plates Through Natural Circulation of Air

Heat transfer is determined from the solution of the energy conservation equation, as formulated for a lumped heat capacity approach for the fuel plates and the associated cooling channel⁽⁴⁾.

$$\rho_f \cdot C_f \cdot \frac{dT_f}{dt} = h_T \cdot (T_f - T_C) + \frac{P(t)}{2 \cdot N \cdot S_f} \dots\dots\dots(38)$$

$$\rho_C \cdot C_C \cdot b \cdot \frac{dT_C}{dt} + \frac{2}{H} \cdot \rho_C \cdot C_C \cdot b \cdot U \cdot (T_C - T_\infty) = h_T \cdot (T_C - T_f) \dots\dots\dots(39)$$

Where

T is the temperature , ρ the density, C the specific heat, h_T the heat transfer coefficient, d the fuel plate half-width, b the cooling channel half-width H the height of the channel, S_f the fuel plate

surface, U the air velocity in the channel, and N the number of plates in the core. The subscripts f, c and ∞ refer to fuel plate coolant (air) and free stream (ambient air), respectively.

For simplicity, the heat transfer coefficient is taken constant, determined as

$$h_T = \frac{Nu \cdot \lambda_c}{D_h} \dots\dots\dots(40)$$

Where

λ_c is the air thermal conductivity, D_h the cooling channel hydraulic diameter, and Nu the Nusselt number. We used a Nusselt number Nu = 7.5 this selection is based on available analytical solutions for laminar flow heat transfer in rectangular ducts of arbitrary aspect ratio.

The velocity U at which air rises in the channel is unknown, and has to be determined from the balance between buoyancy and frictional forces⁽⁵⁾. The pressure differential due to buoyancy is

$$\Delta P = (\rho_\infty - \rho_c) \cdot g \cdot H \dots\dots\dots(41)$$

Hence, the momentum balance can be expressed as:

$$\Delta P = \frac{1}{2} \cdot \rho_c \cdot U^2 \cdot \left(1 + \sum \zeta + 4 \cdot f \cdot \frac{H}{D_h} \right) \dots\dots\dots(42)$$

Where

∑ ζ the sum of the various local resistances such as inlet and exit effects suppose = 0, and f the friction factor. Assuming laminar flow, the friction factor is determined as:

$$f = \frac{C_f}{Re} \dots\dots\dots(43)$$

Where

C_f is constant depending on the aspect ratio of the rectangular channel cross-section and (Re) is the Reynolds number. The latter is defined by

$$Re = \frac{\rho_c \cdot U \cdot D_h}{\mu_c} \dots\dots\dots(44)$$

Where

μ_c is the air viscosity. By substituting the preceding expressions into Eq. (42), it can be verified that velocity U becomes the solution of a quadratic equation. The result is

$$U = \frac{4 \cdot C_f \cdot \mu_c \cdot H / \rho_C \cdot D_H^2 + \sqrt{\Delta}}{2(1 + \sum \zeta)} \dots\dots\dots(45)$$

Where the discriminant Δ is

$$\Delta = \left(\frac{4 \cdot C_f \cdot \mu_c \cdot H}{\rho_c \cdot D_H^2} \right)^2 + \frac{8(1 + \sum \zeta) \cdot \Delta P}{\rho_c} \dots\dots(46)$$

Equations 37 - 39 in conjunction with Eqs. (41), (45) and (46) give rise to a non-linear dynamic system that can be solved numerically.

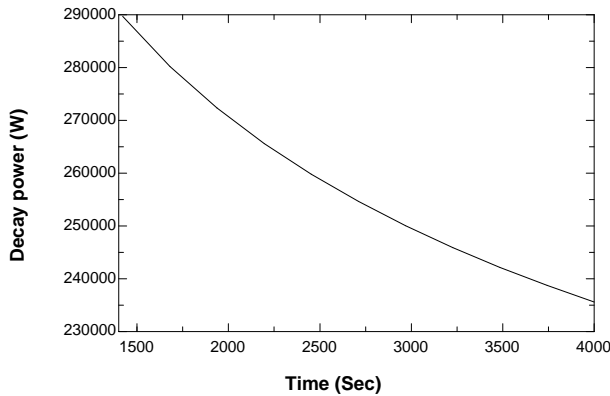


Fig. 9 - Variation of Decay Power With Time During Cooling by Free Air

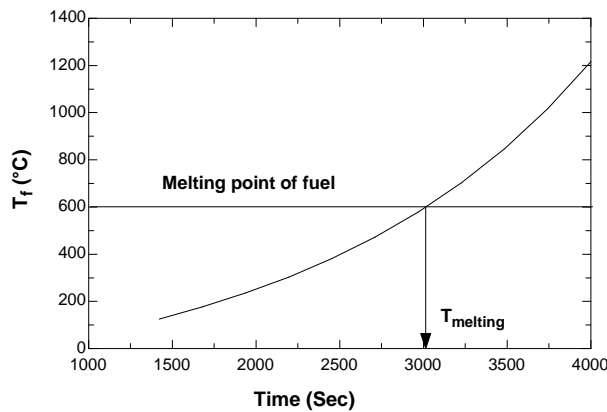


Fig. 10 - Fuel Temperature Response During Uncovered Core phase

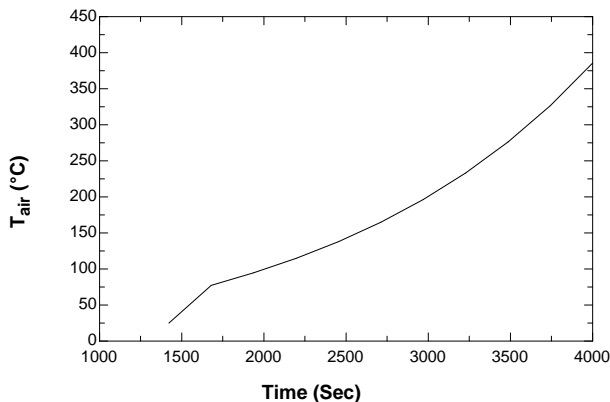


Fig.11- Air Temperature Response During Uncovered Core Phase

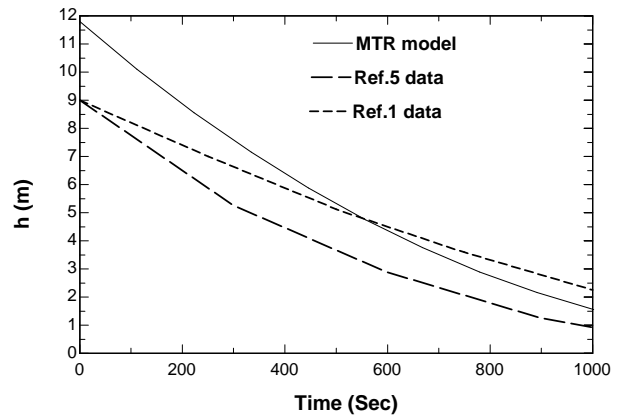


Fig. 12- Comparison Between Current Model and Model of C. Housiadas

RESULTS AND DISCUSSION

As an illustrative case of the results, the primary pipe is assumed broken guillotine-like due to earthquake between the flat plate heat exchanger and primary cooling pump outlet. The height of pool water start to decrease gradually with the time and the reactor supposed to shutdown at the same moment of the earthquake occurring so the reactor power at this point is the decay power, the level of the pool reach to the top of the reactor core after (1113.9 sec) and reach to the core bottom after 1422.3 sec and the core totally uncovered after 1800 sec as shown in Fig.(2).

During (LOCA) accident the water velocity in the core were calculated in each time step which decreased with the time because it is function in the breakage water velocity as shown in Fig.(3).

The total pressure drop of the system along (LOCA) streamline were calculated as a function of the breakage water velocity we observed that the pressure drop of the flat plate heat exchanger has greater contribution than the pressure drop of the core, fitting and the pipe line. So as the breakage water velocity decreased with the time the total pressure drop along the system also decreased with the time as shown in Fig.(4).

Figure (5) depicts the variation of the decay power with the time. The reactor power decreased from 22 MW to 1.7 MW in 1 sec and continue to decrease with the time according to equation (37) and decreased to 0.289 MW in 1422 sec.

Figure (6) depicts the time evolution of the fuel plate, clad and coolant temperatures in average channel during the (LOCA) accident. We found that each time step the fuel, clad and coolant

temperatures increases with the time. Because, as the pool water level decreases with the time, the pool temperature increased with the time, also coolant velocity inside the core decrease with the time so Reynolds also decrease and Nusselt number decrease so the heat transfer coefficient decrease, hence the clad and fuel temperatures increased also. The coolant temperature starts with 45 °C at the beginning of the (LOCA) event and reached to 68.54 °C at the top of the core. also the fuel and clad temperature reached to 116.4 , 125.4, °C respectively.

Figure (7) shows the time evolution of the fuel plate, clad and coolant temperatures in the hot channel during the (LOCA) accident. We notice that bulk boiling will start occurring after 900 sec i.e (15 min).

Figure (9) shows the variation of decay power with time, its value was 0.289 MW at the bottom of the core.

Figure (10) shows the time evolution of the fuel plate temperature during cooling by natural air, i.e totally core uncover. We notice that the core start to meltdown at time equal 1548.3 sec i.e. The fuel

will start to meltdown after 25.8 (mint) following core uncoverage.

Figure (11) shows the air temperature during the core uncoverage phase, with the time the temperature of cooling air gradually increases starting with 25 °C.

Figure (12) shows comparison between A.Yilmazer, C.Housiadas and the current model of MTR. C.Housiadas investigated the loss of coolant accident via complete break of 10 – inch inlet pipe for GRR-1(Greece Research Reactor) which is 5 MW full power and 9 (m) the height of water inside the pool. We notice that the three curves have the same trend decreasing with the time during LOCA accident but we have different slope of decreasing due to different LOCA pipeline path lengths which leads to different pressure drops.

CONCLUSION

The loss of coolant accident (complete break of the 12-inch outlet pipe) will lead to core uncover after 23.7 (min) and complete pool drainage after 30 (min). Air cooling is not adequate to remove decay heat (hence, core melt will occur).

REFERENCES

- 1- A. Yilmazer and H. Yavuz ; *Kerntechnik* ; 69, 154 (2004).
- 2- B. Tayfun and Y. Hasbi; "*Proceeding of the Second Eurasian Conference on Nuclear Science and its Application*"; 85 (2003).
- 3- A. B. Salah, B.Meftah, T. Hamidouche and E. Si-Ahmed; *Annals of Nuclear Energy*; 33,405 (2006).
- 4- A. Yilmazer and H. Yavuz; "*Proceeding of Nuclear Science and its Applications Conference*"; 1,33 (2003)
- 5- C. Housiadas; *Annals of Nuclear Energy*; 29, 1315 (2002).