Assessment of Cooling System Reliability based on its Success Criteria during Transient Condition

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ABSTRACT
Evaluation of cooling system reliability of any heat generation system has important impact on system engineering safety during transient conditions. Loss or reduction of flow is the main transient initiating event that leads to reduction in heat transfer ability of the cooling system.

The research target is to evaluate the reliability of typical cooling system theoretically based on its success criteria during both steady & transient states. It emphasis on analytical approach to fix the main success criteria of cooling system based on calculated heat transfer parameters during flow reduction transient, while it use the probabilistic approach for evaluating overall system reliability based on this success criteria. Four types of design layout is specified during this study which fulfill cooling system design criteria during postulated cooling deficiency that leads to sequential local or nucleate boiling on heat resource surface and extends to film boiling and boiling crisis later on.

System reliability calculations are conducted for two types of success criteria. The first is based on 75% of full cooling capacity, while the second requires 50% of full cooling capacity for each type of design layout which ensures minimum cooling requirements during above mentioned transient conditions. The results show the effect of redundant pumping branches increase on the overall system reliability during steady state operation. It investigates further system reliability versus redundancy percentage based on the number of cooling system branches required for each design type during transient condition based on its success maintain certain acceptable temperature on heat source surface during transient conditions.

Keywords
Reliability, success criteria, flow reduction transient, nucleate and film boiling.

1. INTRODUCTION
Several researches have been conducted to estimate cooling system reliability based on deterministic approach which deals directly with the boiling safety margins as design criteria during both steady and transient conditions.

Qing Lu et al. 2009 [1], investigated the course of the partial and total blockage of a channel in the IAEA 10 MW MTR pool type research reactor core without scram. The analysis was performed with best estimate code RELAP5/MOD3.3. The interaction of the obstruction channel and its adjacent channels has been taken into account. The results indicated that even when the flow channel has been totally blocked, there is still no boiling occurrence, and the fuel temperature is low enough to maintain its integrity. ***Hainoun et al. 2010*** [2], used the thermal hydraulic code **MERSAT**, (Model for Evaluation of Reactor Safety and Analysis of Thermal hydraulic) in his study. Detailed model including primary and secondary loop was developed for the International Atomic Energy Agency, IAEA reference research reactor material MTR 10MW. The developed model enables the simulation of expected neutronic and thermal hydraulic phenomena during normal operation, reactivity and loss of flow accidents. They found that two different losses of flow accident have been simulated using slow and fast decrease time of core mass flow rate. In both cases the expected flow reversal from downward forced to upward natural circulation has been successfully simulated. His results indicated that in accidents the limit of onset of sub-cooled boiling was not arrived and consequently no exceed of design limits in term of thermal hydraulic instability or **DNB** is observed. ***Hong Gao and Xuewu Cao 2011***[3], developed a mathematical model for solving flow rate transient and pump speed transient during flow coast down period. The flow rate and pump speed solved analytically. The calculated non-dimensional flow rate and non-dimensional pump speed using the model compared with published experimental data of two nuclear power plants and a reactor model test on flow coast down transient. The comparison results showed a good agreement. As the flow rate approaches to zero, the difference between experimental and calculated values increases due to the effect of mechanical friction loss.

A.W. Ezzat & S. I. Hasan [4], conduced thermal analysis for immersed heat source during flow reduction transient. The authors introduced theoretical and experimental study of transient heat transfer parameters related to downward flowing water in a circular concentric annular channel. The cooling channel is exposed internally to sinusoidal heat flux and has an adiabatic outer surface. The present theoretical study investigated the heat transfer and thermodynamic parameters during of 25%, 50%, and 75% flow reduction transients. The related experiments to such flow reductions simulates the loss of flow accidents (***LOFA***) in the research nuclear reactors initiated by loss of main power supply, pump failure, heat exchanger blockage, pipe blockage or valve closing. It is concluded that ***K*** value reaches around unity for 25% and 50% of flow reduction percentage transient at around 5 and 3 seconds respectively from transient initiation while the ***K*** value dropped below the unity at 75% of flow reduction transient. The surface dry out takes place during 75% and 100% flow reduction at normalized distance of 0.65 away from the cooling channel entrance based on experimental observation due to the onset of flow instability

(***OFI***) that encounter the downward flow direction at low pressure and low velocity system (***LPLV***). It's also conclude that the elapsed time required for the surface temperature to reach its steady state values after each transient scenario is less than that related to bulk water temperature as long as the water temperature kept below its saturation temperature.

L. Burgazzi [5] investigated in his research reliability based design approach based on thermal – hydraulic thermal system. The concept of functional failure, i.e possibility that the heat will exceed the capacity in reliability frame work in terms of performance parameter is introduced by the author for the reliability evaluation of a natural circulation passive system, designed for decay heat removal of innovative light water reactor. Water flow rate circulating is selected as passive system performance characteristic parameter and the related limit state or performance function is defined. The probability of system failure is assessed in terms of safety margin, corresponding to the LSF. Results obtained from the research help the designer to determine the allowable limits or set the safety margin for the system operation parameters, to meet the safety and reliability requirements.

2. THEORETICAL ASSUMPTIONS AND CALCULATIONS

The heat generation system consists of heat source that produce 147.7 KW heat power. The heat source consist of 100 heating elements, each element is cooled by water inside an annulus between its outer surface and the water channel that contain the heating element as shown in figure (1). The total water flow rate in the cooling system required to cool the heat source is (6.4 m^3/hr), which ensures water velocity inside each cooling channel of 0.1 m/s.

Taking into account the friction losses in the system and flow control valve reduction ratio the cooling system design criteria requires 7.5 m^3/hr water flow rate during normal steady state condition. Fuel element and water channel dimensions are shown in figure (1).

Steady state operation, Case (1):
The following equations show the heat and mass balance for each cooling channel during steady state condition;

$Ah = 0.6 * \pi (0.02) = 3.77 * 10^{-2}\ m^2$

$Af = [(2.5 * 10^{-2})^2] * \frac{\pi}{4} = 1077 * 10^{-4}\ m^2$

$V = 0.1$ m/s

$\dot{m}_e = \rho\ v\ A\ f$

$10^3 * 0.1 * 1.77 * 10^{-4} = 1.77 * 10^{-2}$ kg

$\dot{m}_t = 1.77 * 10^{-2} * 10^2 = 1.77$ kg/ s

$\dot{m}_t = 1.77$ kg/s $* m^3/10^3$ kg $* 3600$s/ hr $= 6.4\ m^3$/hr

$h = 0.021\ \rho\ G\ (1+2.3D_e/L) / [(D_e\ G/\mu)^{0.2}\ Pr_f^{0.66}\ (\mu_w/\mu_b)^{0.14}]$

$h = 778\ w/m^2$

Where:

$De = 5 * 10^{-3}$, $\mu = 8.6x10^{-4}$, $Pr = 5.85$

$Qe = Q_t/100 = 147.4x1000/100 = 1474$ w

$q'' = 1474/(3.77x10^{-2}) = 3.9x10^4\ w/m^2$

$\Delta T_w = Q/\ m\ C_p = 1474/(1.77x10^{-2}x4170) = 20^oC$

$Tw_o = 40 + 20 = 60$

$Tc_o = Tw_o + q''/h = 60 + 3.9x10^4/778 = 120^oC$

Under full cooling system pressure, the local pressure in the thermal outlet ensures water sub cooled state near the heating surface.

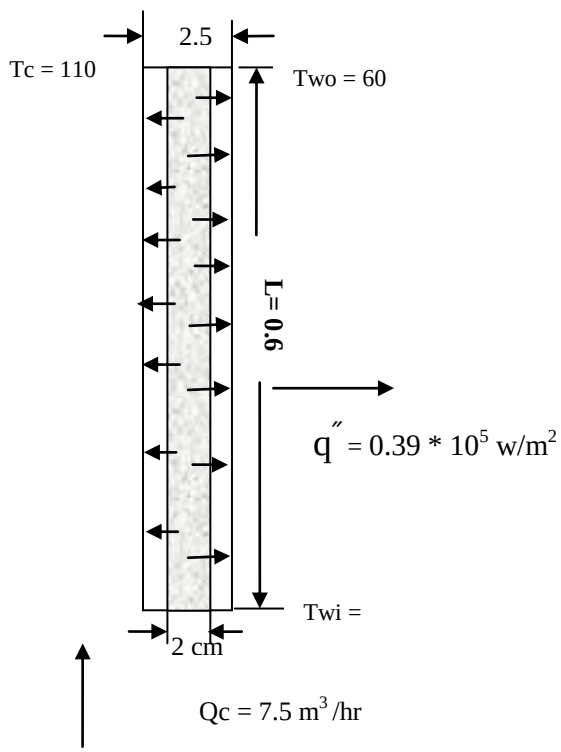

Figure 1: Cooling channel of heat source

Transient Conditions:
Case (2): (75% of full capacity)
$V = 0.075$ m/s, $Tc_o = 129.6$ °C, $Tw_o = 66.5$ °C

The postulated transient case ensures heating surface temperature above the water saturation temperature based on its local pressure which in turn leads to nucleate boiling that may extend to film boiling in case if it is not mitigated.

Case (3): (50% of full capacity)

$V = 0.05$ m/s, $Tc_o = 167^OC$

The postulated transient case ensures bulk water temperature close from water saturation temperature based on estimated two phase heat transfer coefficient.

<u>Design types considered in the calculations</u>: Cooling system water flow rate, Qp =7.5 m^3/hr

A. 1 pump ⇒ each 7.5 m^3/hr
B. 2 pumps ⇒ each 3.75 m^3/hr
C. 3 pumps ⇒ each 2.5 m^3/hr
D. 4 pumps ⇒ each 1.875 m^3/hr

Case 1: <u>To reach Full Capacity (Qp = 7.5 m^3/hr)</u>

A. Use (2) pumps ⇒ s.c = 1/2
B. Use (3) pumps ⇒ s.c = 2/3
C. Use (4) pumps ⇒ s.c = 3/4
D. Use (5) pumps ⇒ s.c = 4/5

Case 2: <u>To reach 75% Capacity (Qp = 5.625 m^3 /hr)</u>

A. Use (2) pumps ⇒ s.c = 1/2

B. Use (3) pumps ⇒ s.c = 2/3

C. Use (4) pumps ⇒ s.c = 3/4

D. Use (5) pumps ⇒ s.c = 3/5

Case 3: <u>To reach 50% Capacity (Qp = 3.75 m^3 /hr)</u>

A. Use (2) pumps ⇒ s.c = 1/2

B. Use (3) pumps ⇒ s.c = 1/3

C. Use (4) pumps ⇒ s.c = 2/4

D. Use (2) pumps ⇒ s.c = 2/5

The cooling system consists of temperature sensing and flow controlling system which initiates and control the pumping branches used to cool the heat source and ensure steady state cooling requirements and keep heat source surface temperature below saturation temperature of the adjacent coolant to avoid nucleate boiling on its surface which may proceeds to film boiling during transient conditions.

Four types of design are chosen for analysis. Each of it has design criteria that ensure steady state safe operation during normal conditions and it has also to fulfill heat source integrity for a postulated period during transient conditions based on 75% of cooling system capacity and to withstand film boiling influence on heat removal by ensuring heat source integrity for additional time margin based on 50% of cooling capacity.

The design criteria of the cooling system is based on maximum (8) continuous operation hours per day during steady state operations while the transient condition requires certain time margin for 75% and 50% cooling system capacity to ensure system safety during transient condition. Due to special safety requirements of the heat generation system the cooling system operation and maintenance requirement refers to complete preventive test and maintenance on daily basis to return back system reliability to its original values during this mention period, each pumps line is isolated using the upstream for downstream valves.

Figure (2) shows system layouts for 4 design types while figure (3) illustrates the reliability block diagram for each system type. For the purpose of overall system reliability evaluation the reliability of each branch is estimated first using the following general equation which depends on the number of branches k that are required to success out of the total number of branches for each case, (design type), n.

$$\mathbf{Rb\,(k, n, r) = \sum^{n}_{r=k} \binom{n}{r} R_i^{k} (1 - R_i)^{n-r}}$$

Where:

n: is the minimum number of lines in each case per each type of design

k: is the minimum number of branches required for system success

R *i*: is the reliability of each branch

Note that this equation will be used for each system type based on their different success criteria. Figure (3) shows the reliability block diagram for the whole cooling system, RDB.

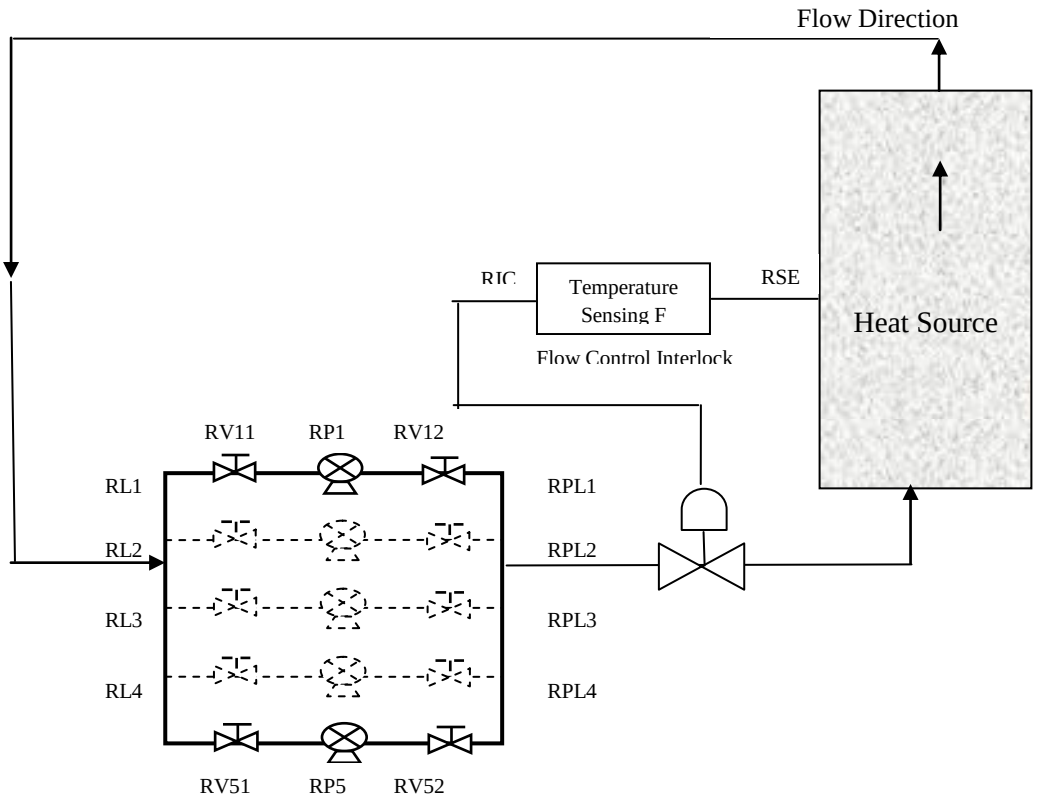

Figure 2: System layouts for 4 design types

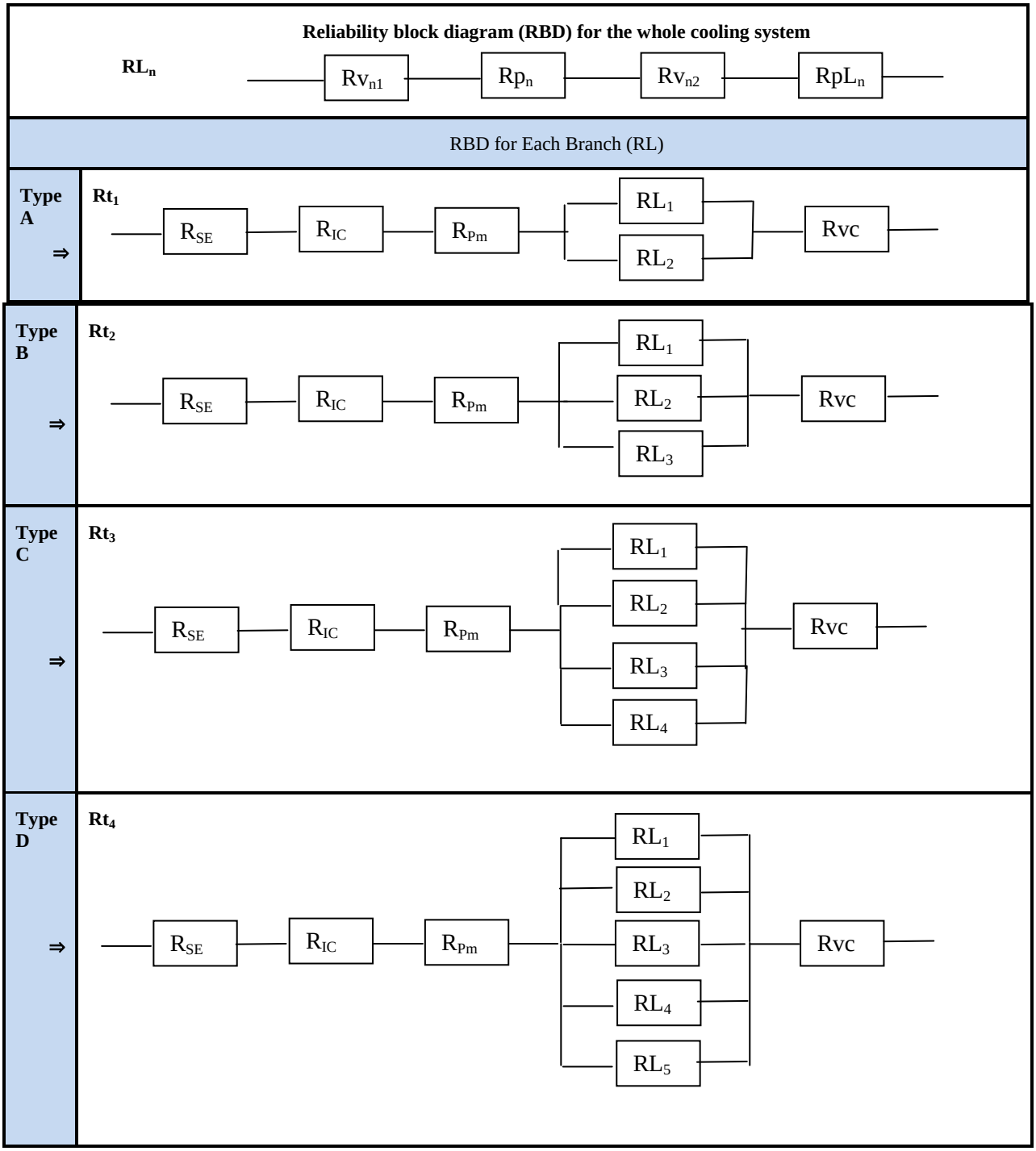

Figure 3: Reliability block diagram, RDB for the four cooling systems types

$\mathbf{RL_n = Rv_{n1}.\ Rp_n.\ Rv_{n2}.\ Rpl_n}$

Where:

n= 1, 2 for system type (A)

n= 1, 2, 3 for system type (B)

n= 1, 2, 3, 4 for system type (C)

n= 1, 2, 3, 4, 5 for system type (D)

3. RESULTS AND DISCUSSION

The reliability of cooling system components is estimated based on their failure rates using typical data for different mission times. Table (1) shows the failure rates and the estimated reliability of each component.

Table (1): System equipment reliability based on their failure rates during steady state and both cases of transient states.

Component	Failure rate, ⍲	Component Reliability, R_c based on 1/4 hr time interval	Component Reliability, R_c based on 1/2 hr time interval	Component Reliability, R_c based on 1 hr time interval	Component Reliability, R_c based on 2 hr time interval	Component Reliability, R_c based on 4 hr time interval	Component Reliability, R_c based on 8 hr time interval
Pump, P_n	$3*10^{-2}$/ hr	0.992	0.985	0.970	0.941	0.886	0.787
Branch pipeline, Pl_n	$1*10^{-4}$ / hr	0.999	0.999	0.999	0.999	0.999	0.999
Valve, V_n	$2*10^{-3}$/ hr	0.999	0.999	0.998	0.996	0.992	0.984
Main pipeline Pm_n	$2*10^{-4}$/ hr	0.999	0.999	0.999	0.999	0.999	0.998
Indicator controller, IC_n	$5*10^{-3}$/ hr	0.998	0.997	0.995	0.990	0.980	0.960
Sensing element, SE_n	$4*10^{-3}$/ hr	0.999	0.998	0.996	0.992	0.984	0.968
Control valve, VC_n	$1*10^{-2}$ / hr	0.997	0.995	0.990	0.980	0.960	0.923

Typical calculation procedure for estimation the reliability of different cooling system types for different success criteria during normal operation mode based on (8) hours continuous operation is shown below.

Type (A) System Design:

For such type of system the expected operation modes during steady state and transient cases are based on the number of branched required to be ready during these cases which are 0/2 and 1/2.

$\mathbf{Rs_{A,\,0/2} \Rightarrow R_{SE} \,.\, R_{IC} \,.\, R_{Pm} \,.\, (RL_1, RL_2)_{0/2} \,.\, Rvc}$

$RL_n = 0.984 * 0.787 * 0.984 * 0.999 = 0.761$

Where:

$\mathbf{(RL_1, RL_2)_{0/2} = \sum^{2}_{r=0} \binom{2}{0} RLn^r (1 - RLn)^{2-r}}$

$\mathbf{(RL_1, RL_2)_{0/2} = (1 - RL_n)^2 + 2\, RL_n\, (1 - RL_n) + RL_n^2}$

Thus;

$\mathbf{Rs_{A,\,0/2}} \Rightarrow 0.968 * 0.96 * 0.998 * [(1 - 0.761)^2 + \mathbf{2} * (0.761) * (1 - 0.761) + (0.761)^2\ ] * 0.923 = 0.856$

$\mathbf{Rs_{A,\,1/2} \Rightarrow R_{SE} \,.\, R_{IC} \,.\, R_{Pm} \,.\, (RL_1, RL_2)_{1/2} \,.\, Rvc}$

$RL_n = 0.984 * 0.787 * 0.984 * 0.999 = 0.761$

Where:

$\mathbf{(RL_1, RL_2)_{1/2} = \sum^{2}_{r=1} \binom{2}{1} RLn^r (1 - RLn)^{2-r}}$

$(RL_1, RL_2)_{1/2} = 1 - [(1 - RL_1) * (1 - RL_2)]$

Thus;

$\mathbf{Rs_{A,\,1/2}} \Rightarrow 0.968 * 0.96 * 0.998 * [1 - (1 - 0.761)^2] * 0.923 = 0.841$

Type (B) System Design

For such type of system the expected operation modes during steady state and transient cases are based on the number of branched required to be ready during these two cases which are 1/3 and 2/3.

$\mathbf{Rs_{B,1/3} \Rightarrow R_{SE} \,.\, R_{IC} \,.\, R_{Pm} \,.\, (RL_1, RL_2, RL_3)_{1/3} \,.\, Rvc}$

$\mathbf{RL_n} = 0.984 * 0.787 * 0.984 * 0.999 = 0.761$

Where:

$\mathbf{(RL_1, RL_2, RL_3)_{1/3} = \sum^{3}_{r=1} \binom{3}{1} RLn^r (1 - RLn)^{3-r}}$

$\mathbf{(RL1, RL2, RL3)_{1/3} = 3\, RL_n\, (1 - RL_n)^2 + 3\, RL_n^2 * (1 - RL_n) + RL_n^3}$

Thus;

$\mathbf{Rs_{B,1/3}} \Rightarrow 0.968 * 0.96 * 0.998 * [3 * (0.761) * (1-0.761)^2 + 3 * (0.761)^2 * (1-0.761) + (0.761)^3\ ] * 0.923 = 0.844$

$\mathbf{Rs_{B,2/3} \Rightarrow R_{SE} \,.\, R_{IC} \,.\, R_{Pm} \,.\, (RL_1, RL_2, RL_3)_{2/3} \,.\, Rvc}$

$\mathbf{RL_n} = 0.984 * 0.787 * 0.984 * 0.999 = 0.761$

Where:

$\mathbf{(RL_1, RL_2, RL_3)_{2/3} = \sum^{3}_{r=2} \binom{3}{2} RLn^r (1 - RLn)^{3-r}}$

$\mathbf{(RL_1, RL_2, RL_3)_{2/3} = 3\, RL_n^2 * (1 - RL_n)^1 + RL_n^3 * (1 - RL_n)^0}$

Thus;

$\mathbf{Rs_{B,2/3}} \Rightarrow 0.968 * 0.96 * 0.998 * [3 * (0.761)^2 * (1-0.761) + (0.761)^3] * 0.923 = 0.732$

Type (C) System Design

For such type of system the expected operation modes during steady state and transient cases are based on the number of branched required to be ready during these cases which are 1/4 , 2/4 and 3/4.

$\mathbf{Rs_{C,1/4} \Rightarrow R_{SE} * R_{IC} * R_{Pm} * (RL_1, RL_2, RL_3, RL_4)_{1/4} * Rvc}$

$\mathbf{RL_n} = 0.984 * 0.787 * 0.984 * 0.999 = 0.761$

Where:

$\mathbf{(RL_1, RL_2, RL_3, RL_4)_{1/4} = \sum^{4}_{r=1} \binom{4}{1} RLn^r (1 - RLn)^{4-r}}$

$\mathbf{(RL_1, RL_2, RL_3, RL_4)_{1/4} = 4* RL_n * (1 - RL_n)^3 + 6* RL_n^2 * (1 - RL_n)^2 + 4\, RL_n^3 * (1 - RL_n) + RL_n^4}$

Thus;

$\mathbf{Rs_{C,1/4}} \Rightarrow 0.968 * 0.96 * 0.998 * [4* (0.761) * (1-0.761)^3 + 6 * (0.761)^2 * (1-0.761)^2 + 4* (0.761)^3 * (1-0.761) + (0.761)^4\ ] * 0.923 = 0.853$

$\mathbf{Rs_{C,2/4} \Rightarrow R_{SE} \,.\, R_{IC} \,.\, R_{Pm} \,.\, (RL_1, RL_2, RL_3, RL_4)_{2/4} \,.\, Rvc}$

$\mathbf{RL_n} = 0.984 * 0.787 * 0.984 * 0.999 = 0.761$

Where:

$(RL_1, RL_2, RL_3, RL_4)_{2/4} = \sum^{4}_{r=2} \binom{4}{2} RLn^r (1 - RLn)^{4-r}$

$(RL_1, RL_2, RL_3, RL_4)_{2/4} = 6 * RL_n^2 * (1 - RL_n)^2 + 4 * RL_n^3 * (1 - RL_n) + RL_n^4$

Thus;

$Rs_{C,2/4} \Rightarrow 0.968 * 0.96 * 0.998 * [6 * (0.761)^2 * (1-0.761)^2 + 4 * (0.761)^3 * (1-0.761) + (0.761)^4] * 0.923 = 0.818$

$Rs_{C,3/4} \Rightarrow R_{SE} . R_{IC} . R_{Pm} . (RL_1, RL_2, RL_3, RL_4)_{3/4} . Rvc$

$RL_n = 0.984 * 0.787 * 0.984 * 0.999 = 0.761$

Where:

$(RL_1, RL_2, RL_3, RL_4)_{3/4} = \sum^{4}_{r=3} \binom{4}{3} RLn^r (1 - RLn)^{4-r}$

$(RL1, RL2, RL3, RL4)_{3/4} = 4 * RLn^3 * (1 - RLn) + RLn^4 * (1 - RLn)^0$

Thus;

$Rs_{C,3/4} \Rightarrow 0.968 * 0.96 * 0.998 * [4 * (0.761)^3 * (1-0.761) + (0.761)^4 *$

$(1-0.761)^0] * 0.923 = 0.648$

Type (D) System Design

For such type of system the expected operation modes during steady state and transient cases are based on the number of branched required to be ready during these cases which are 2/5, 3/5 and 4/5 .

$Rs_{D,2/5} \Rightarrow R_{SE} * R_{IC} * R_{Pm} * (RL_1, RL_2, RL_3, RL_4, RL_5)_{2/5} * Rvc$

$RL_n = 0.984 * 0.787 * 0.984 * 0.999 = 0.761$

Where:

$(RL_1, RL_2, RL_3, RL_4, RL_5)_{2/5} = \sum^{5}_{r=2} \binom{5}{2} RLn^r (1 - RLn)^{5-r}$

$(RL1, RL2, RL3, RL4, RL5)_{2/5} = 10 * RLn^2 * (1 - RLn)^3 + 10 * RLn^3 * (1 - RLn)^2 + 5 RLn^4 * (1 - RLn) + RLn^5$

Thus;

$Rs_{D,2/5} \Rightarrow 0.968 * 0.96 * 0.998 * [10 * (0.761)2 * (1-0.761)3 + 10 * (0.761)3 * (1-0.761)^2 + 5 (0.761)^4 * (1 - 0.761) + (0.761)^5] * 0.923 = 0.845$

$Rs_{D,3/5} \Rightarrow R_{SE} * R_{IC} * R_{Pm} * (RL_1, RL_2, RL_3, RL_4, RL_5)_{3/5} * Rvc$

$RL_n = 0.984 * 0.787 * 0.984 * 0.999 = 0.761$

Where:

$(RL_1, RL_2, RL_3, RL_4, RL_5)_{3/5} = \sum^{5}_{r=3} \binom{5}{3} RLn^r (1 - RLn)^{5-r}$

$(RL1, RL2, RL3, RL4, RL5)_{3/5} = 10 * RLn^3 * (1 - RLn)^2 + 5 * RLn^4 * (1 - RLn) + RLn^5$

Thus;

$Rs_{D,3/5} \Rightarrow 0.968 * 0.96 * 0.998 * [10 * (0.761)^3 * (1-0.761)^2 + 5 * (0.761)^4 * (1-0.761) + (0.761)^5] * 0.923 = 0.777$

$Rs_{D,4/5} \Rightarrow R_{SE} * R_{IC} * R_{Pm} * (RL_1, RL_2, RL_3, RL_4, RL_5)_{4/5} * Rvc$

$RL_n = 0.984 * 0.787 * 0.984 * 0.999 = 0.761$

Where:

$(RL_1, RL_2, RL_3, RL_4, RL_5)_{4/5} = \sum^{5}_{r=4} \binom{5}{4} RLn^r (1 - RLn)^{5-r}$

$(RL1, RL2, RL3, RL4, RL5)_{4/5} = 5 RLn^4 * (1 - RLn)^1 + RLn^5 * (1 - RLn)^0$

Thus;

$Rs_{D,4/5} \Rightarrow 0.968 * 0.96 * 0.998 * [5 * (0.761)^4 * (1-0.761)^1 + (0.761)^5 *$

$(1-0.761)^0] * 0.923 = 0.562$

Table (2) shows the reliability of different system types based on their success criteria and operation mission time. The first column refers to the adopted success criteria for system type. The white cells in the first column refers to success criteria of system type A, light gray cells refers to success criteria of system type B, moderate gray refers to success criteria of system type C while those related to system type D are colored by dark gray.

Table 2: System types reliability based on their success criteria and operation mission time

Type of system operation mode	System Reliability, R_s based on 1/4 hr time interval	System Reliability, R_s based on 1/2 hr time interval	System Reliability, R_s based on 1 hr time interval	System Reliability, R_s based on 2 hr time interval	System Reliability, R_s based on 4 hr time interval	System Reliability, R_s based on 8 hr time interval
0/2	0.993	0.989	0.980	0.961	0.925	0.856
1/2	0.993	0.989	0.979	0.956	0.909	0.841
1/3	0.993	0.989	0.980	0.961	0.923	0.844
2/3	0.992	0.988	0.977	0.949	0.882	0.732
1/4	0.856	0.8560099	0.85600871	0.85599169	0.85577294	0.853
2/4	0.993	0.989	0.980	0.960	0.918	0.818
3/4	0.992	0.987	0.973	0.937	0.848	0.648
2/5	0.993	0.989	0.980	0.961	0.924	0.845
3/5	0.993	0.989	0.980	0.959	0.909	0.777
4/5	0.992	0.986	0.969	0.923	0.807	0.562

As mentioned before system reliability during normal operation is based on full system capacity for continuous (8) hours operation. System reliability during transient condition based on 75% system capacity which leads to nucleate boiling on the heat source surface is estimated based on 30 minutes mission time while system reliability during transient condition that leads to film boiling during 50% system capacity operation mode is estimated based on 15 minutes mission time.

During steady state operation the system needs all their components including their branches based on the adopted success criteria. Such systems reliabilities are highlighted by blue color in last column of table (2) for (8) hour continuous operation mode. Figure (8) shows the relationship between system reliability and the redundant percentage RD% for each system design type. RD% refers also to the additional cost percentage during such adopted design.

Where:

Number of cooling branches available for such design type

RD% = ----------

Number of cooling branches required to fulfill steady state operation

During transient operation condition that leads to nucleate boiling the system needs all their components including their branches based on adopted success criteria highlighted by yellow colors shown in table (2) for minimum half an hour continuous operation mode. It is clear that for short times system reliability is not affected by the success criteria of each system design type. During transient operation condition that leads to film boiling the system needs all their components including their branches based on adopted success criteria highlighted by orange colors shown in table (2) for minimum quarter hour continuous operation mode. Same conclusion is reached regarding the minor effect of system design types on system reliability due to the short mission time. Figures (8&9) show the relation between system reliability and redundant percentage during both steady state and transient conditions.

4. CONCLUSIONS

It could be concluded that during steady state operation as system redundancy percentage increases its reliability increases but this reliability saturates at high redundant values, which means that system types C&D are more optimum than the other types. It is also clear that during transient conditions design types A&B does not pass through the nucleate boiling phenomena rather than it passes directly from normal operation mode to film boiling case which could be regarded as considerable drawback in addition to the extra cost of such type of systems estimated from their redundant percentage versus minor reliability enhancement gained from such types of cooling system designs. Accordingly optimum system design is adopted based on its reliability enhancement versus system cost which is related to its redundant percentage.

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6. REFERENCES

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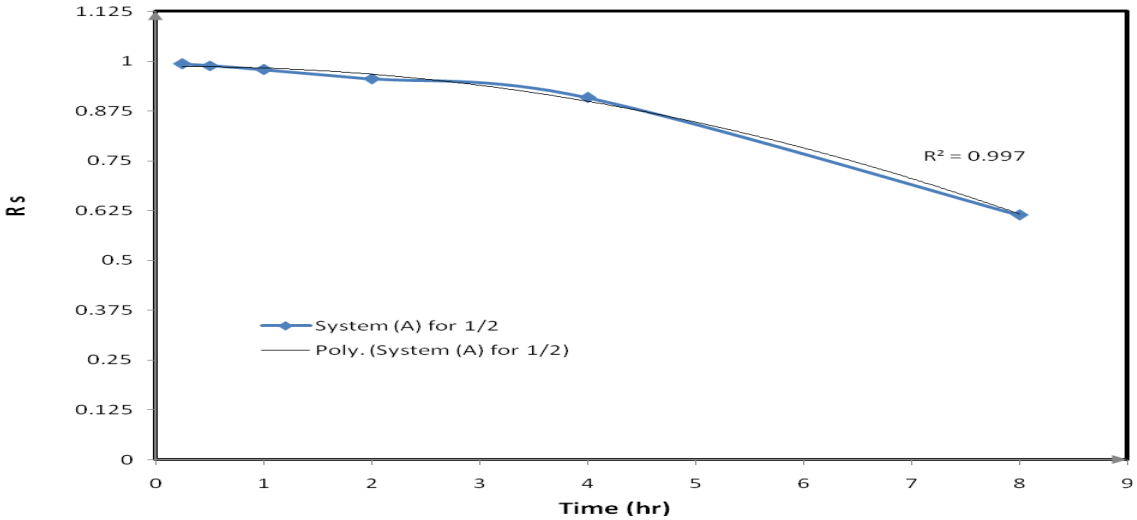

Figure 4: Relaibility of Cooling system type A based on 1/2 success crtieria

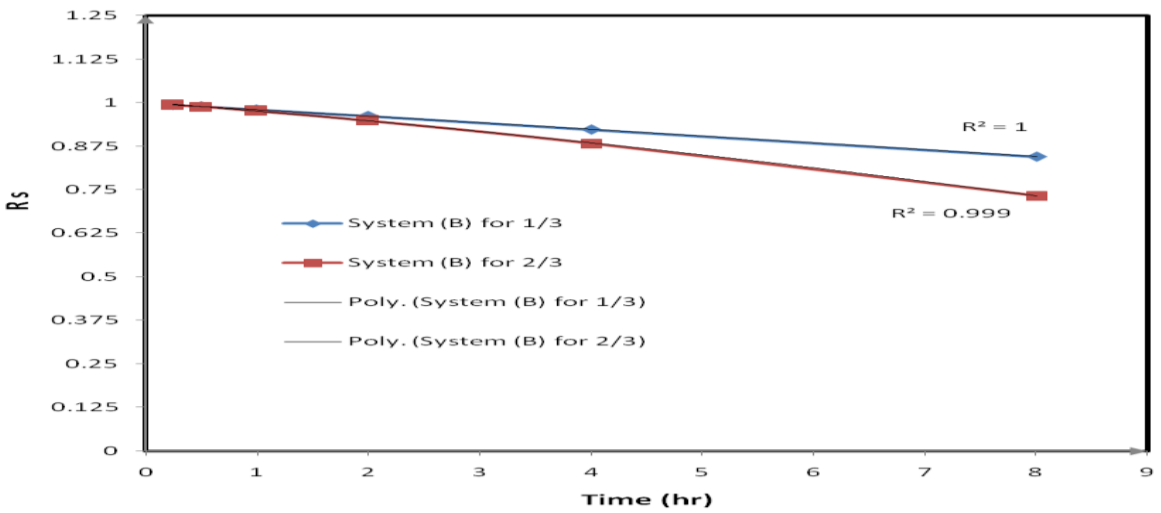

Figure 5: Relaibility of Cooling system type B based on 1/2 success crtieria

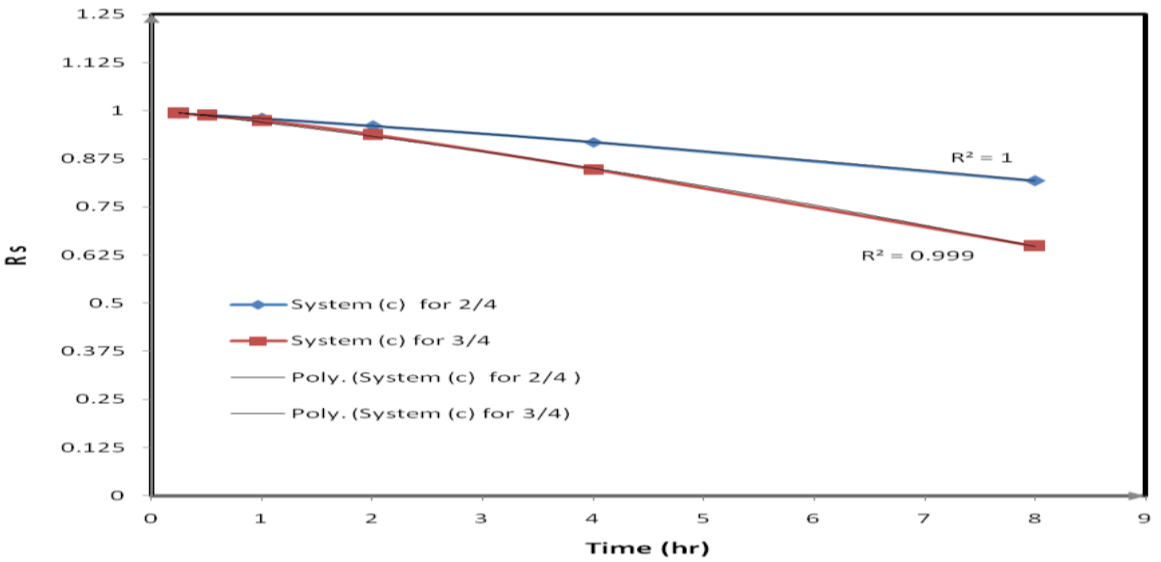

Figure 6: Relaibility of Cooling system type C based on 1/2 success crtieria

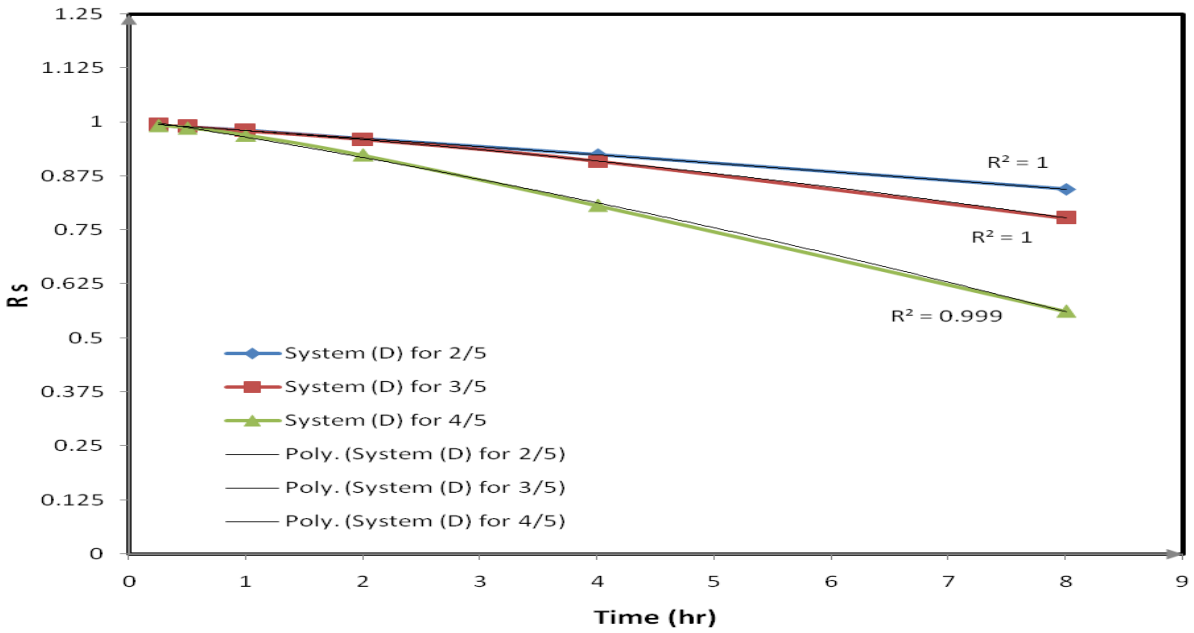

Figure 7: Relaibility of Cooling system type D based on 1/2 success crtieria

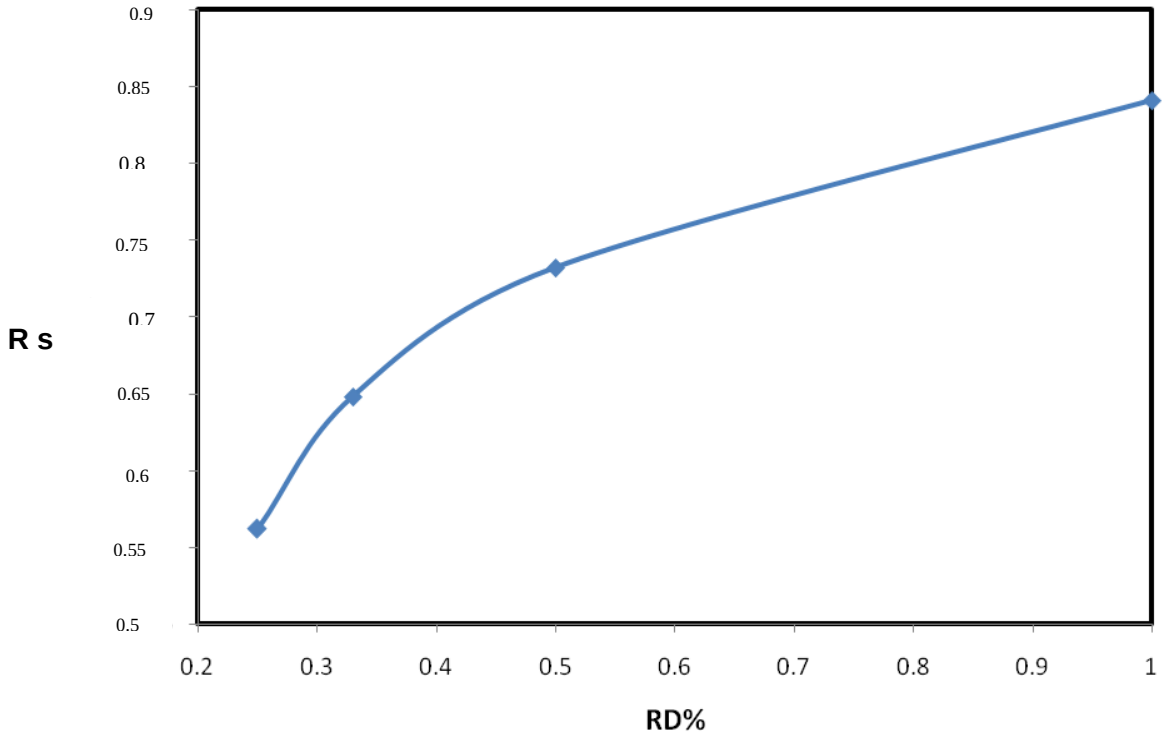

Figure 8: Cooling System Relaibility versus redundant percentage during steady state condition

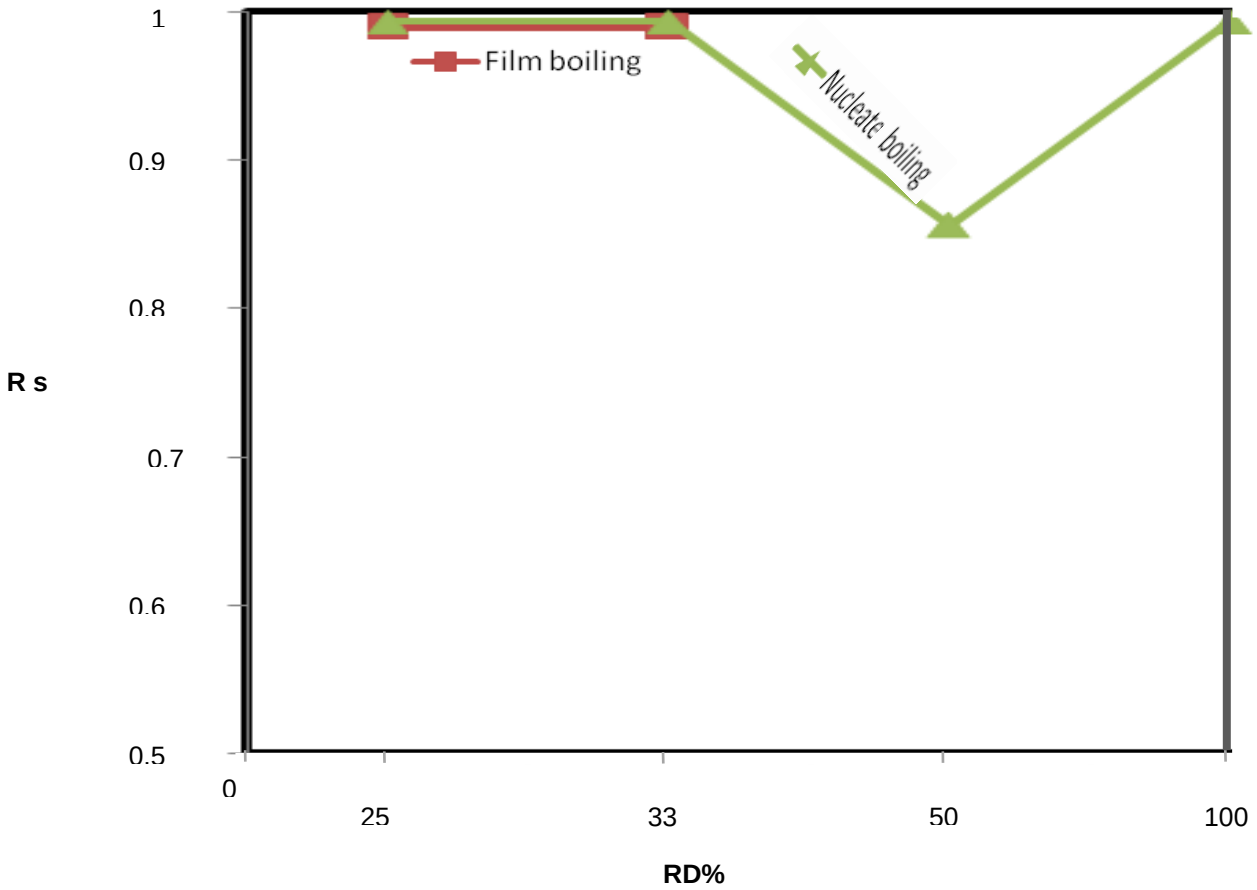

Figure 9: Cooling System Relaibility versus redundant percentage during transient condition