## NRCExecSec Resource

**From:** Timothy Margulies <t.margulies@gmail.com>
**Sent:** Monday, January 07, 2019 8:38 AM
**To:** NRCExecSec Resource
**Subject:** [External_Sender] Report
**Attachments:** TurkeyPtUnitsSevere Accident.pdf

Please find attached an investigation that may be of interest. It relates to an economic risk analysis applied to severe accidents at Turkey Point, FL Units.

Thank you for your attention to this matter.

Tim Margulies, Ph.D.

Severe Accident Modeling for Design Objectives: Prevention or Mitigation

The purpose of this investigation is to provide an economic analysis for life extension of a nuclear generating station that is vulnerable to severe accidents. The Turkey Point, FL Units 3 and 4 are chosen for the calculation. The site consists of 3-loop pressurized water reactors with dry, ambient pressure, containments. They reside approximately twenty-five miles South of Miami (location is latitude 25° 26' 04" North and longitude 80° 19' 52" West). A renewed operating license allows an additional twenty years of operation to their licensed forty years (1972-2012) with extension to the year 2032.

A Code of Federal Regulation, Part 50, 10 CFR Appendix I, calculation for design back-fit for normal operation, or expected occurrences, would only use a surrogate $1000 per person-REM conversion factor for latent cancers. This was increased to $2000 in 1995 and to $ 5100 for cost-benefit analysis. A value of a life saved of $9.0 million, and the ICRP 103 risk coefficient of 5.7 x 10-4 per rem obtains $5100 per person-rem. The dollar per person-rem conversion factor is for stochastic effects only. Figure 1 displays a range of valuations.

The amounts for converting, or valuing person-REM to dollars ranges up to $25000 per person-REM averted as displayed in the figure considering 400 to 500 person-REM and 1 to 10 million dollars for a life saved as shown Figure 1. NRC adopted (1991) risk conversion factors of 4 x 10-4 (0.0004 latent cancer fatalities) per person-REM for workers and 5 x 10-4 (0.0005 latent cancer fatalities) per person-REM for the general public.

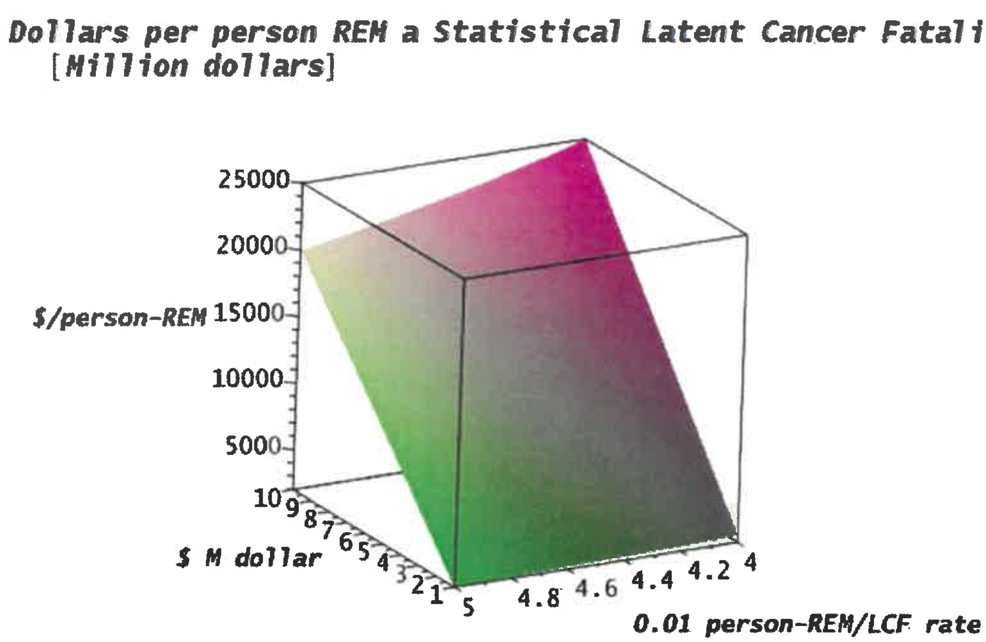


Figure 1: Regulatory Cost-Benefit Valuation

Therefore,

$$10.9\ \frac{expected\ person{-}REM}{reactor{-}year} \cdot \frac{\$5{,}100}{person{-}REM} \cdot 20\ reactor\ years,\ \text{or}\ \$\,1.1\ \text{M}\,.$$

Uncertainties or external event contributions would significantly increase the calculated results.

Data from the Turkey Point Units 3 & 4 submitted in a Life-Extension Licensing Application (Appendix F) were used to independently calculate the core-melt probability and expected off-site person-Sievert (1 Sv = 100 REM)). The reported core-melt probability and offsite person-REM [total collective effective dose equivalent] were verified.

Newer onsite and offsite costs were calculated for a range of interest rates (1% to 7% per year). The expectation of core-melt probability was increased by a factor of three, as well as, the expected person-REM.

Offsite person-REM := 32.633

Probability of Core Melt := 0.274 e-4 / Reactor-Year

Averted Costs calculated assuming $ 5,000/Person-REM

versus Interest Rates 1 through 7 %/year

$7.715965012\ 10^{7}, 6.394434939\ 10^{7}, 5.334474691\ 10^{7}, 4.479472229\ 10^{7},$
$3.785867476\ 10^{7}, 3.219995713\ 10^{7}, 2.755723629\ 10^{7}$

Averted Costs calculated assuming $ 2000/Person-REM

versus Interest Rates 1 through 7 %/year

$7.444511433\ 10^{7}, 6.157579724\ 10^{7}, 5.126914452\ 10^{7}, 4.296804554\ 10^{7},$
$3.624427058\ 10^{7}, 3.076721803\ 10^{7}, 2.628052579\ 10^{7}$

The expected consequences reflect wind rose probabilities which are debatable, since during Three Mile Island incident the winds rotated around the compass. At Miami the wind direction, wind speeds, and frequencies are displayed in a wind rose figure. The large population of Miami is situated North. Projected population estimates for the year 2025 were used in the off-site calculations of total collective dose.

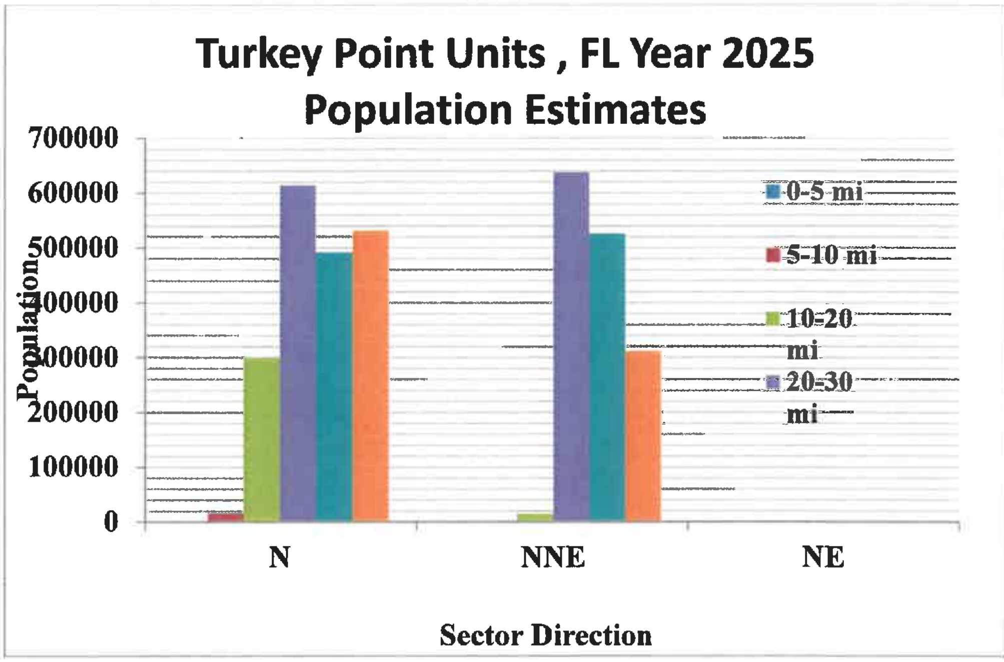


Figure 2

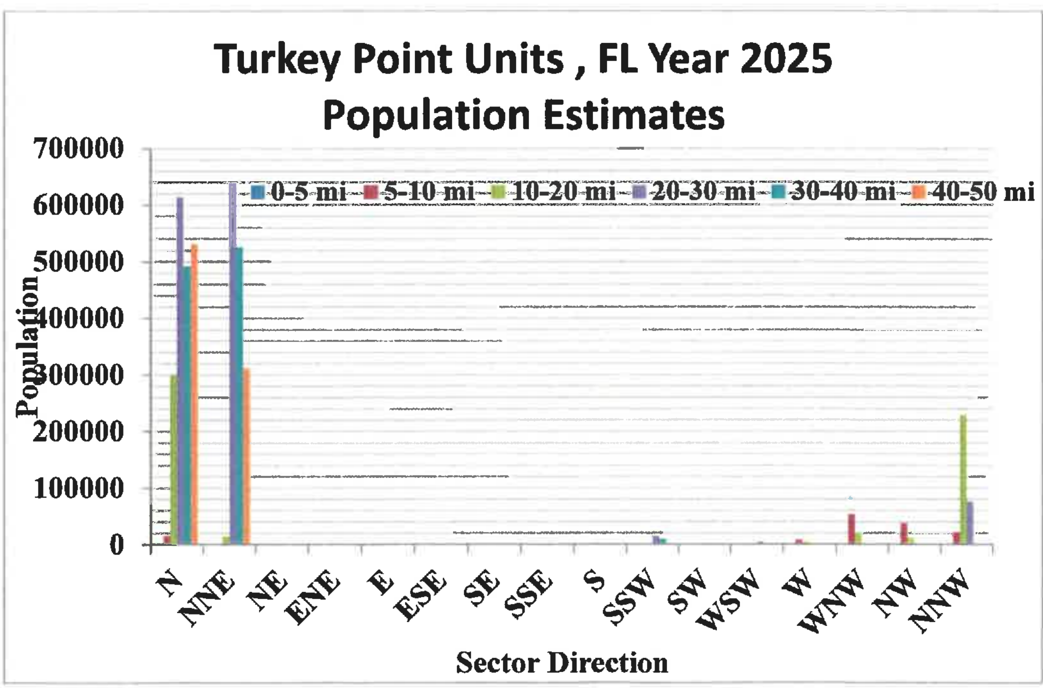


Figure 3

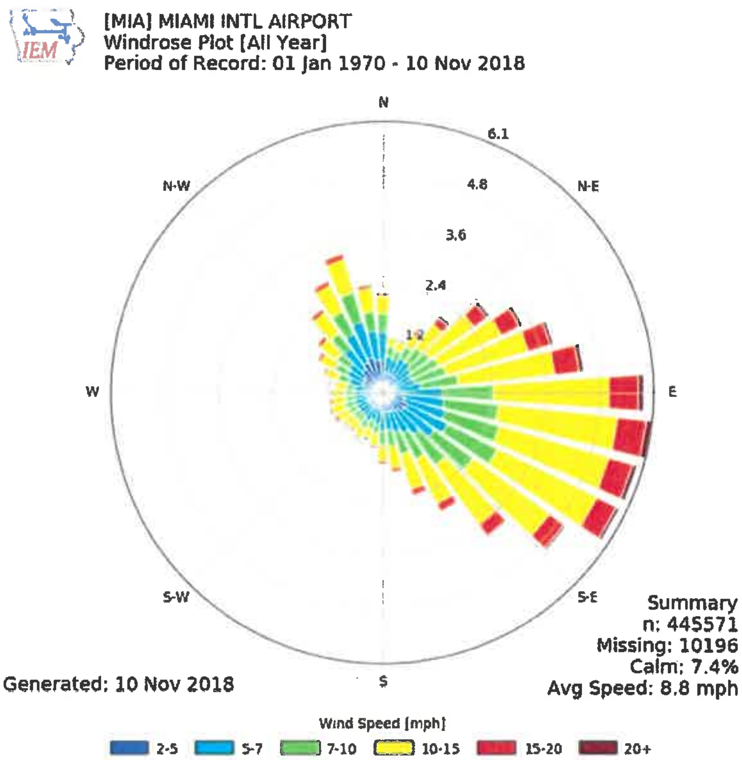


Figure 4: Wind rose packed with wind speeds, frequencies, and particular directions [Iowa Environmental Mesoset, Iowa State University].

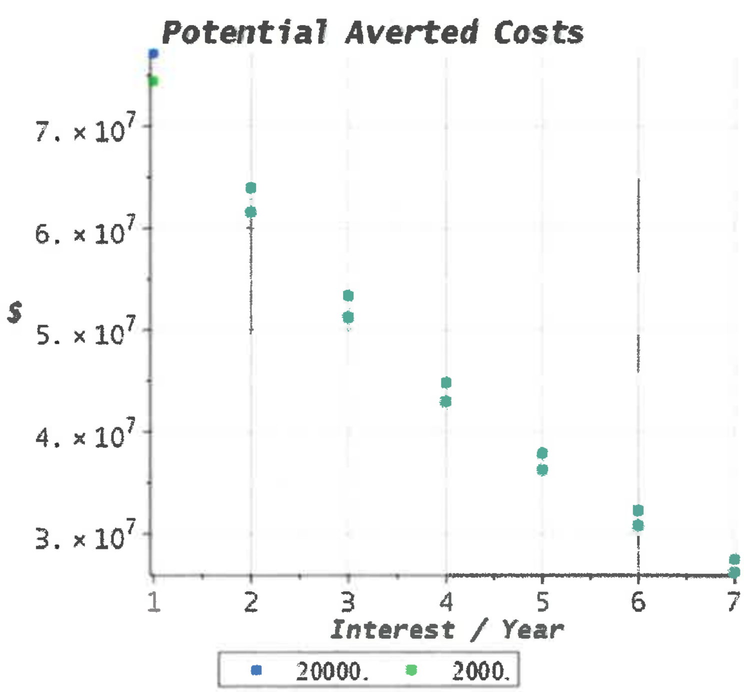


Figure 5: Onsite and Offsite Cost

The accident model scenarios account for containment barrier leaks (probability of $4.02 \cdot \frac{10^{-6}}{Reactor-Year}$), ruptures (probability of $3.84 \cdot \frac{10^{-6}}{Reactor-Year}$), or bypass of radioactivity to the atmosphere (probability of $7.95 \cdot \frac{10^{-8}}{Reactor-Year}$).

The technical probabilities are small; however, the accompanying disastrous consequences may not constitute an acceptable level of surety safety engineering for beyond the normal licensed service life. Prevention of core damage is generally achieved by stopping the fission chain reactions and by providing adequate coolant for heat removal requiring pumping, with its water and electrical supplies. The heat generated after shutdown would decay over a long period of time from accumulated fission products. The analysis would justify additional design hardware for achieving prevention or mitigation of accident consequences. To date, nuclear system safety is approached by safety goals, by aging management programs, by on-site inspections, by emergency preparedness, and by insurance. It is noted that Three Mile Island accident (March 28, 1979 ) liability claims cost: $ 70 M. and the Price-Anderson insurance for the nuclear industry is $ 450 M. per year. The final barrier to isolate large radioactive releases to the atmosphere remains vulnerable for these severe accidents beyond design basis assumptions.

| Additions/Modifications | $ Million | Subtotal |
|---|---|---|
| Reactivity poison (boric acid) injection system (valve explosive bolts) | 0.8 | |
| filtered hardened vent | 15.0 | 15.8 |
| ( costs range from $ 5M for sand/gravel to $ 30 M) | | |
| DC battery capacity | 1.8 | 17.6 |
| transfer & isolation switches | 2. | 19.6 |
| diesel generator | 10.8 | 30.4 |
| | | |
| Independent high pressure injection system | 29.2 | 59.6 |

Consider a discrete expected risk formulation, where the change in risk when a system modification is made is calculated by,

$$\Delta R = \sum_{i=1}^{k} p_i \, c_i - \sum_{i=1}^{k} p_i^m \, c_i^m$$

A conversion factor for costs would also be included.

Two special cases may be obtained.

Case 1: Probabilities of core melt are essentially the same, $p_i = p_i^m$, so that the expected risk change is dominated by the change in consequences as in effective filtering mitigation of particulates.

$$\Delta R = \sum_{i=1}^{k} p_i \, (c_i - c_i^m)$$

Case 2: Consequences remain essentially the same, $c_i = c_i^m$, such that the change in expected risk is driven by a probability of core melt change, such as, from a preventative modification.

$$\Delta R = \sum_{i=1}^{k} c_i \, (p_i - p_i^m)$$

Federal regulation, Title 10 CFR 50.109, addresses that a backfit may only be imposed if the NRC determines that "there is a substantial increase in the overall protection of the public health and safety or the common defense and security to be derived from the backfit and that the direct and indirect costs of implementation for that facility are justified in view of this increased protection." This rule also provides the exceptions.

References:

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L. Rahm-Crites , How Health Risk from Radiation is Assessed , UCRL-ID-118487 (July 1994)

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*NUREG/BR-0058 Revision 4, Regulatory Analysis Guidelines of the U.S. Nuclear Regulatory Commission*

Margulies, T., "United States Nuclear Power Safety Risk", Presentation, Research Gate, DOI: 10.13140/RG.2.2.18082.68805 (2016).

Margulies, T., "Simple Cost Risk-Benefit Calculation: Nuclear Plant Back-fit Analysis," *Reliability Engineering and System Safety*, vol. 86/13, 2004.

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restart : with(Student) : with(LinearAlgebra) : with(plots) : M1 := Matrix(47, 7, [[A1, 5.46
  × 10^1, 5.49 × 10^1, 5.46 × 10^1, 1.18 × 10^1, 1.19 × 10^4, 1.18 × 10^7], [A2, 2.48
  × 10^4, 2.48 × 10^4, 2.48 × 10^4, 4.48 × 10^9, 4.47 × 10^9, 4.48 × 10^9 ], [B1, 8.46 × 10
  ^2, 8.47 × 10^2, 8.46 × 10^2, 1.49 × 10^7, 3.06 × 10^6, 1.49 × 10^7 ], [B2-L, 2.64 × 10
  ^4, 2.65 × 10^4, 2.64 × 10^4, 5.11 × 10^9, 5.10 × 10^9, 5.11 × 10^9], [ B2-R, 3.73 × 10
  ^4, 3.74 × 10^4, 3.73 × 10^4 , 9.37 × 10^9, 9.36 × 10^9, 9.37 × 10^9 ], [B3-L, 8.46 × 10
  ^2, 8.47 × 10^2, 8.46 × 10^2, 1.49 × 10^7, 3.06 × 10^6, 1.49 × 10^7], [B3-R, 1.92 × 10
  ^3, 1.92 × 10^3, 1.92 × 10^3, 5.12 × 10^7, 3.93 × 10^7, 5.12 × 10^7 ], [B4-L , 2.64 × 10
  ^4, 2.65 × 10^4, 2.64 × 10^4, 5.11 × 10^9, 5.10 × 10^9, 5.11 × 109], [B4 − R, 3.78 × 10
  ^4, 3.78 × 10^4, 3.78 × 10^4, 9.38 × 10^9, 9.37 × 10^9, 9.38 × 10^9 ], [B5-L, 1.54 × 10
  ^3, 1.54 × 10^3, 1.54 × 10^3, 2.74 × 10^7, 1.56 × 10^7, 2.74 × 10^7 ], [B5-R, 3.28 × 10
  ^3, 3.28 × 10^3, 3.28 × 10^3, 1.23 × 10^8, 1.12 × 10^8, 1.23 × 10^8 ], [B6-L , 2.29 × 10
  ^4, 2.29 × 10^4, 2.29 × 10^4, 3.84 × 10^9, 3.83 × 10^9, 3.84 × 10^9], [B6-R, 2.74 × 10
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  8.07 × 10^3, 8.08 × 10^3, 8.07 × 10^3, 7.99 × 10^8, 7.93 × 10^8, 7.99 × 10^8], [C1-L,
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  1.92 × 10^3, 1.92 × 10^3, 1.92 × 10^3, 5.12 × 10^7, 3.93 × 10^7, 5.12 × 10^7], [C2-L,
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  8.46 × 10^2, 8.47 × 10^2, 8.46 × 10^2, 1.49 × 10^7, 3.06 × 10^6, 1.49 × 10^7 ], [C3-R,
  1.92 × 10^3, 1.92 × 10^3, 1.92 × 10^3, 5.12 × 10^7, 3.93 × 10^7, 5.12 × 10^7 ], [C4-L,
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  3.79 × 10^4, 3.80 × 10^4, 2.48 × 10^4, 9.38 × 10^9, 9.37 × 10^9, 4.37 × 10^9 ], [C5-L ,
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  8.20 × 10^3 , 8.83 × 10^3 , 8.20 × 10^3, 8.01 × 10^8, 7.95 × 10^8 , 8.01 × 10^8 ], [D2
  -L, 3.04 × 10^4 , 3.07 × 10^4 , 3.04 × 10^4 , 6.98 × 10^9 , 6.97 × 10^9, 6.98 × 10^9 ],
  [D2-R, 2.87 × 10^4, 3.92 × 10^4 , 2.87 × 10^4, 8.78 × 10^9, 8.77 × 10^9, 8.78 × 10^9 ],
  [D3-L , 1.63 × 10^4, 1.64 × 10^4, 1.63 × 10^4, 1.77 × 10^9, 1.76 × 10^9, 1.77 × 10^9 ],
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  [D4-L , 2.73 × 10^4, 2.76 × 10^4 , 2.73 × 10^4 , 5.23 × 10^9, 5.22 × 10^9, 5.23 × 10^9],
  [ D4-R, 2.69 × 10^4 , 3.56 × 10^4, 2.69 × 10^4, 7.14 × 10^9, 7.14 × 10^9, 7.14 × 10^9],
  [ E1-L, 5.70 × 10^3, 5.72 × 10^3, 5.70 × 10^3, 3.18 × 10^8, 3.07 × 10^8, 3.18 × 10^8],
  [ E1-R, 8.38 × 10^3, 9.05 × 10^3, 8.38 × 10^3, 8.02 × 10^8 , 7.95 × 10^8, 8.02 × 10^8],
  [ E2-L, 3.20 × 10^4, 3.23 × 10^4, 3.20 × 10^4, 6.98 × 10^9, 6.97 × 10^9, 6.98 × 10^9],
  [ E2 − R, 3.05 × 10^4, 4.22 × 10^4, 3.05 × 10^4 , 8.78 × 10^9, 8.78 × 10^9, 8.78 × 10
  ^9], [ E3-L , 5.70 × 10^3, 5.72 × 10^3, 5.70 × 10^3 , 3.18 × 10^8, 3.07 × 10^8, 3.18 × 10
  ^8], [ E3-R, 8.38 × 10^3, 9.05 × 10^3 , 8.38 × 10^3 , 8.02 × 10^8, 7.95 × 10^8, 8.02 × 10
  ^8], [ E4 − L, 3.20 × 10^4 , 3.23 × 10^4, 3.20 × 10^4 , 6.98 × 10^9, 6.97 × 10^9 , 6.98
  × 10^9], [ E4-R, 3.05 × 10^4, 4.22 × 10^4, 3.05 × 10^4, 8.78 × 10^9, 8.78 × 10^9 , 8.78
  × 10^9], [ E5-L, 1.63 × 10^4, 1.64 × 10^4, 1.63 × 10^4, 1.77 × 10^9, 1.76 × 10^9, 1.77
  × 10^9], [ E5-R, 1.89 × 10^4, 2.29 × 10^4 , 1.89 × 10^4, 3.41 × 10^9, 3.41 × 10^9, 3.41
  × 10^9], [ E6-L , 2.83 × 10^4, 2.86 × 10^4 , 2.83 × 10^4, 5.26 × 10^9, 5.25 × 10^9 , 5.26
  × 10^9], [ E6-R, 2.83 × 10^4, 3.80 × 10^4, 2.83 × 10^4 , 7.15 × 10^9, 7.14 × 10^9, 7.15
  × 10^9]])
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proby := Matrix(47, 2, [[ A1, 2.49 × 10^(-7) ], [A2, 1.18 × 10^(-7)], [ B1, 8.45 × 10^(
  -7 )], [B2 − L, 1.48 × 10^(-7) ], [B2 − R, 1.47 × 10^(-7) ], [B3 − L, 2.90 × 10^(
  -7) ], [B3 − R, 2.90 × 10^(-7) ], [B4 − L , 1.01 × 10^(-7) ], [B4 − R , 1.01 × 10^(
  -7) ], [B5 − L, 1.44 × 10^(-10) ], [B5 − R, 1.44 × 10^(-10) ], [B6 − L, 6.57 × 10^(
  -11) ], [B6 − R , 6.56 × 10^(-11) ], [BP − V, 6.24 × 10^(-8)], [BP − SGTR, 1.71
  × 10^(-8 )], [C1 − L , 1.06 × 10^(-6) ], [C1 − R , 1.06 × 10^(-6) ], [C2 − L , 7.02
  × 10^(-7) ], [C2 − R , 5.96 × 10^(-7) ], [C3 − L , 1.07 × 10^(-6) ], [C3 − R, 1.07
  × 10^(-6) ], [C4 − L, 6.46 × 10^(-7) ], [C4 − R, 5.59 × 10^(-7) ], [C5 − L , 2.02 × 1C
  ^(-10)], [ C5 − R, 2.02 × 10^(-10) ], [C6 − L, 1.30 × 10^(-10) ], [C6 − R, 1.01 × 1C
  ^(-10)], [D1 − L, 3.25 × 10^(-10)], [D1 − R, 3.25·10^-10], [D2 − L , 1.74 × 10^(
  -10)], [D2 − R, 1.74·10^-10], [ D3 − L , 0], [ D3-R , 3.32 × 10^(-12)], [D4 − L, 0],
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  ^(-10)], [E5 − L, 0 ], [E5 − R , 2.68 × 10^(-11)], [E6 − L, 0], [E6-R, 4.79 × 10^(
  -13)]]); M1[1, 7]; proby[1, 2]; n := 47; prob := [seq(proby[i, 2], i = 1 ..n)]; probt :=
  sort(prob); probs := add(prob); pSv0 := [seq(M1[i, 2]·proby[i, 2], i = 1 ..n)]; pSv0t :=
  sort(pSv0); pSv1 := add(pSv0); case := [seq(1.0·i, i = 1 ..n)]; ptsp := [seq([case[j],
  probt[j]], j = 1 ..n)]; plp := plot(ptsp, style = point, symbol = solidcircle, symbolsize = 12,
  color = blue, gridlines, title ='core melt probability per RY', titlefont
  = [COURIER, Bold, 14], labels = ["bin", "Prob."], labelfont = [COURIER,
  BOLDITALIC, 12], axesfont = [COURIER, 12]); ptsrm := [seq([case[j], pSv0t[j]], j = 1
  ..n)]; plpr := plot(ptsrm, style = point, symbol = solidbox, symbolsize = 12, color = green,
  gridlines, title ='expected population dose per RY', titlefont = [COURIER,
  Bold, 14], labels = ["bin", "person-Sv"], labelfont = [COURIER, BOLDITALIC, 12],
  axesfont = [COURIER, 12]);
```

Severe Accident Cost Analysis Notes

$$C_t = \frac{(1-e^{-i\cdot t_t})}{i} \; ; \; S_m = \frac{1}{m}\cdot\frac{(1-e^{-i\cdot m})}{i} = \frac{(1-e^{-i\cdot m})}{mi}$$

$Ofex = f \cdot prem \cdot LV \cdot C_t$ (Offsite exposure cost after discounting)

$Onst = f \cdot \delta_{OCA} \cdot LV \cdot C_t$ (Onsite exposure cost, short term)

$Ontot = Onst + Ofex$ (Total Onsite cost=short-term + long-term costs)

$OnLT = f \cdot \delta_{OCC} \cdot LV \cdot C_t \cdot S_m$ (Onsite exposure cost, long-term)

$O_{CD} = f \cdot C_{CD} \cdot C_t \cdot S_m$ (expected present value of decontamination & clean-up costs)

$R_P = f \cdot C_{RP} \cdot C_t^2 \cdot P_L$ (Power level factor (per 910MWe))

(replacement power cost summation of single event costs over the facility service life)

$$Total_{Int} = Ontot + O_{CD} + R_P$$

(Total Internal costs=Onsite total +Clean-up & decontamination total + replacement power)

$$Total_{Ext} = \varepsilon \cdot Total_{Int}$$

(External event costs obtained by a multiplier of the internal event cost total)

$$Total = Total_{Int} + Total_{Ext} = (1+\varepsilon)\cdot Total_{Int}$$

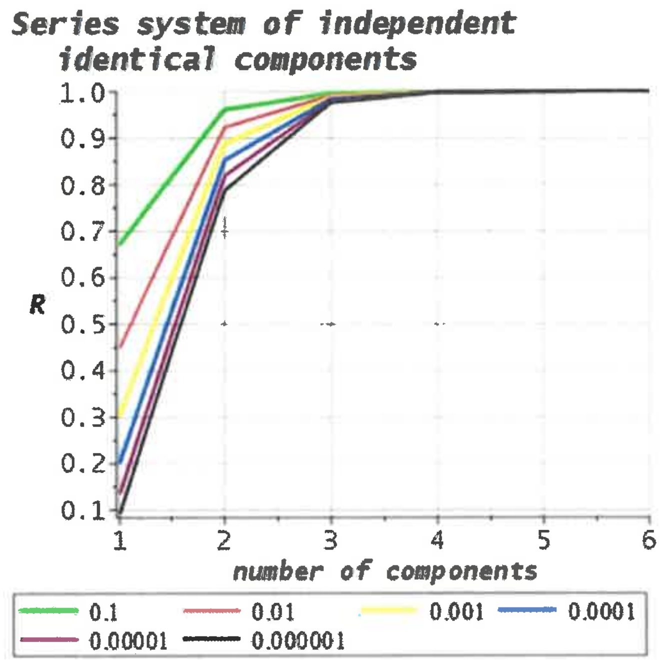
A present value factor useful in the costs calculation yields, $\int_0^T e^{-rt}\,dt = \left[\frac{e^{-rt}}{-r}\right]_0^T = \frac{1-e^{-rT}}{r}$. Note the limit definition of e, $limit_{n\to\infty}\left(1+\frac{1}{n}\right)^n \to e,\; limit_{n\to\infty}\left[\left(1+\frac{1}{n}\right)^n\right]^{-t} \to e^{-t}$

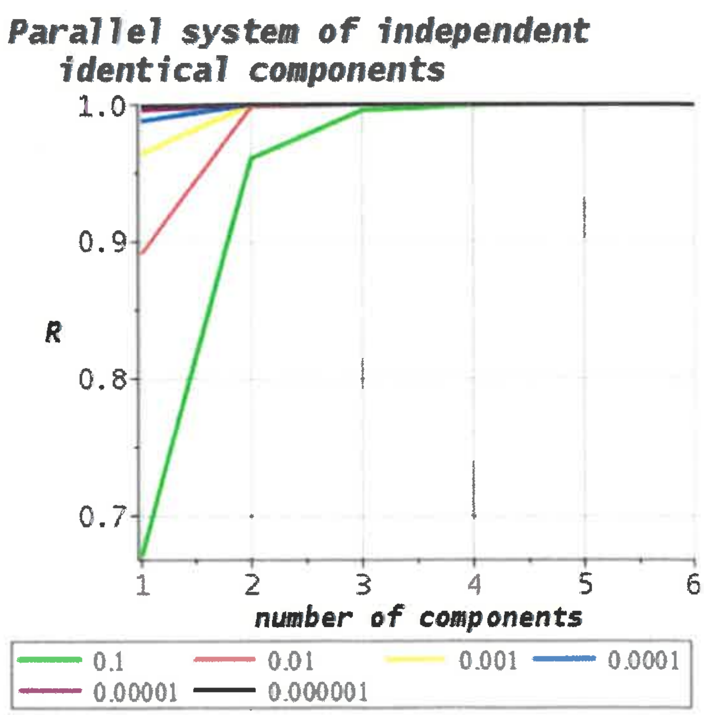
Define, $\frac{r}{N} = \frac{1}{n},\; n = \frac{N}{r}$, where, r = the interest rate per year, N = the number of compounding intervals per year, and, t = term in years. This yields a continuous compounding interest formulation,

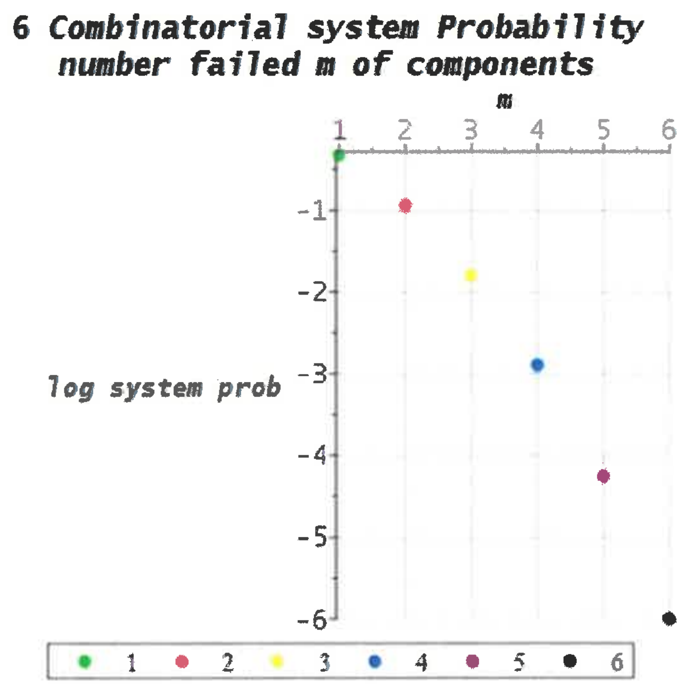
$$limit_{n\to\infty}\left[\left(1+\frac{r}{N}\right)^N\right]^{-t} = limit_{\frac{N}{r}\to\infty}\left[\left(1+\frac{1}{N/r}\right)\right]^{-Nt} = limit_{\frac{N}{r}\to\infty}\left[\left(1+\frac{1}{N/r}\right)\right]^{-\frac{N}{r}\cdot rt} \to e^{-rt}$$

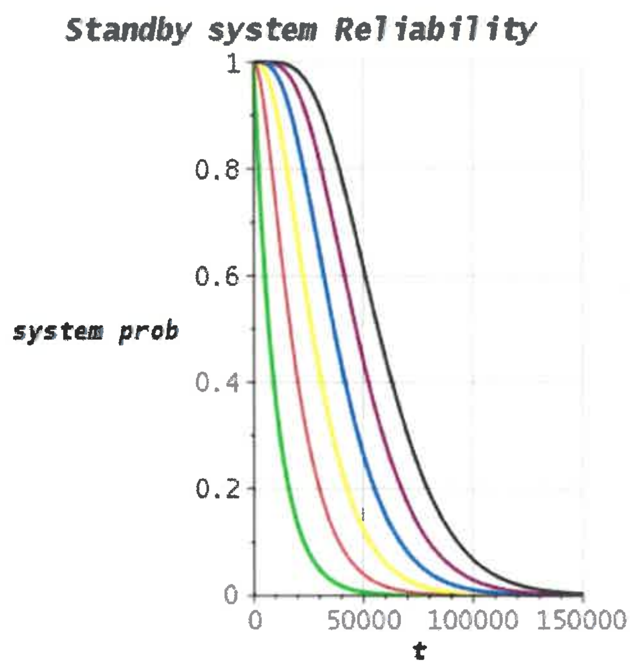
$$= limit_{\frac{N}{r}\to\infty}\left[\left(1+\frac{1}{n}\right)\right]^{-n\cdot rt} \to e^{-rt}$$

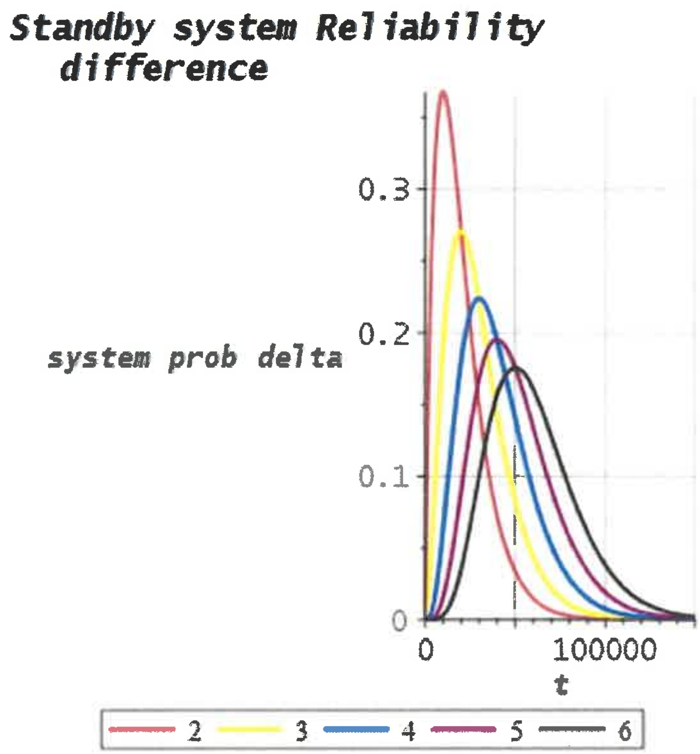
```
restart : with(Student) : with(plots) : ir := 0.01; δoca := 3300.; δocc := 2.·10^4 ; Ccd := 1.5
·10^9 ; Crp := 1.2·10^8; Lvalue := 20000.; ϵ := evalf( 0.0000322 / 0.00000641 ); Onst := 3.·10^9 ;
CoV1 := 2.5; nmes := "Turkey Pts.";
; yrsr := 20.; nt := 7; Ct := seq( (1 − exp(−ir·j·yrsr)) / (ir·j) ,j = 1 ..nt); cmp2 := [cmp·yrsr];
repl := 10; Sm := seq( (1 − exp(−ir·j·repl)) / (repl·ir·j) ,j = 1 ..nt); pwr1 := 2300; PL := 1/910
·pwr1; offprem := 3·10.87769; pcm := 3·9.14522·10^−6;for j from 1 to nt do Offex[j] :=
Lvalue · pcm·offprem·Ct[j]; OnLT[j] := pcm · δocc·Lvalue·Ct[j]·Sm[j]; Onst[j] :=
pcm · Lvalue·δoca·Ct[j]; Ontot[j] := Onst[j] + Offex[j] + OnLT[j]; Ocd[j] := pcm
· Crp·Ct[j]^2.PL; Rp[j] := pcm·Crp·Ct[j]^2·PL; TotInt[j] := Ontot[j] + Ocd[j]
+ Rp[j]; Totext[j] := ϵ·TotInt[j] : Total[j] := TotInt[j] + CoV1·Totext[j] :end do:
pty := seq(Total[j],j = 1 ..nt); ptx := seq(1.0· i, i = 1 ..nt); pts := [seq([ptx[i],pty[i]], i
= 1 ..nt) ]; plt1 := plot(pts, style = point, symbol = solidbox, color = blue, legend
= [Lvalue], gridlines, title ='Potential Averted Costs', titlefont = [COURIER,
Bold, 14], labels = ["Interest / Year", "$"], labelfont = [COURIER, BOLDITALIC, 12],
axesfont = [COURIER, 12]); Lvalue1 := 2000.;for j from 1 to nt do Offex1[j] := Lvalue1
· pcm·offprem·Ct[j]; OnLT1[j] := pcm · δocc·Lvalue1·Ct[j]·Sm[j]; Onst1[j] := pcm
· Lvalue1·δoca·Ct[j]; Ontot1[j] := Onst1[j] + Offex1[j] + OnLT1[j]; Ocd1[j] :=
pcm · Crp·Ct[j]^2.PL; Rp1[j] := pcm·Crp·Ct[j]^2·PL; TotInt1[j] := Ontot1[j] + Ocd1[j]
+ Rp1[j]; Totext1[j] := ϵ·TotInt1[j] : Total1[j] := TotInt1[j] + CoV1·Totext1[j] :
end do: pty1 := seq(Total1[j],j = 1 ..nt); ptx := seq(1.0· i, i = 1 ..nt); pts1 :=
[seq([ptx[i],pty1[i]], i = 1 ..nt) ]; plt2 := plot(pts1, style = point, symbol = solidbox, color
= green, legend = [Lvalue1], gridlines, title ='Potential Averted Costs', titlefont
= [COURIER, Bold, 14], labels = ["Interest / Year", "$"], labelfont = [COURIER,
BOLDITALIC, 12], axesfont = [COURIER, 12]); display({plt1, plt2}); offpremg :=
278.; pcm := 9.14522·10^−6;for j from 1 to nt do Offex[j] := Lvalue · pcm·offpremg
·Ct[j]; OnLT[j] := pcm · δocc·Lvalue·Ct[j]·Sm[j]; Onst[j] := pcm · Lvalue·δoca
·Ct[j]; Ontot[j] := Onst[j] + Offex[j] + OnLT[j]; Ocd[j] := pcm · Crp·Ct[j]^2.PL;
Rp[j] := pcm·Crp·Ct[j]^2·PL; TotInt[j] := Ontot[j] + Ocd[j] + Rp[j]; Totext[j] := ϵ
·TotInt[j] : Total[j] := TotInt[j] + CoV1·Totext[j] :end do: pty3 := seq(Total[j],j = 1
..nt); ptx := seq(1.0· i, i = 1 ..nt); pts3 := [seq([ptx[i],pty3[i]], i = 1 ..nt) ]; plt3 :=
plot(pts3, style = point, symbol = solidbox, color = purple, legend = [Lvalue], gridlines,
title ='Potential Averted Costs', titlefont = [COURIER, Bold, 14], labels
= ["Interest / Year", "$"], labelfont = [COURIER, BOLDITALIC, 12], axesfont
= [COURIER, 12]); Lvalue1 := 2000.;for j from 1 to nt do Offex1[j] := Lvalue1 · pcm
·offpremg·Ct[j]; OnLT1[j] := pcm · δocc·Lvalue1·Ct[j]·Sm[j]; Onst1[j] := pcm
· Lvalue1·δoca·Ct[j]; Ontot1[j] := Onst1[j] + Offex1[j] + OnLT1[j]; Ocd1[j] :=
pcm · Crp·Ct[j]^2.PL; Rp1[j] := pcm·Crp·Ct[j]^2·PL; TotInt1[j] := Ontot1[j] + Ocd1[j]
+ Rp1[j]; Totext1[j] := ϵ·TotInt1[j] : Total1[j] := TotInt1[j] + CoV1·Totext1[j] :
end do: pty4 := seq(Total1[j],j = 1 ..nt); ptx := seq(1.0· i, i = 1 ..nt); pts4 :=
[seq([ptx[i],pty4[i]], i = 1 ..nt) ]; plt4 := plot(pts4, style = point, symbol = solidbox, color
= red, legend = [Lvalue1], gridlines, title ='Potential Averted Costs', titlefont
= [COURIER, Bold, 14], labels = ["Interest / Year", "$"], labelfont = [COURIER,
BOLDITALIC, 12], axesfont = [COURIER, 12]); display({plt3, plt4});
plot3d( dollr·10^6 / (carate·100), dollr = 1 ..10, carate = 4 ..5, title ='Dollars per personREM
·( a Statistical Latent Cancer Fatality Saved  $M) ', titlefont
= [COURIER, Bold, 14], labels = ["$ M dollar", "person-REM/LCF rate",
" $ / (person − REM) "], labelfont = [COURIER, BOLDITALIC, 12], axesfont = [COURIER,
12]);
```


Series system of independent identical components
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
R
1
2
3
4
5
6
number of components
0.1
0.01
0.001
0.0001
0.00001
0.000001


Parallel system of independent identical components
1.0
0.9
0.8
0.7
R
1
2
3
4
5
6
number of components
0.1
0.01
0.001
0.0001
0.00001
0.000001


6 Combinatorial system Probability
number failed m of components
m
1
2
3
4
5
6
-1
-2
-3
-4
-5
-6
log system prob
1
2
3
4
5
6


Standby system Reliability
1
0.8
0.6
0.4
0.2
0
system prob
0
50000
100000
150000
t


Standby system Reliability difference
system prob delta
0.3
0.2
0.1
0
0
100000
t
2
3
4
5
6

```
restart : with(Student) : with(plots) : with(CurveFitting) : with(plottools) : digits := 20;
nt := 6; prob := [seq(.1^k, k = 1 ..nt)]; λ := 1.; α := 4.; probf := [seq((1 - exp(-(prob[i]/λ)^α)), i = 1 ..nt)] : col1 := [green, orange, yellow, blue, purple, black] :
mult := 1.; y1 := mult; for i from 1 to nt do p[i]; sys[i] := [seq((1 - probf[i])^j, j = 1 ..nt)] :
syps[i] := [seq(1 - (probf[i])^j, j = 1 ..nt)] : end do: for j from 1 to nt do ; pts1[j] :=
[seq([i, mult·(sys[i][j])], i = 1 ..nt)] : pts1p[j] := [seq([i, mult·(syps[i][j])], i = 1
..nt)] : end do: for j from 1 to nt do pl1[j] := plot(pts1[j], style = line, thickness = 2, color
= col1[j], gridlines, title =
' Series system of independent identical components', titlefont
= [COURIER, Bold, 14], labels = ["number of components", " R"], labelfont
= [COURIER, BOLDITALIC, 12], axesfont = [COURIER, 12], legend = [prob[j]]);
pl1p[j] := plot(pts1p[j], style = line, thickness = 2, color = col1[j], gridlines, title =
' Parallel system of independent identical components', titlefont
= [COURIER, Bold, 14], labels = ["number of components", " R"], labelfont
= [COURIER, BOLDITALIC, 12], axesfont = [COURIER, 12], legend = [prob[j]]);
pl12[j] := PolynomialInterpolation(pts1[j], x); plsp2[j] := plot({pl12[j], pts1[j]}, x
= 1 ..6, y = 0 ..y1, gridlines, color = col1[j]); end do: display(seq(pl1[j], j = 1 ..nt));;
display(seq(pl1p[j], j = 1 ..nt)); nc := [seq(1. i, i = 1 ..nt)]; n := 6; for k from 2 to nt
do pcmb1[k, 2] := Sum(binomial(nt, m)·(1 - probf[2])^m·(probf[2])^(nt - m), m = k .. nt) : pcmb1[k, 3] :=
Sum(binomial(nt, m)·(1 - probf[3])^m·(probf[3])^(nt - m), m = k .. nt) : pcmb1[k, 4] := Sum(binomial(nt, m)·(1 - probf[4])^m
·(probf[4])^(nt - m), m = k .. nt) : end do: probc := .1; pcn := [seq(nt!/(m!·(nt - m)!)·probc^m·(1
- probc)^(nt - m), m = 1 ..nt)] : for j from 1 to nt do psysc[j] := Sum(pcn[m], m = j .. nt) : end do: for k
from 1 to nt do plc[k] := plot([[k, log10(psysc[k])]], style = point,
symbol = solidcircle, color = col1[k], symbolsize = 12, gridlines, title =
' Combinatorial system Probability number failed m of n components',
titlefont = [COURIER, Bold, 14], labels = ["m", " log system prob"], labelfont
= [COURIER, BOLDITALIC, 12], axesfont = [COURIER, 12], legend = [k]); end do:
display(seq(plc[k], k = 1 ..nt)); λs := .0001; tot := 1.5·10^5; for k from 1
to nt do Rsb[k] := t1 → exp(-λs·t1)·Sum((λs·t1)^g/g!, g = 0 .. k - 1) : plr[k] :=
plot(Rsb[k](t1), t1 = 0 ..tot, thickness = 2, color = col1[k], gridlines, title =
' Standby system Reliability ', titlefont = [COURIER, Bold, 14], labels
= ["t", " system prob"], labelfont = [COURIER, BOLDITALIC, 12], axesfont
= [COURIER, 12]) : col2 := [green, orange, yellow, blue, purple, black]; end do: for j
from 2 to nt do sbd1[j] := t2 → exp(-λs·t2)·(Sum((λs·t2)^g/g!, g = 0 .. j - 1)
- Sum((λs·t2)^g/g!, g = 0 .. j - 2)); plrd[j] := plot(sbd1[j](t2), t2 = 0 ..tot, thickness = 2,
color = col2[j], gridlines, title =' Standby system Reliability difference ',
titlefont = [COURIER, Bold, 14], labels = ["t", " system prob delta"], labelfont
= [COURIER, BOLDITALIC, 12], axesfont = [COURIER, 12], legend = [j]) : end do:
display(seq(plr[k], k = 1 ..nt)); display(seq(plrd[j], j = 2 ..nt));
```

About The Author

Timothy S. Margulies enjoys presenting a collection of investigations and explorations for introducing and for teaching quantitative studies. He earned both Masters and Doctorate degrees at The Johns Hopkins University in Baltimore, Maryland. His career path is comprised of ten years at The Applied Physics Laboratory of Johns Hopkins, nine years at the US NRC, and eight at the US EPA. He was a Lecturer at Johns Hopkins on Risk Mathematics, Management, and System Safety. He was awarded a Civil Service Special Achievement Award and Civil Service Peer Award, Civil Service Bronze Medal.