LCLS Power Supply Availability

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Objective	*Determine if 0.98 power supply Availability for 6600 hour runs is feasible for LCLS power supplies* *Reference: Bob Dalesio proposal of June 2005*
Result	*The 0.98 availability criterion is reasonable. The 2% unavailability is not overly generous. The availability criterion is achievable with or without redundant power supplies*

Glossary	
Term	**Definition**
MTBF	Mean time between failures in hours
$MTBF_O$	The increased MTBF in hours that considers equipment operation at lower than rated power levels
$MTBF_R$	The rated MTBF in hours
MTTR	The mean time to repair and recover beam in hours
R(t)	Reliability or probability of success with time
λ, λ_O, λ_R	Failure rates in hr^{-1}. These are the reciprocals of the MTBFs
1FR	One full rated power supply. Rated power = delivered power
1DR	Double rated power supply. Rated power = 2X that delivered
1/2	One out of two redundant power supply configuration
2/3	Two out of three redundant power supply configuration
4/5	Four out of five redundant power supply configuration

Survey - Argonne National Laboratory, Advanced Photon Source Power Supplies

- *Based on discussions with John Carwardine and Ju Wang June 16, 2005*
- *15 year old power supplies*
- *All are switchmode type. No power supply redundancy*
- *2000 power supplies, but in 5000 running hours only 10 beam trips attributed to power supplies*
- *Single power supply MTBF is 1,000,000 hours, < 1 hour MTTR*
- *2000 power supply MTBF is 500 hours*
- *This translates to a 2000 power supply Availability of 0.9980*
- *To improve availability, before the start of a run, they stress their power supplies at an elevated power level. They inspect the PS with a thermo camera to identify and correct hot spots prior to the run. Any hot spots are investigated and failed weak links are repaired prior to the run*

Survey - SSRL SPEAR 3 Power Supplies

- *Operating since January 2004. Data covers January 2005 through June 2005*
- *3486.9 hours operating*
- *No power supply redundancy. All are switchmode type*
- *70 large power supplies not including Dipole Power Supply*
- *2 large power supply failures and 1 BitBus controller failure**
- *Power Supply MTBF = 122,042 hours*, BitBus MTBF = 233,622 hours*
- *118 MCOR30 corrector power supplies and controllers– no failures during normal operation**. MTBF > 411,466 hours*
- *MTTR < 1 hour. Power supply system availability > 0.9992*

** Based on discounting 21 of 24 failures attributable to a recurring problem with one power supply system later traced to a defective BitBus controller auxiliary supply.*

*** Excessive energy dumps from magnets during overly fast feedback testing damaged several MCOR30s. This operation is outside the MCOR30 capability*

Survey - Diamond Light Source

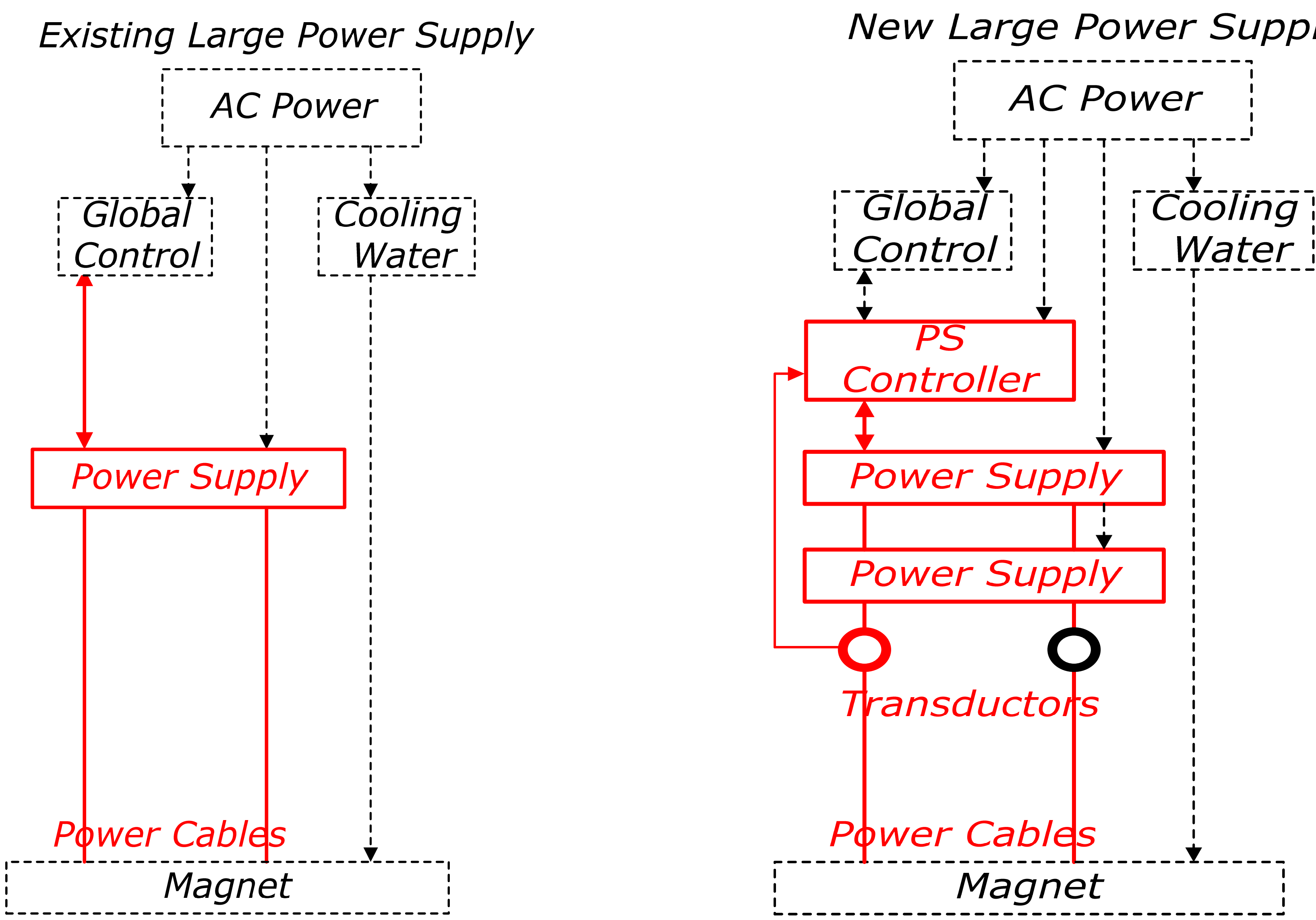
- *Under construction so no empirical availability data*
- *No reliability studies or analysis*
- *No corrector power supply redundancy (except small bulks are paralleled)*
- *Large power supplies are redundant 4/5 configuration.*
- *800 corrector and 450 large power supplies*

Survey of other Sources

- *The PEP II availability budget for all magnet power supplies was 0.97*
- *MCOR12 MTBF 860,000 hours based on several hundred units running in PEP and the LINAC – Source Greg Leyh*
- *SCOR6 MTBF 300,000 hours John Shepard, second-hand from Greg Leyh*
- *EMI-Lambda, IE Power, Power Ten 60,000 hours to 100,000 hours*

LCLS Power Supply Quantities			
	Quantity Existing	Quantity New	Totals
Large (non-corrector)	91	121	212
Corrector	154	156	310*
			522

* Quantity does not include 39 bulk power supplies, but they are in the Availability calculations.


Existing Large Power Supply
AC Power
Global Control
Cooling Water
Power Supply
Power Cables
Magnet
New Large Power Supply
AC Power
Global Control
Cooling Water
PS Controller
Power Supply
Power Supply
Transductors
Power Cables
Magnet

Large Power Supply Availability Assumptions and References

Existing

1. *Large PS are primarily QE string and boost power supplies. These are old. Estimated MTBF is 55,000 hours based on the low end of the discussed MTBFs. No redundancy.*

New

1. *MTBF of large power supply is 110,000 hours based on Cherrill Spencer SLAC studies spanning several years*

3. *MTBF PEP II PS controller is 288,889 hr per PAC 2001 reliability paper*

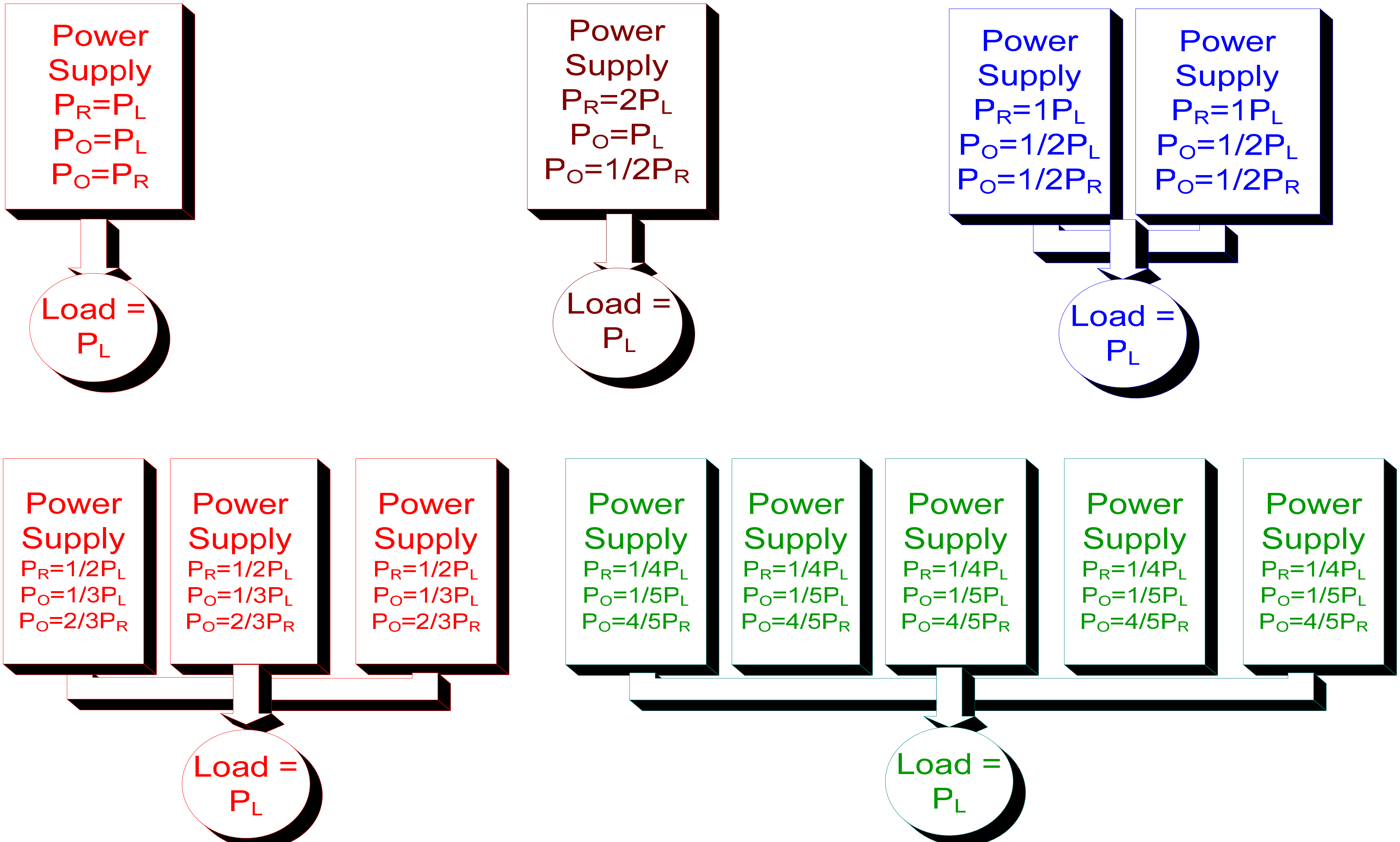
4. *MTBF transductors is 1,300,000 hr per PAC 2001 reliability paper. Only one (feedback loop) of two transductors used in availability analysis*

5. *MTBF cables is 2,600,000 hr per PAC 2001 reliability paper*

6. *MTTR = 2 hours based on all available information*

7. *When redundancy is considered it is Active redundancy*

Availability Improvement By Oversizing or Redundancy



Availability Improvement By Redundancy

The general, exponential form of the Binomial Distribution is

$$R(t) = \sum_{k=m}^{n} \left(\frac{n!}{(n-k)!\,k!}\right)\left(e^{-\lambda t}\right)^{k}\left(1-e^{-\lambda t}\right)^{n-k}$$

λ= constant=failure rate

m= minimum number of system power supplies needed for operation

n = total number of power supplies in the system

A special case occurs when $m = n$ or when $m=n=1$

$R(t)=e^{-n\lambda t}$ $\quad\quad$ $R(t)=e^{-\lambda t}$

Availability Improvement by Redundancy
Binomial Expansion 2 out of 3 example

$$R_{2/3}(t) = \sum_{k=m=2}^{n=3} \left(\frac{n!}{(n-k)!\,k!}\right)(e^{-\lambda t})^{k}(1-e^{-\lambda t})^{n-k}$$

$k = 2$

$$\frac{3!}{1!\,2!} e^{-2\lambda t}(1-e^{-\lambda t}) = 3 \quad e^{-2\lambda t} \quad (1-e^{-\lambda t})$$

3 cases, probability of success, probability of failure

S	S	F
S	F	S
F	S	S

3 Cases

$k=3$

$$\frac{3!}{0!3!} e^{-3\lambda t}(1-e^{-\lambda t})^{0} = 1 \quad e^{-2\lambda t}$$

1 case, probability of success, no failure

S	S	S

1 Case

$$R_{2/3}(t) = 3e^{-\lambda t} - 2e^{-3\lambda t}$$

$R_{2/3}(t) = 3e^{-\lambda t} - 2e^{-3\lambda t}$

Derivation

When $\lambda(t)$ is a function of time

General form $R(t) = e^{-\lambda(t)t}$

$$\frac{dR(t)}{dt} = -\frac{d\lambda(t)}{dt} e^{-\lambda(t)t} - \lambda(t) e^{-\lambda(t)t}$$

$$\frac{d\lambda(t)}{dt} \text{ is } << \lambda(t)$$

$$\frac{dR(t)}{dt} = -\lambda(t) e^{-\lambda(t)t} \quad \text{but } e^{-\lambda(t)t} = R(t)$$

$$\lambda(t) = \frac{-\frac{dR(t)}{dt}}{R(t)}$$ *If λ is a constant then the above reduces to $\lambda(t)=\lambda$*

$$MTBF(t) = \frac{R(t)}{-\frac{dR(t)}{dt}}$$

Availability

1 power supply where operating power=the rated power

$$P_O = P_R$$

$$MTBF_O = MTBF_R$$

$$\lambda_O = \frac{P_R}{P_O} \lambda_R$$

$$R_O(t) = e^{-\lambda_O t}$$

$$A_{O1FR} = \frac{MTBF_O}{MTBF_O + MTTR}$$

Availability Improvement By Oversizing

1 double rated power supply with power rating 2X the operating (load) power. Conservative assumption is that operating MTBF increases linearly with oversizing

$$P_O = \frac{1}{2} P_R$$

$$MTBF_O = \frac{P_R}{P_O} MTBF_R \qquad MTBF_O = 2\ MTBF_R$$

$$\frac{\lambda_O}{\lambda_R} = \frac{MTBF_R}{MTBF_O}$$

$$\lambda_O = \frac{1}{2} \lambda_R$$

$$R_O(t) = e^{-\lambda_O t}$$

$$A_{O1DR} = \frac{MTBF_O}{MTBF_O + MTTR}$$

Availability Improvement by Redundancy

2- full rated power supplies. Each power supply operates at 1/2 rated P_R

$$P_O = \frac{1}{2} P_R$$

$$MTBF_O = \frac{P_R}{P_O} MTBF_R = 2\,MTBF_R \qquad \lambda_O = \frac{1}{2}\lambda_R$$

For the m=1 out of n=2 case

$$R_{1/2}(t) = \sum_{k=m}^{n} \left(\frac{n!}{(n-k)!\,k!} \right) \left(e^{-\lambda_O t} \right)^k \left(1 - e^{-\lambda_O t} \right)^{n-k} = -e^{-2\lambda_O t} + 2e^{-\lambda_O t}$$

$$MTBF_{1/2}(t) = \frac{1}{\lambda_{O1/2}(t)} = \frac{2e^{-\lambda_O t} - e^{-2\lambda_O t}}{-2\lambda_O e^{-2\lambda_O t} + 2\lambda_O e^{-\lambda_O t}}$$

$$A_{1/2}(t) = \frac{MTBF_{O1/2}(t)}{MTBF_{O1/2}(t) + MTTR}$$

Availability Improvement by Redundancy

3-1/2 rated power supplies. Each power supply operates at 2/3 rated P_R

$$MTBF_O = \frac{P_R}{P_O} MTBF_R = \frac{3}{2} MTBF_R \qquad \lambda_O = \frac{2}{3}\lambda_R$$

For the m=2 out of n=3 case

$$R_{2/3}(t) = \sum_{k=m}^{n} \left(\frac{n!}{(n-k)!\,k!}\right)\left(e^{-\lambda_O t}\right)^k \left(1 - e^{-\lambda_O t}\right)^{n-k} = 3e^{-2\lambda_O t} - 2e^{-3\lambda_O t}$$

$$MTBF_{2/3}(t) = \frac{1}{\lambda_{O2/3}(t)} = \frac{3e^{-2\lambda_O t} - 2e^{-3\lambda_O t}}{6\lambda_O e^{-2\lambda_O t} - 6\lambda_O e^{-3\lambda_O t}}$$

$$A_{2/3}(t) = \frac{MTBF_{O2/3}(t)}{MTBF_{O2/3}(t) + MTTR}$$

Availability Improvement by Redundancy

5- 1/4 load rated power supplies. Each power supply operates at 4/5 rated P_R

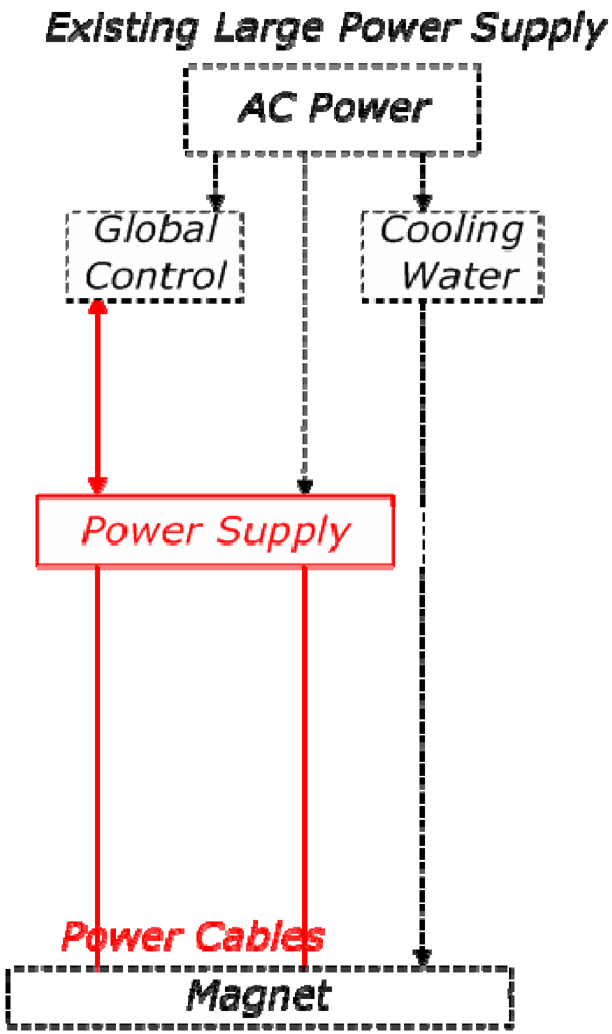
$$MTBF_O = \frac{P_R}{P_O} MTBF_R = \frac{5}{4} MTBF_R \qquad \lambda_O = \frac{4}{5}\lambda_R$$

For the m=4 out of n=5 case

$$R_{4/5}(t) = \sum_{k=m}^{n} \left(\frac{n!}{(n-k)!\,k!}\right)\left(e^{-\lambda_O t}\right)^k \left(1-e^{-\lambda_O t}\right)^{n-k} = 5e^{-4\lambda_O t} - 4e^{-5\lambda_O t}$$

$$MTBF_{4/5}(t) = \frac{1}{\lambda_{O4/5}(t)} = \frac{5e^{-4\lambda_O t} - 4e^{-5\lambda_O t}}{20\lambda_O e^{-4\lambda_O t} - 20\lambda_O e^{-5\lambda_O t}}$$

$$A_{4/5}(t) = \frac{MTBF_{4/5}(t)}{MTBF_{4/5}(t) + MTTR}$$



Existing Large Power Supplies

$$\lambda_{1sys}(t) = \lambda_{PS}(t) + \lambda_{cables}$$

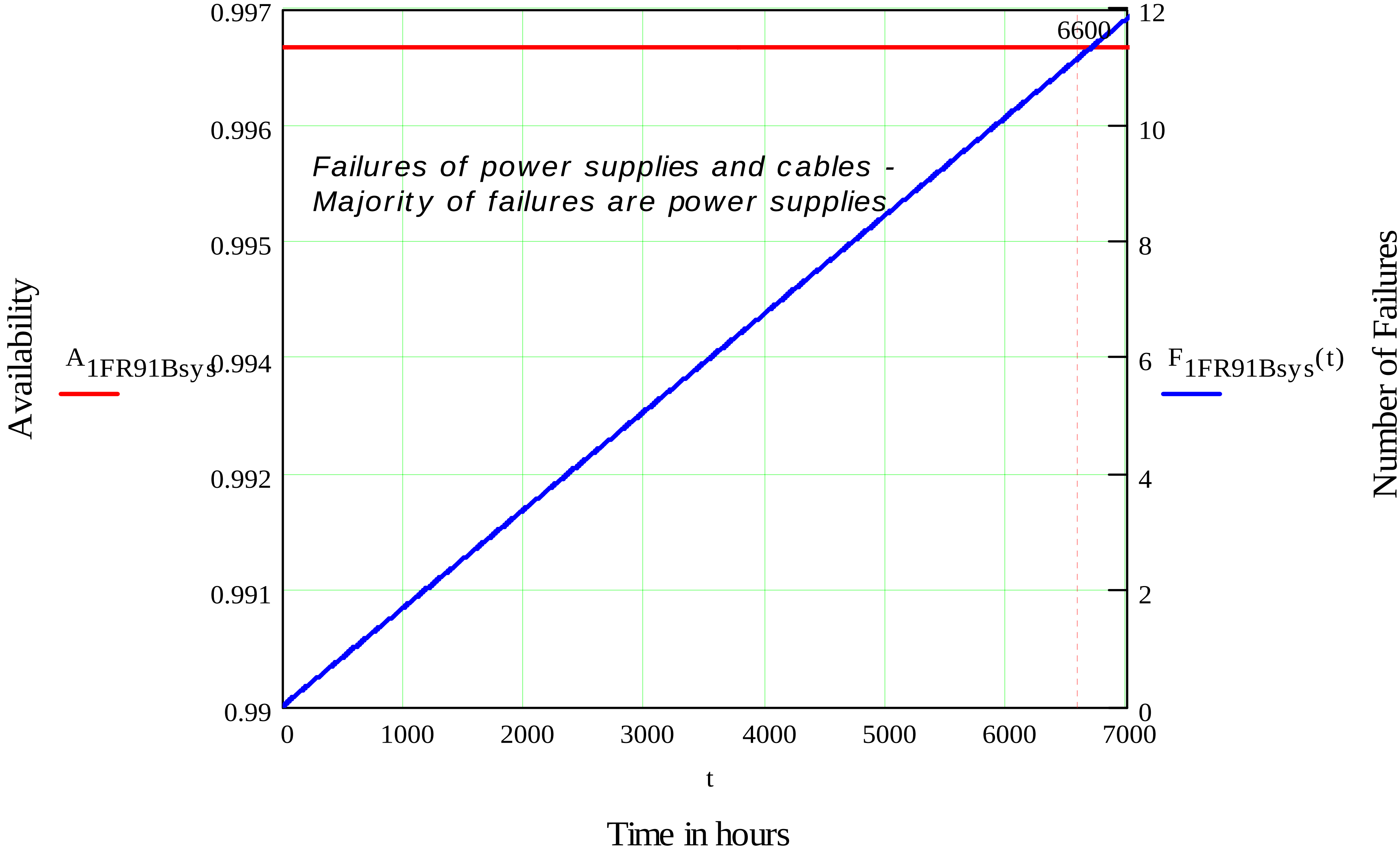
$$MTBF_{1sys}(t) = \frac{1}{\lambda_{1sys}(t)} \quad MTTR = 2 \text{ hours}$$

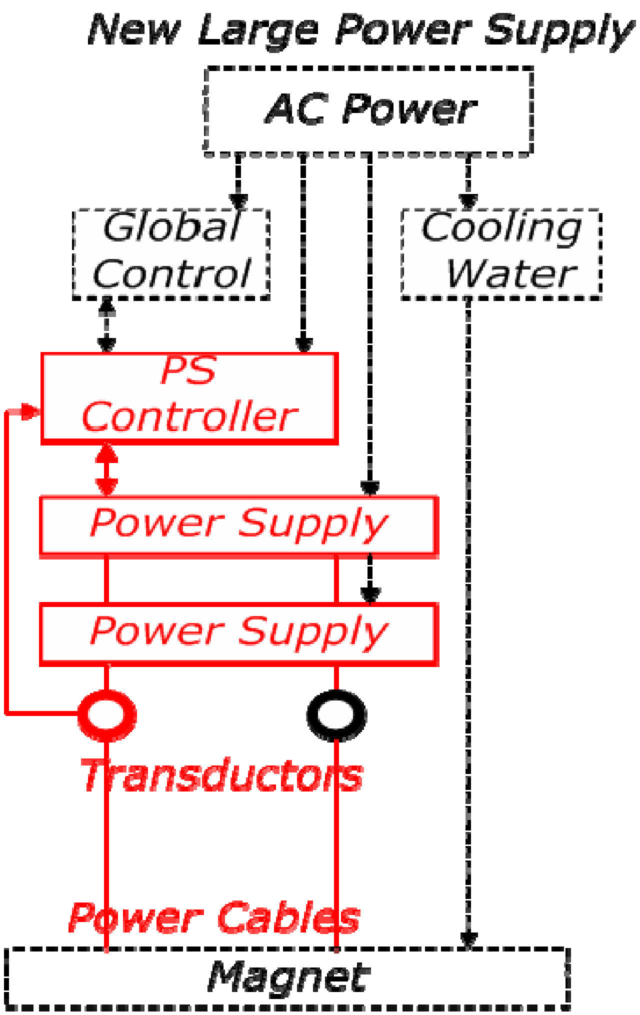
$$Availability_{1sys}(t) = \frac{MTBF_{1sys}(t)}{MTBF_{1sys}(t) + MTTR}$$

$$Availability_{91sys}(t) = Availability_{1sys}^{91}(t)$$

$$Failures_{91sys} = \lambda_{1sys}(t) * 91 * t$$

91 Existing Large PS Systems





New Large Power Supplies

$$\lambda_{1sys}(t) = \lambda_{PS}(t) + \lambda_{controller} + \lambda_{transductor} + \lambda_{cables}$$

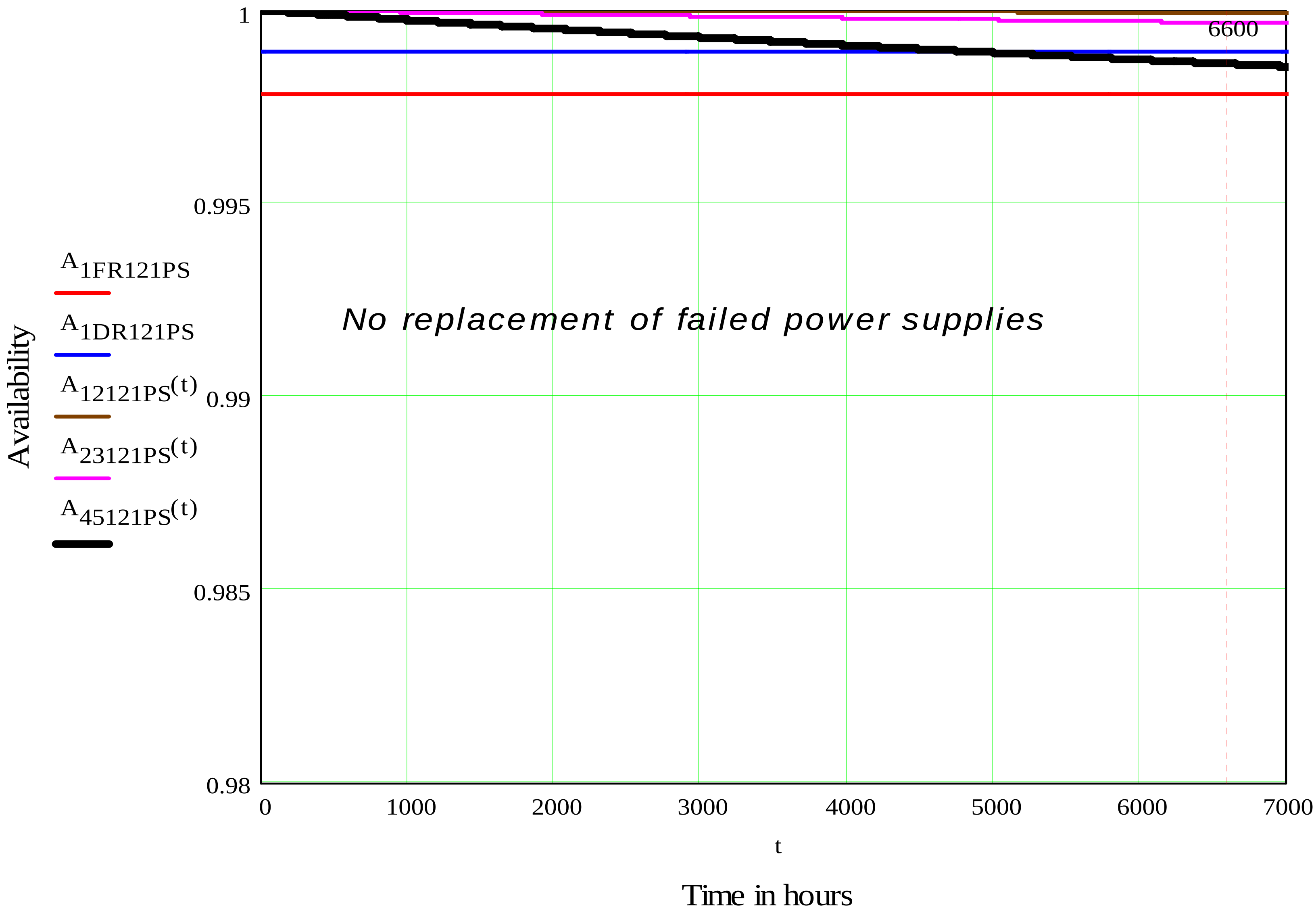
$$MTBF_{1sys}(t) = \frac{1}{\lambda_{sys}(t)} \qquad MTTR = 2 \text{ hours}$$

$$Availability_{1sys}(t) = \frac{MTBF_{1sys}(t)}{MTBF_{1sys}(t) + MTTR}$$

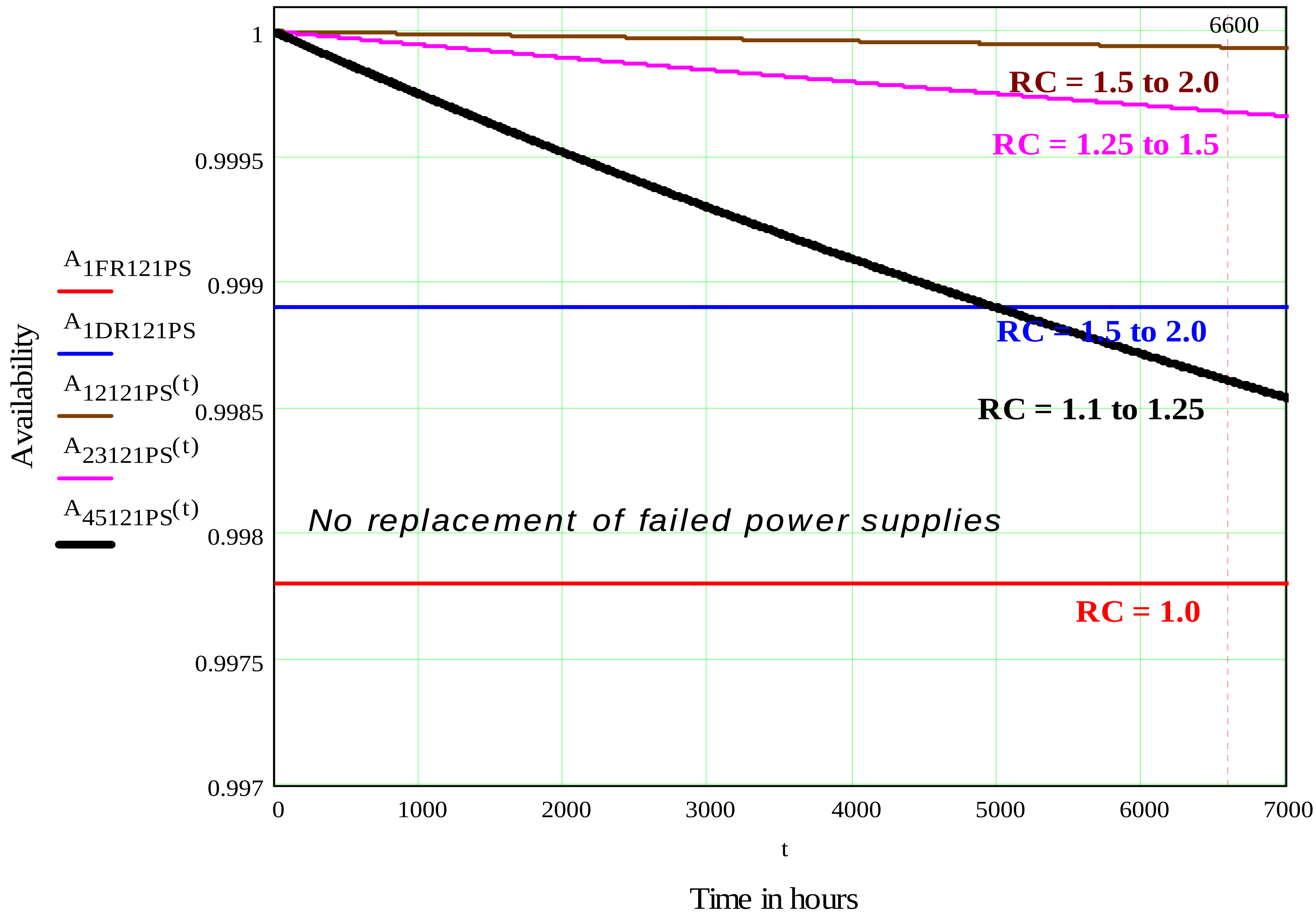
$$Availability_{121sys}(t) = Availability_{1sys}^{121}(t)$$

$$Failures_{121sys} = \lambda_{1sys} * 121 * t$$

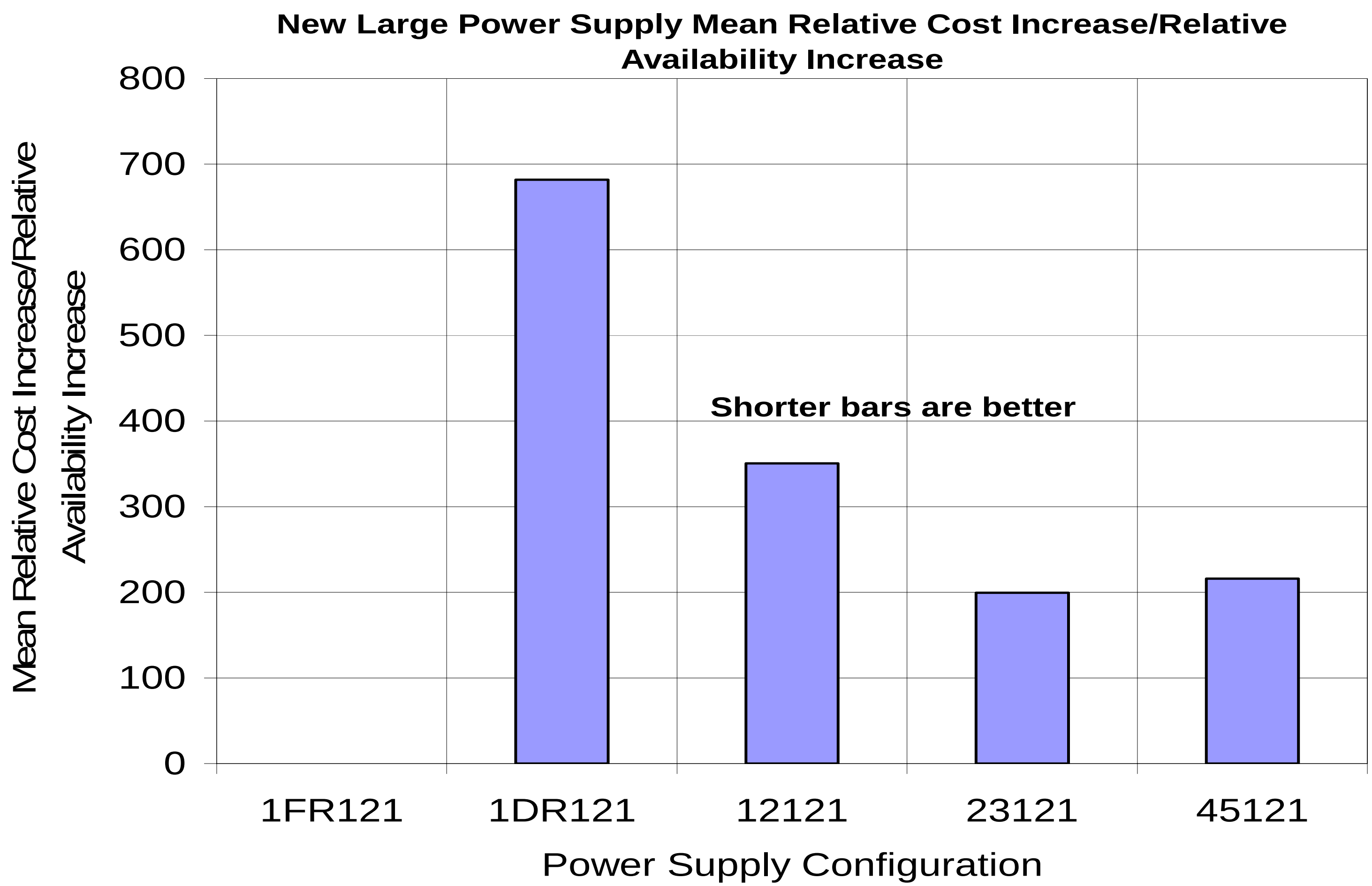
121 New Large Power Supply Availability

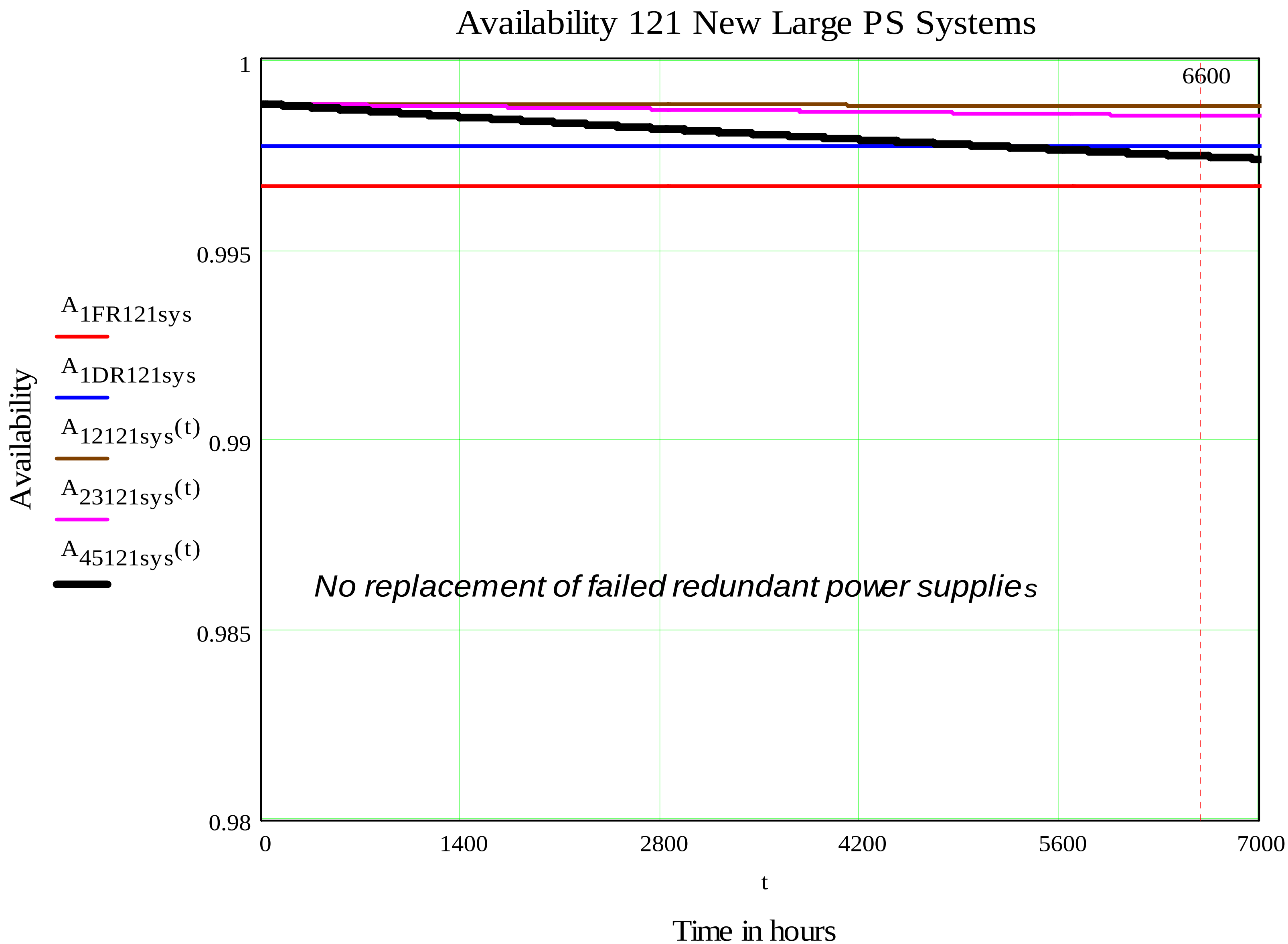


121 New Large Power Supply Availability

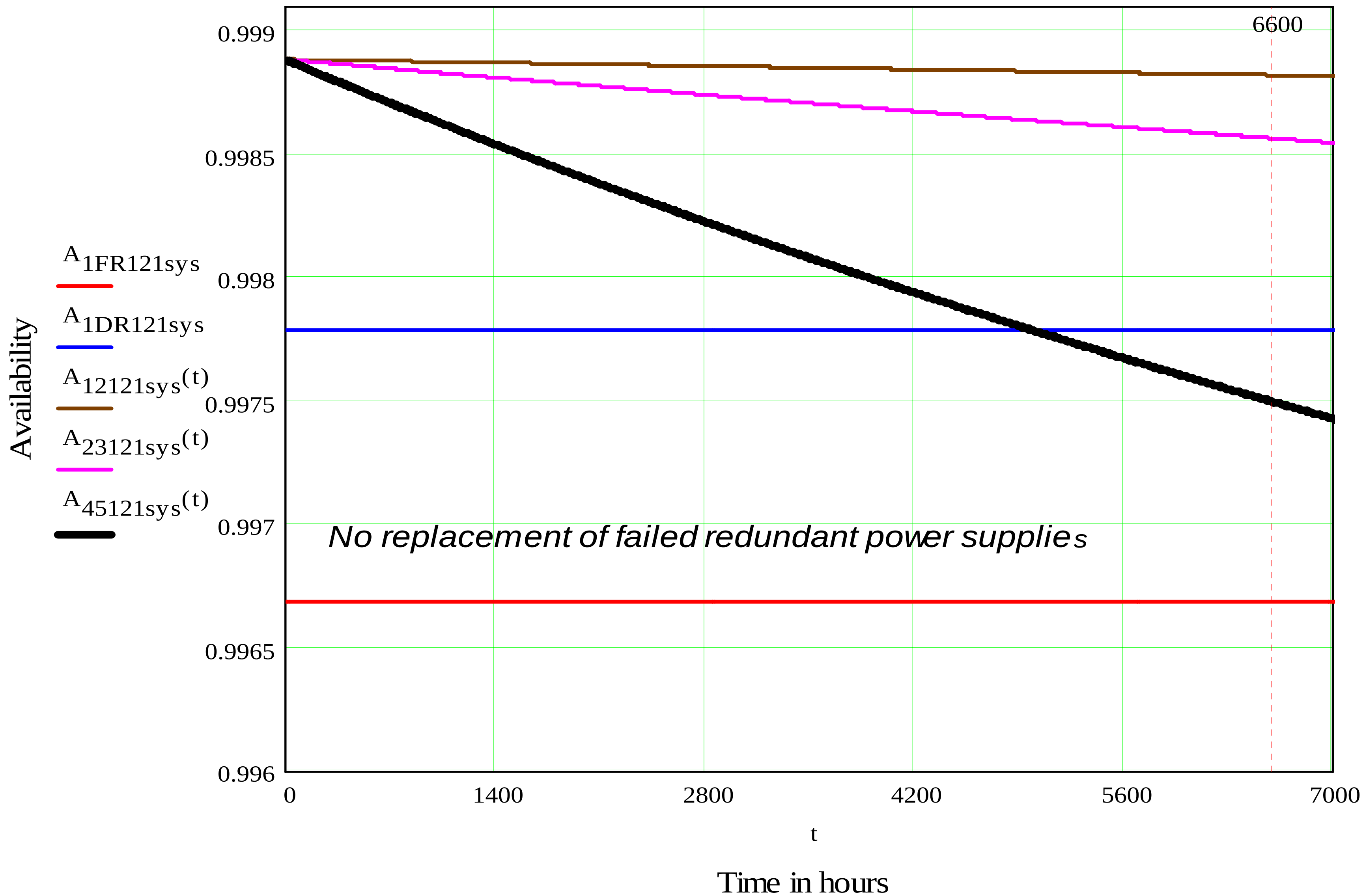


Power Supply	6600 hour Availability	Availability Increase	Mean RC	Mean RC Increase	MRC Inc / MRAvail Incr	121 2.5kW PS Cost	2.5kW PS Cost Increase k$
1FR121	0.99780	0.00000	1.000	0.000	0	363	0
1DR121	0.99890	0.00110	1.750	0.750	682	635	272
12121	0.99994	0.00214	1.750	0.750	350	635	272
23121	0.99968	0.00188	1.375	0.375	199	499	136
45121	0.99861	0.00081	1.175	0.175	216	427	64

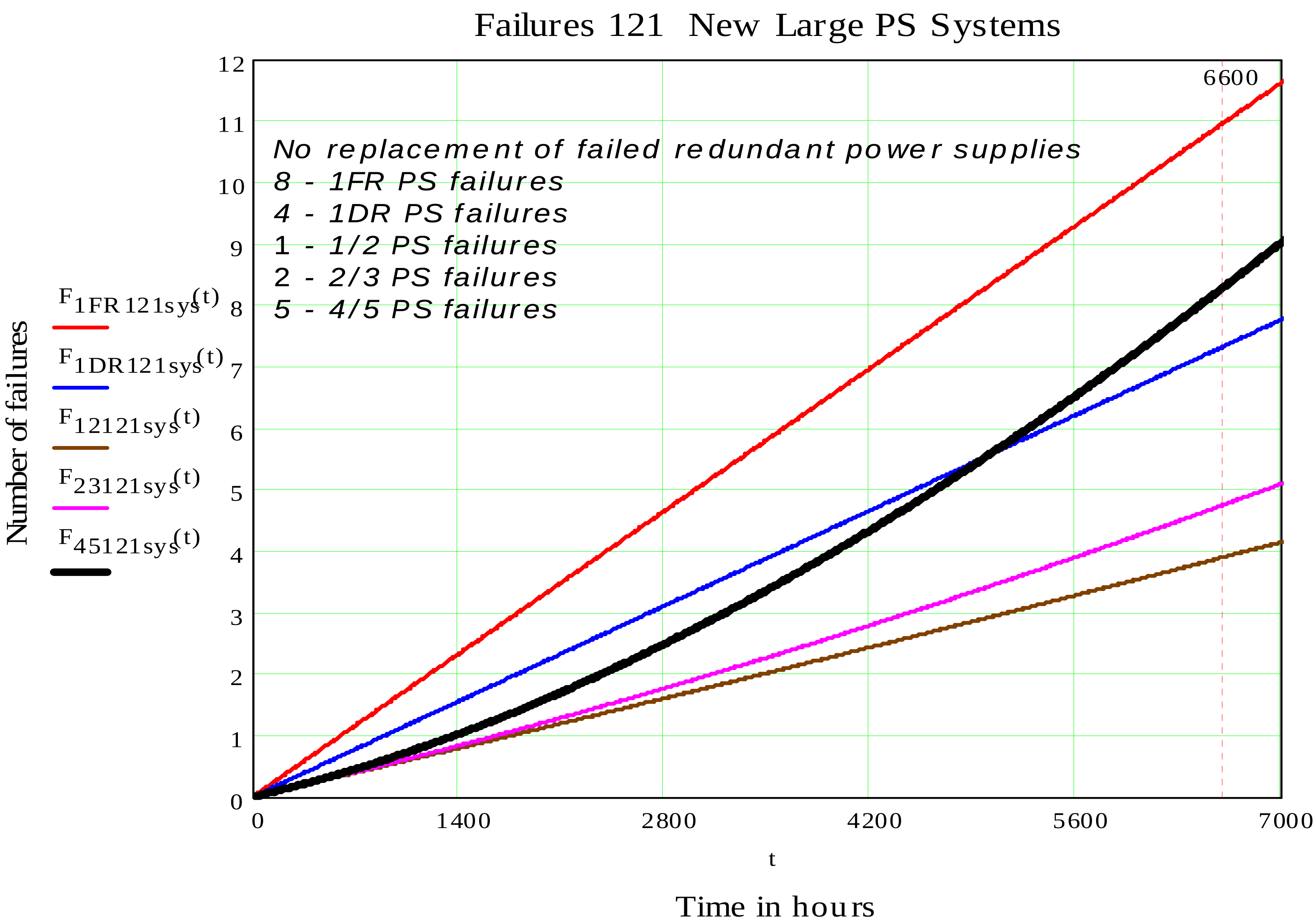



Availability 121 New Large PS Systems
1
0.995
0.99
0.985
0.98
6600
A1FR121sys
A1DR121sys
A12121sys(t)
A23121sys(t)
A45121sys(t)
Availability
No replacement of failed redundant power supplies
0
1400
2800
4200
5600
7000
t
Time in hours

Availability 121 New Large PS Systems



$F_{45121sys}(t) := \lambda_{451sys}(t) \cdot Q_{PS} \cdot t$

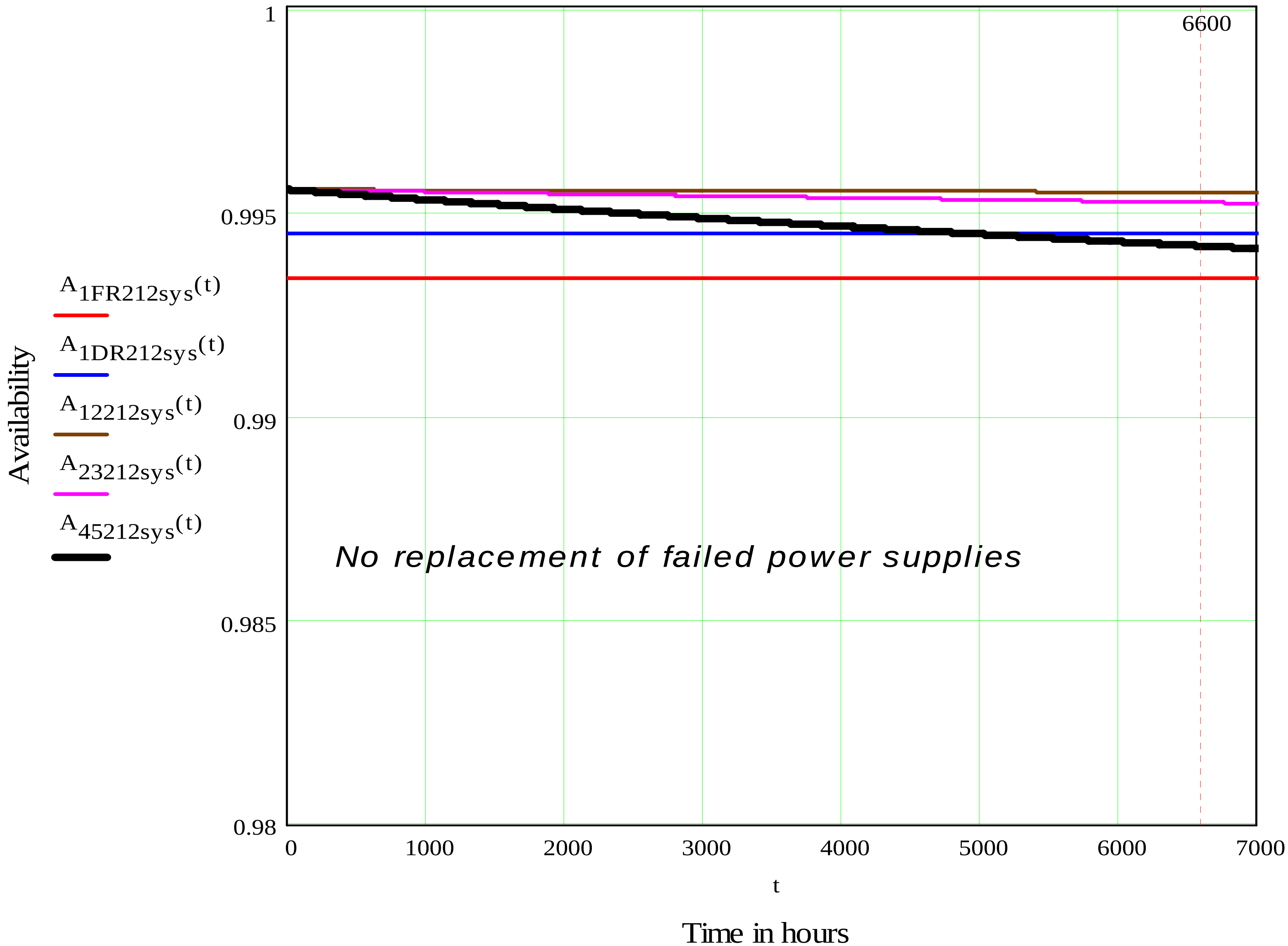


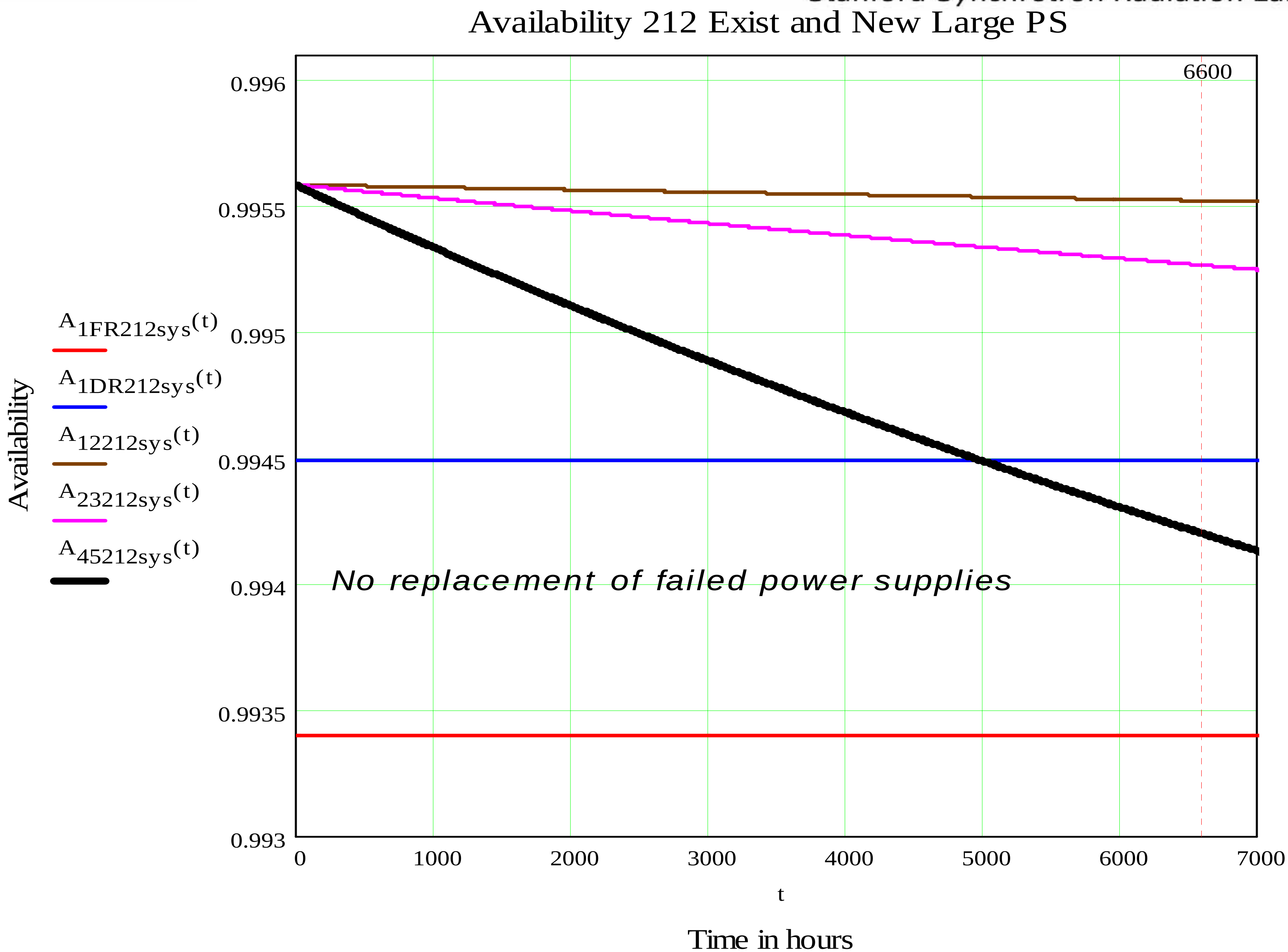
91 Existing and 121 New Large Power Supplies

$$Availability_{212} = Availability_{91existing} * Availability_{121new}$$

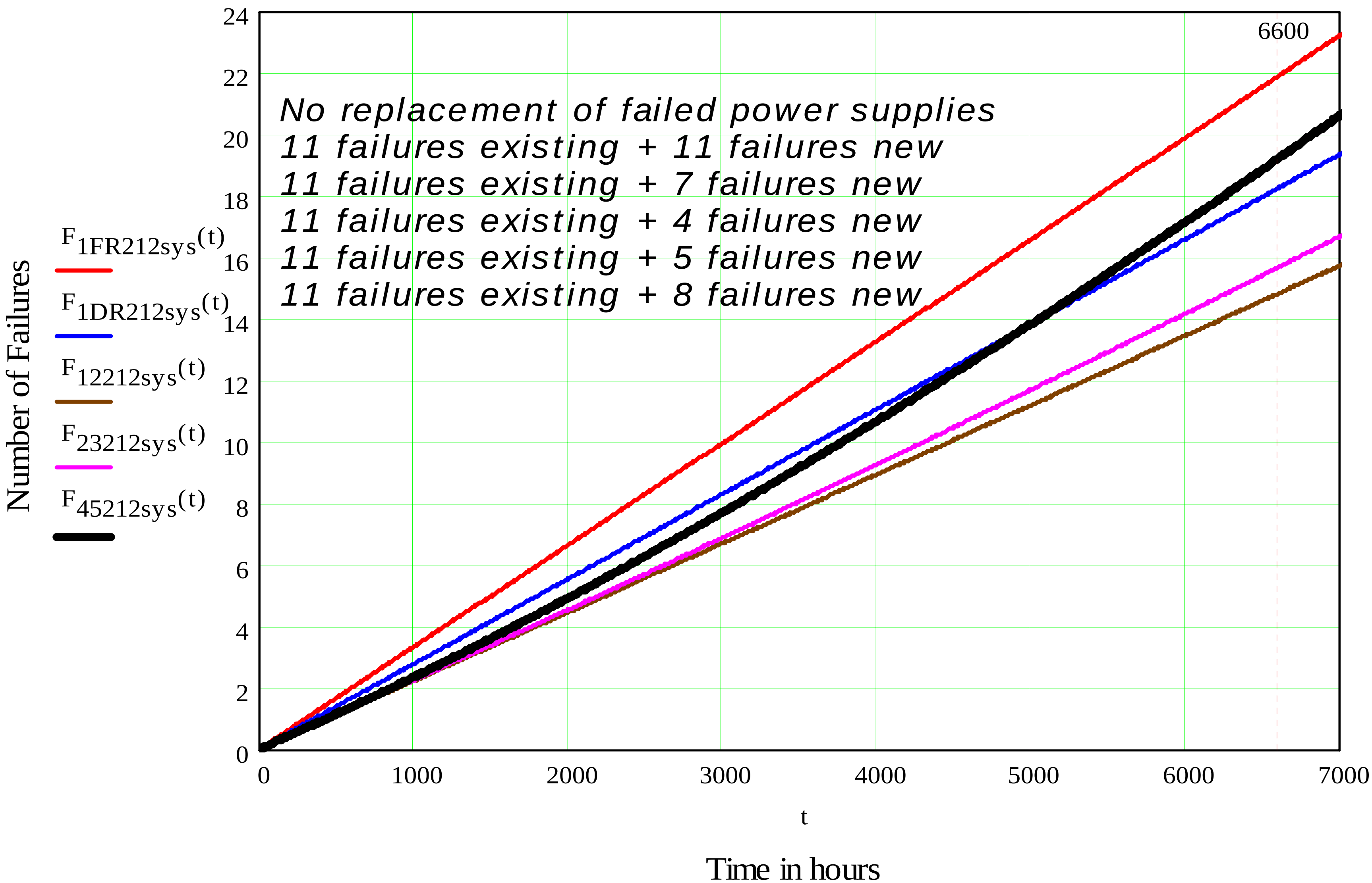
$$Failures_{212} = Failures_{91existing} + Failures_{121new}$$

Availability 212 Exist and New Large PS

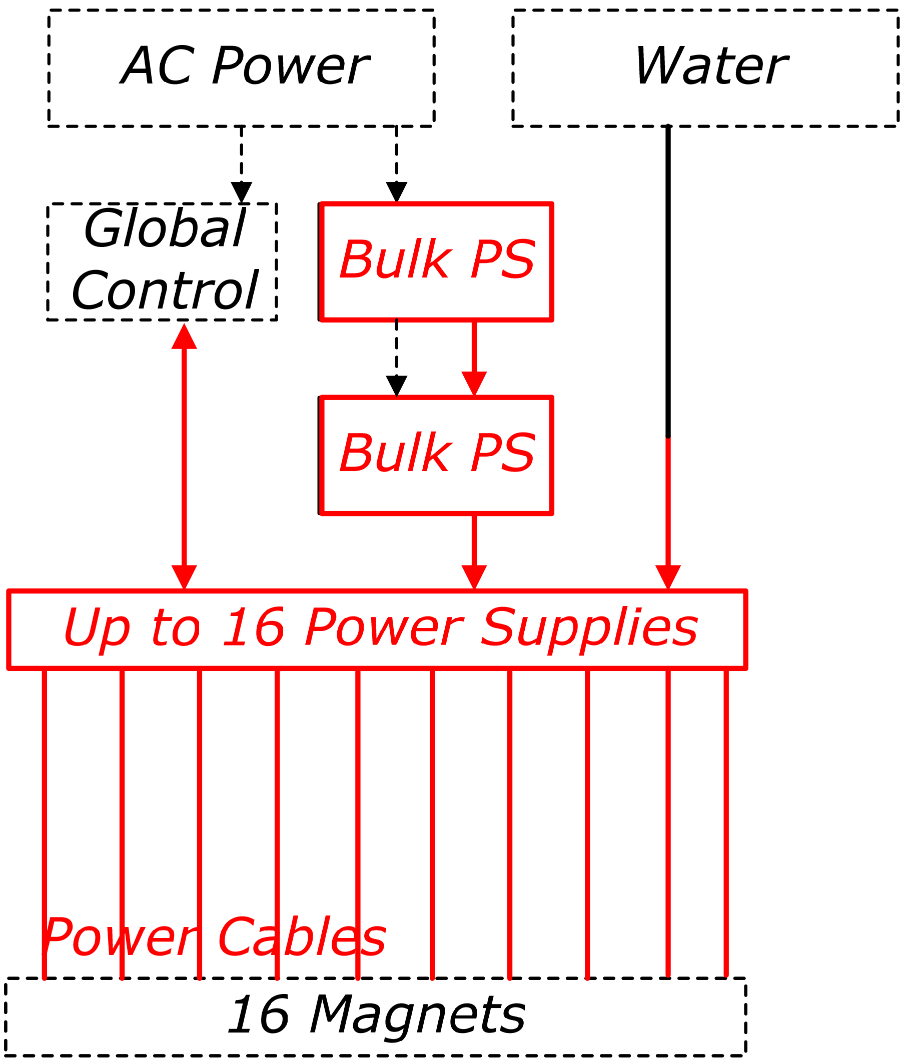



Availability 212 Exist and New Large PS
Availability
0.996
0.9955
0.995
0.9945
0.994
0.9935
0.993
6600
A1FR212sys(t)
A1DR212sys(t)
A12212sys(t)
A23212sys(t)
A45212sys(t)
No replacement of failed power supplies
0
1000
2000
3000
4000
5000
6000
7000
t
Time in hours

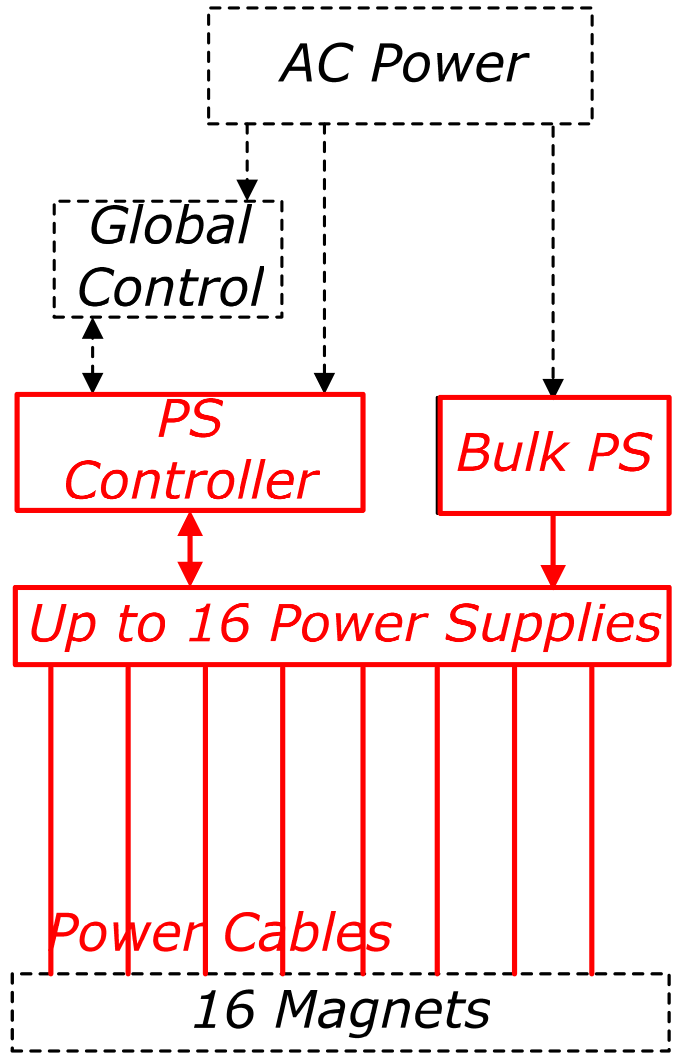
Failures - 212 Exist and New Large PS



Existing Corrector Power Supplies



New Corrector Power Supplies



Corrector Power Supply Availability Assumptions and References

Existing

1. *Correctors are primarily SCOR6. These are old. Use 55,000 hours. The heatsinks have an MTBF of about 40,000 hours (6 years). Most are 20 years old and approaching end of life*

2. *No redundancy. MTTR is 2 hours*

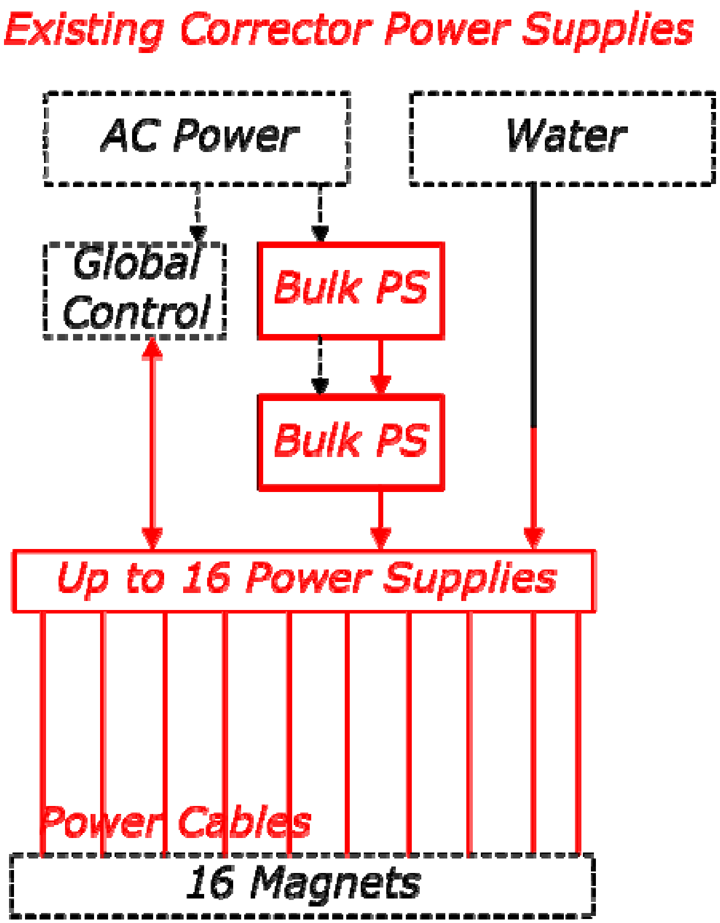
New

1. *MTBF of new corrector power supply is 110,000 hr*

2. *MTBF PS controllers is 288,889 hr per PAC 2001 reliability paper*

3. *MTBF cables is 2,600,000 hr per PAC 2001 reliability paper*

4. *No redundancy. MTTR is 2 hours*



Existing Corrector Power Supplies

$$\lambda_{1sys} = 12\lambda_{PS} + 2\lambda_{bulk} + \lambda_{heat\,sink} + \lambda_{cables}$$

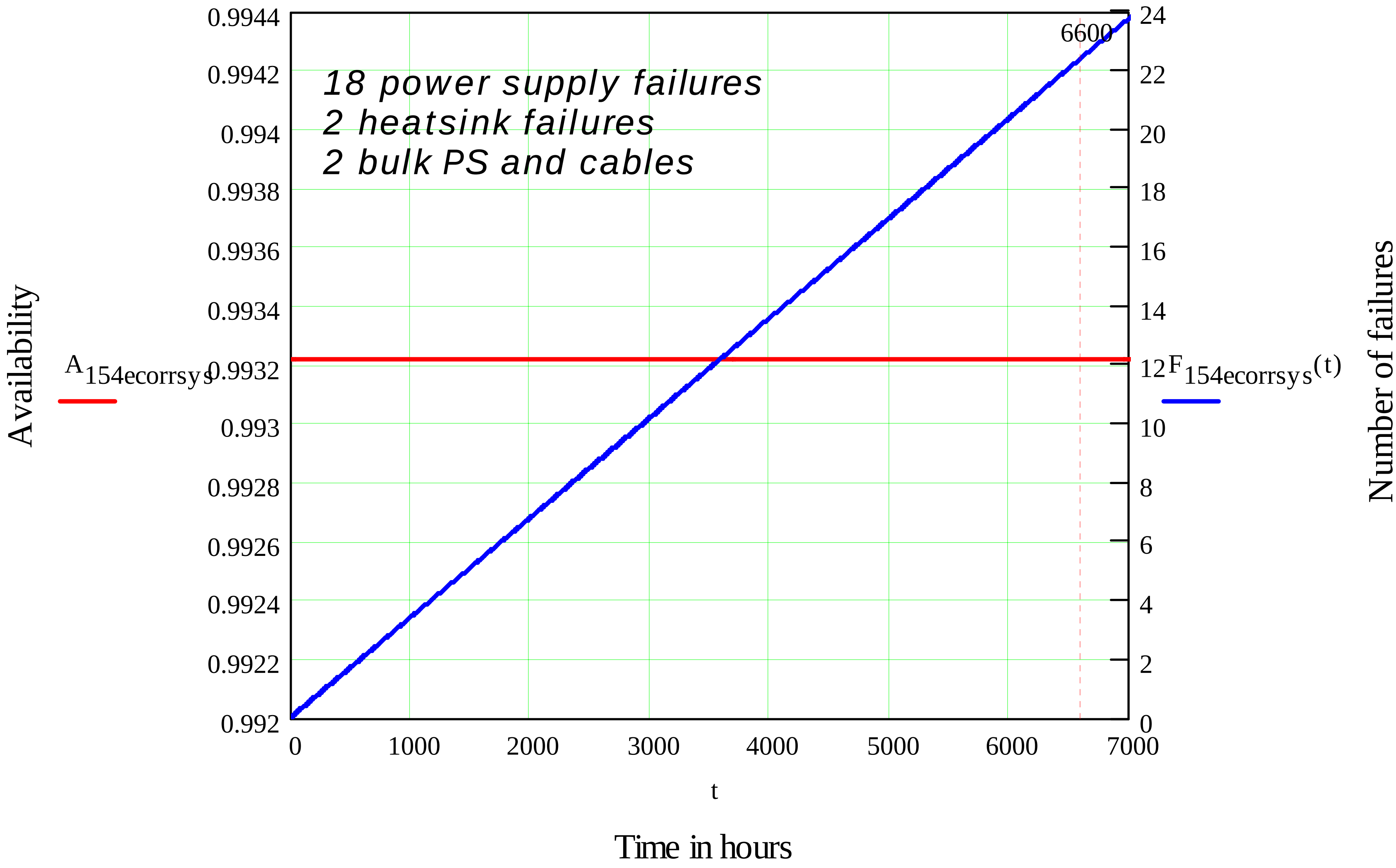
$$MTBF_{1sys} = \frac{1}{\lambda_{1sys}} \qquad MTTR = 2\ hours$$

$$Availability_{1sys} = \frac{MTBF_{1sys}}{MTBF_{1sys} + MTTR}$$

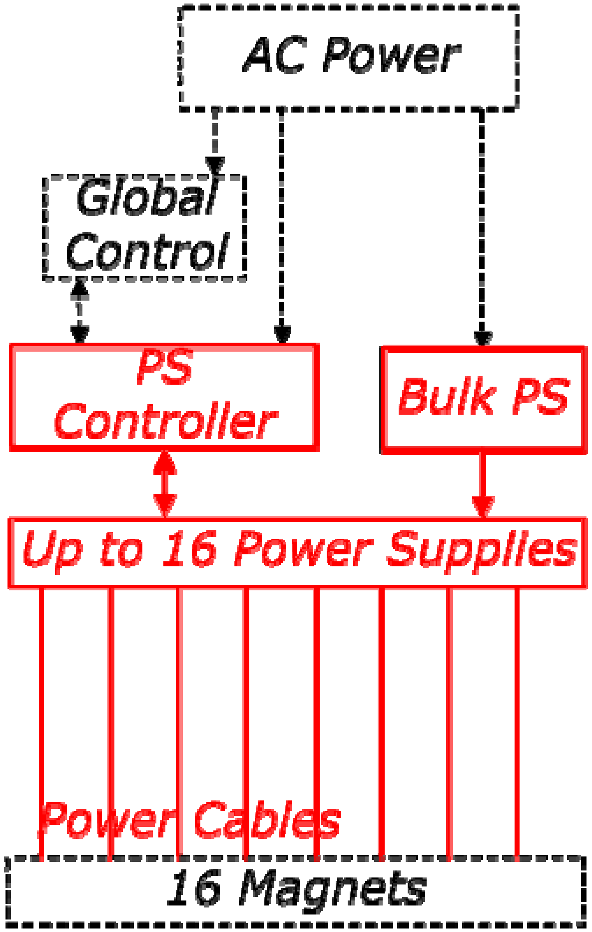
$$Availability_{13sys} = Availability_{1sys}^{13}$$

$$Failures = \lambda_{1sys} * 13 * t$$

154 Existing Correctors



New Corrector Power Supplies



New Corrector Power Supplies

$$\lambda_{1sys} = 12\lambda_{PS} + \lambda_{bulk} + \lambda_{controller} + \lambda_{cables}$$

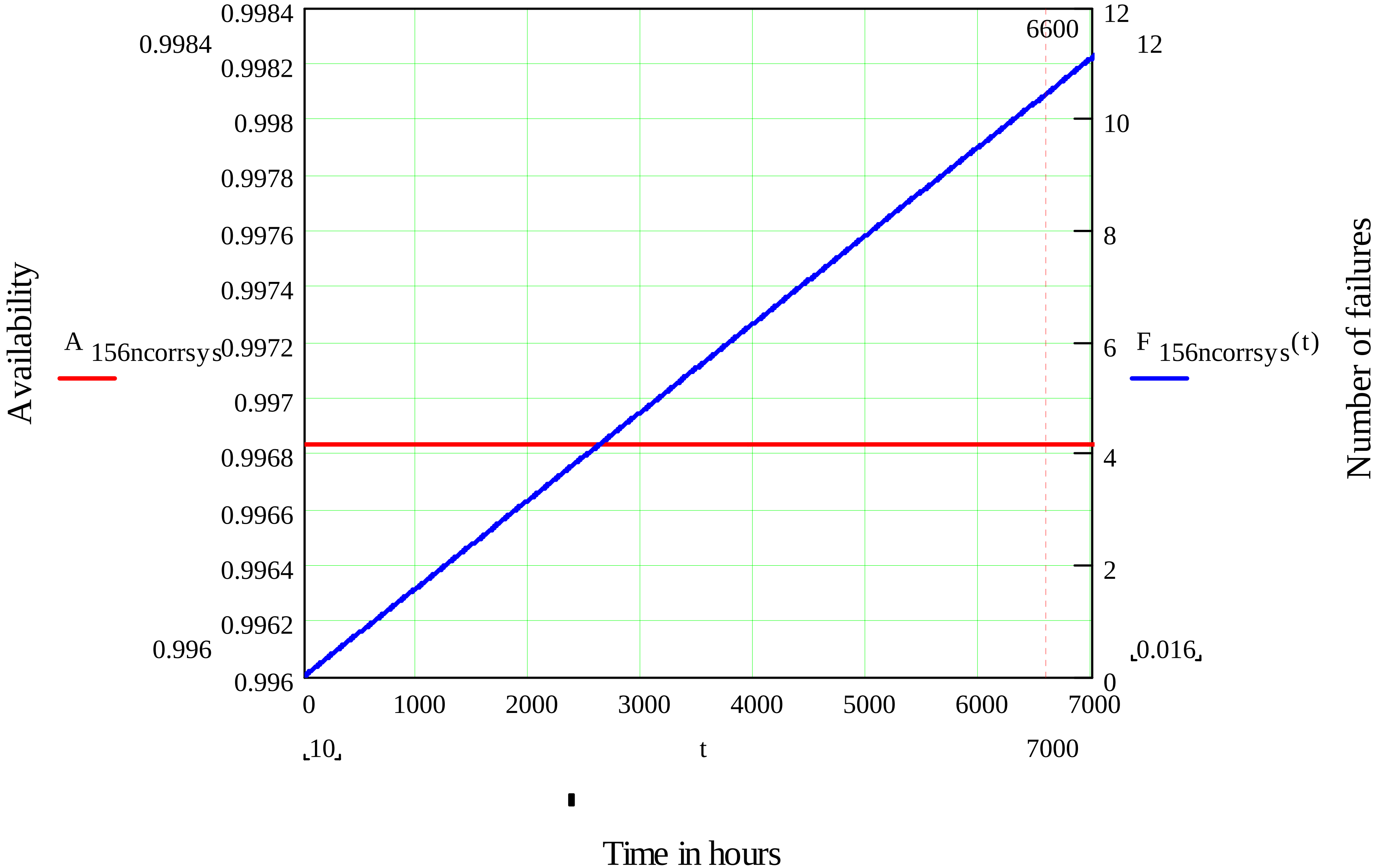
$$MTBF_{1sys} = \frac{1}{\lambda_{1sys}} \qquad MTTR = 2 \text{ hours}$$

$$Availability_{1sys} = \frac{MTBF_{1sys}}{MTBF_{1sys} + MTTR}$$

$$Availability_{13sys} = Availability_{1sys}^{13}$$

$$Failures = \lambda_{1sys} * 13 * t$$

156 New Correctors

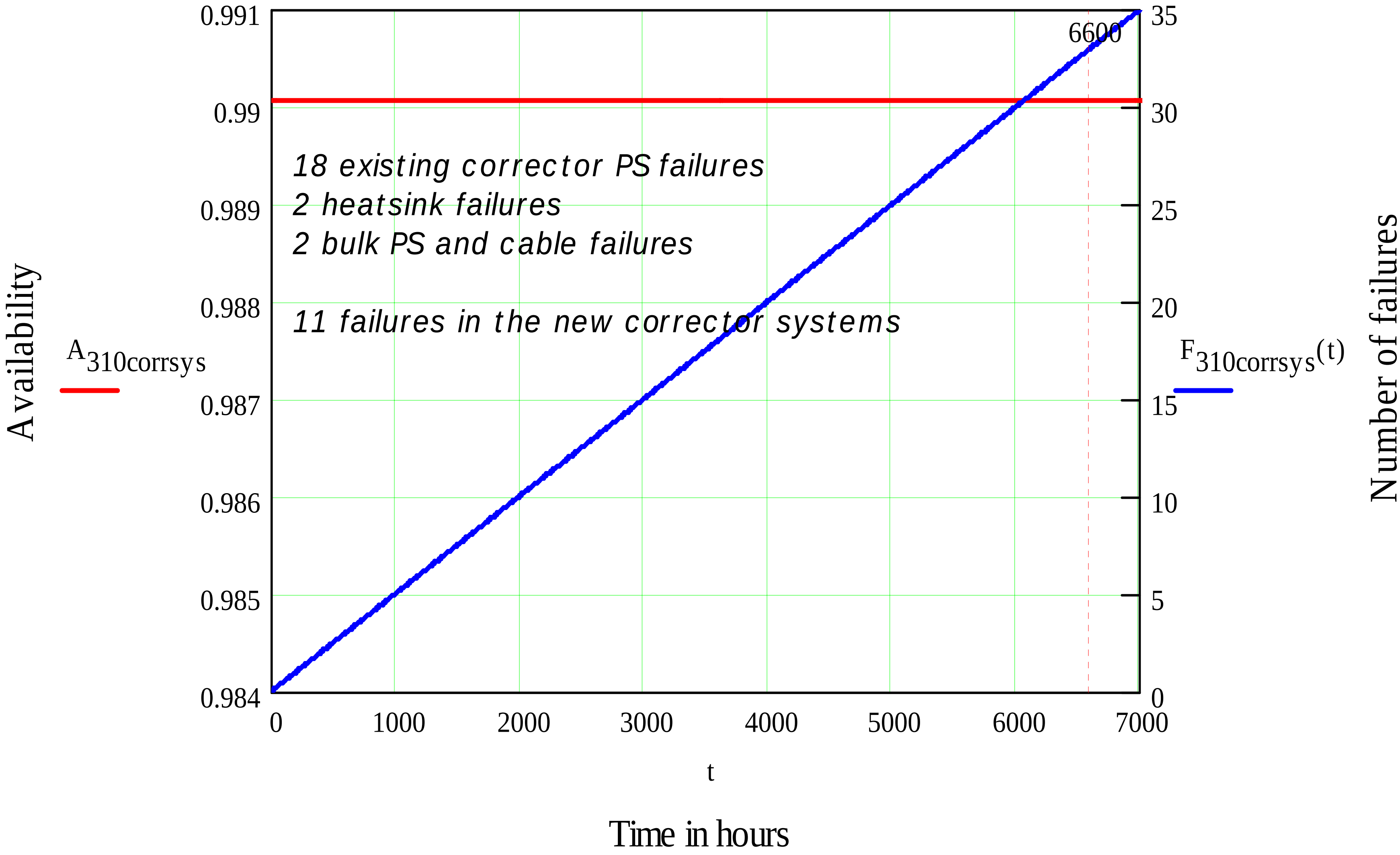


154 Existing and 156 New Corrector Power Supplies

$$Availability_{310} = Availability_{154existing} * Availability_{156new}$$

$$Failures_{310} = Failures_{154existing} + Failures_{156new}$$

310 Exist and New Corrector Systems

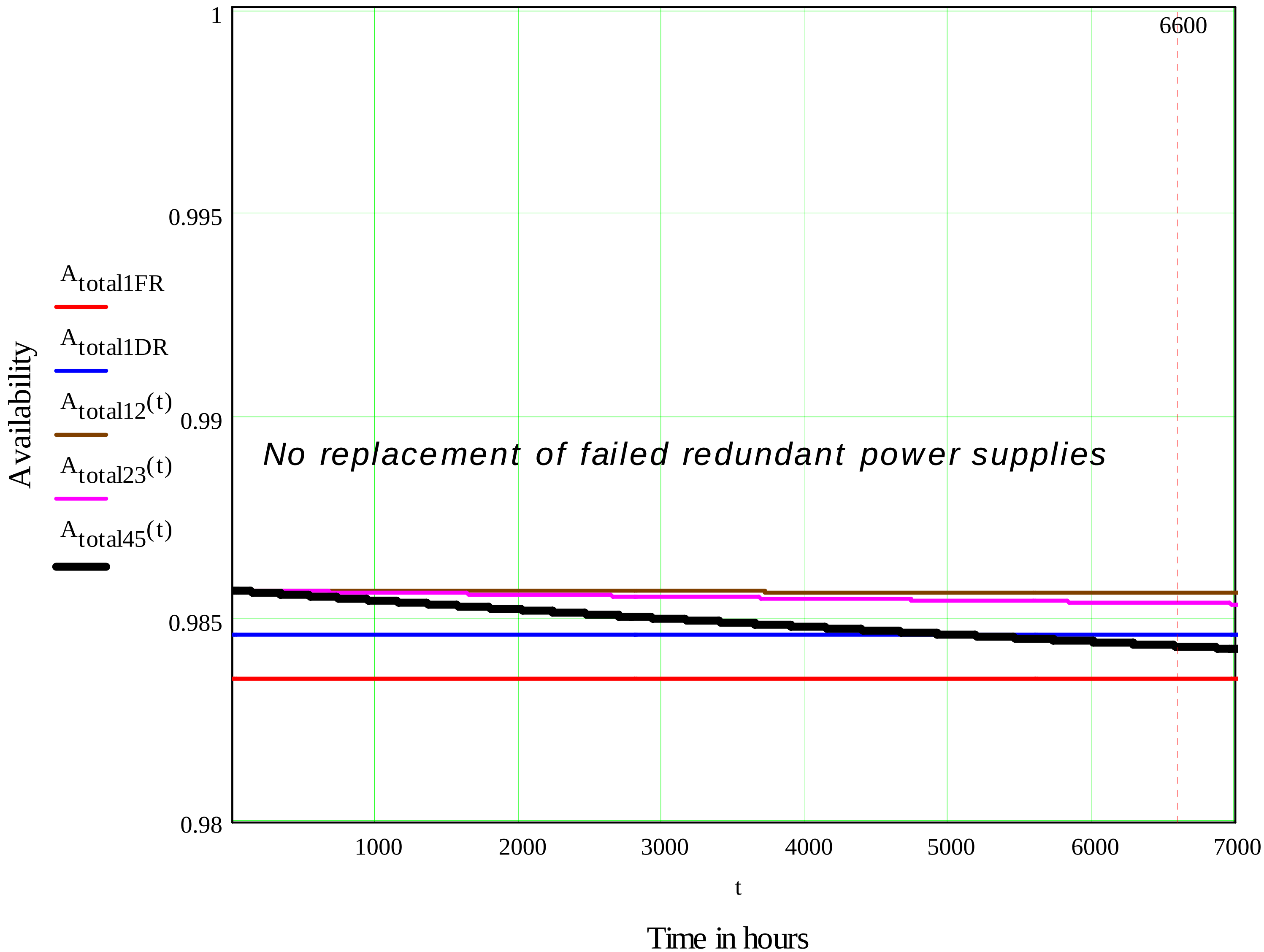


522 Large and Corrector Power Supplies

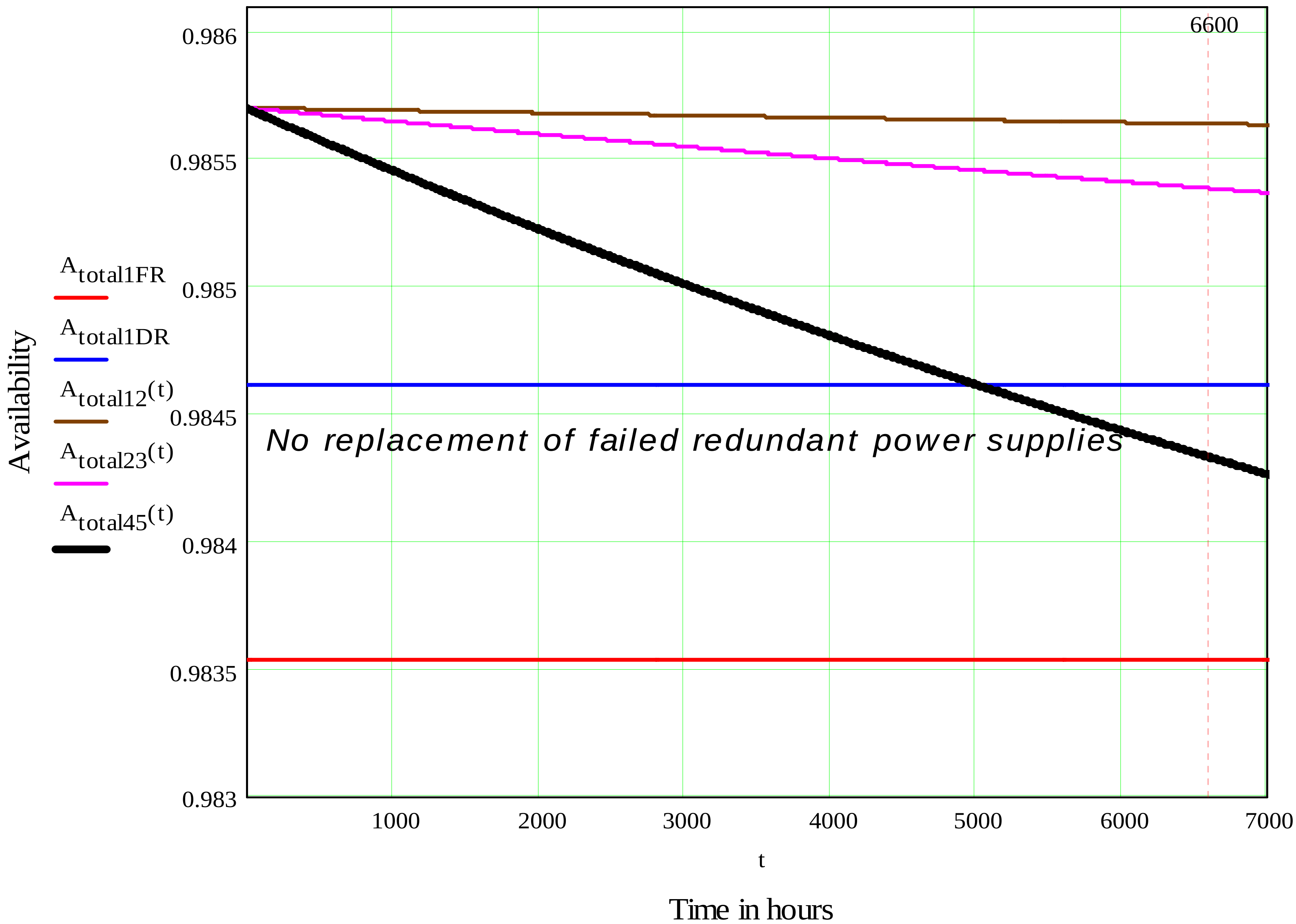
$$Availability_{522sys} = Availability_{212large} * Availability_{310corrector}$$

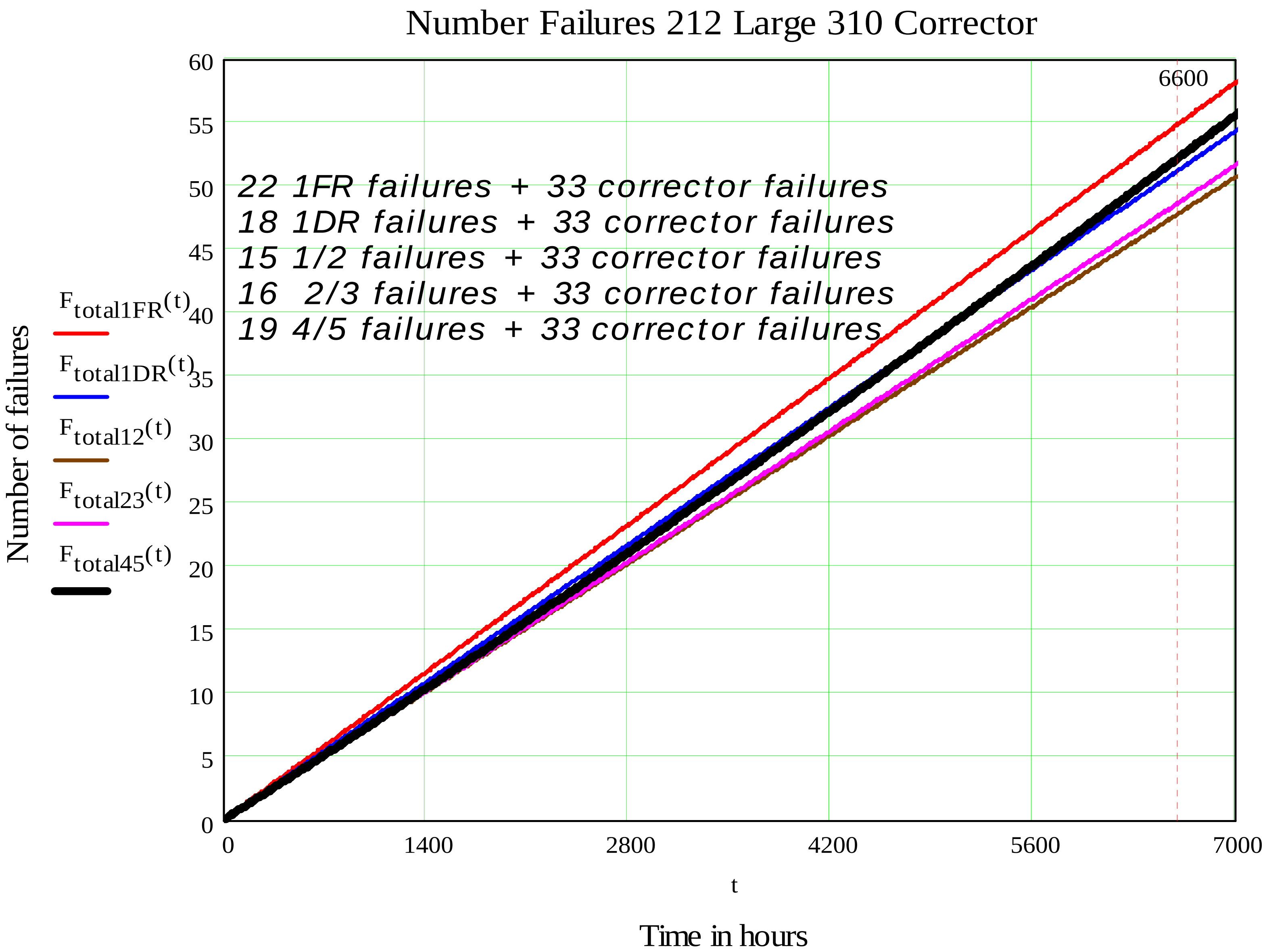
$$Failures_{522sys} = Failures_{212large} + Failures_{310corrector}$$

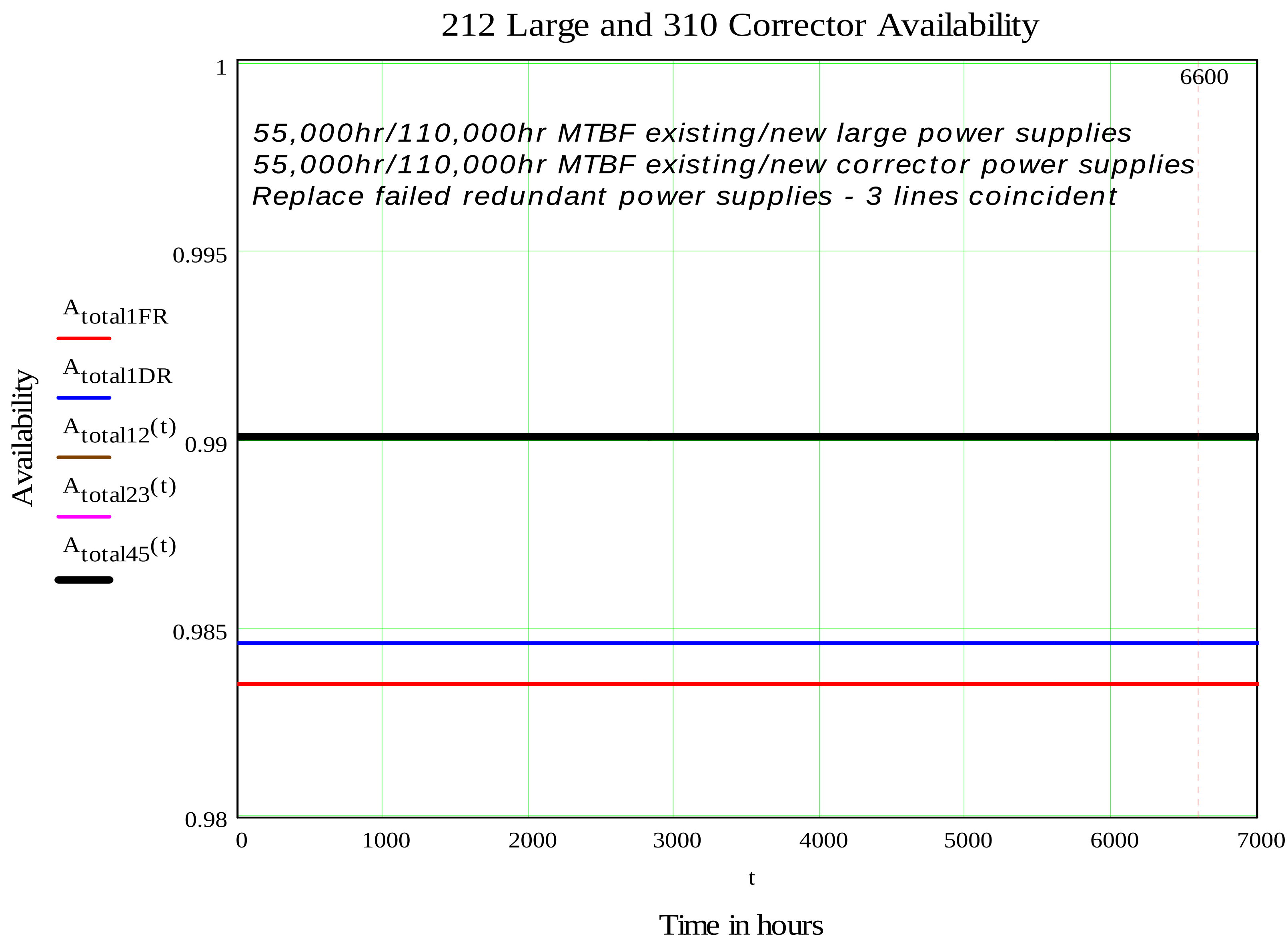
242 Large and 342 Corrector Availability



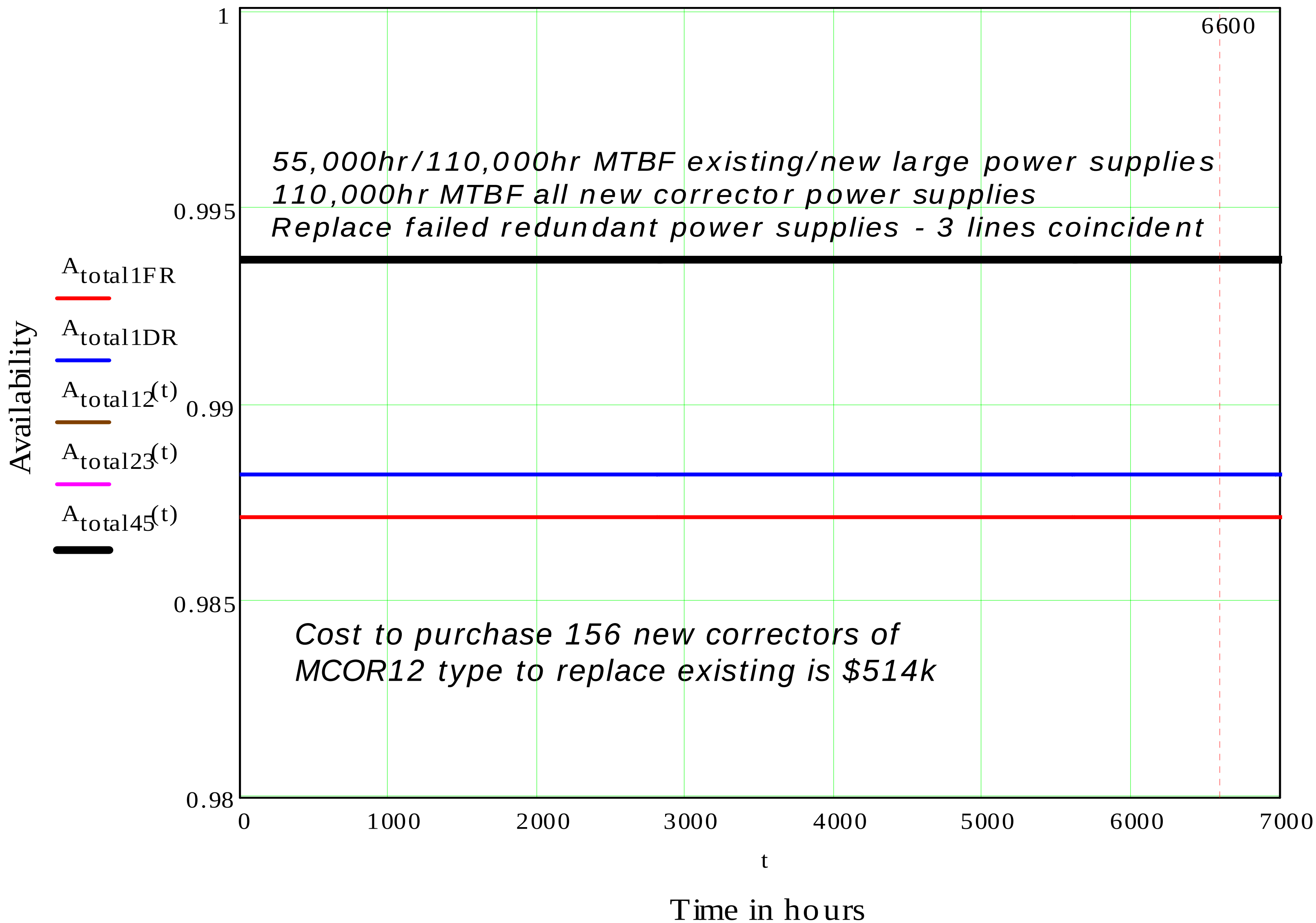
242 Large and 342 Corrector Availability



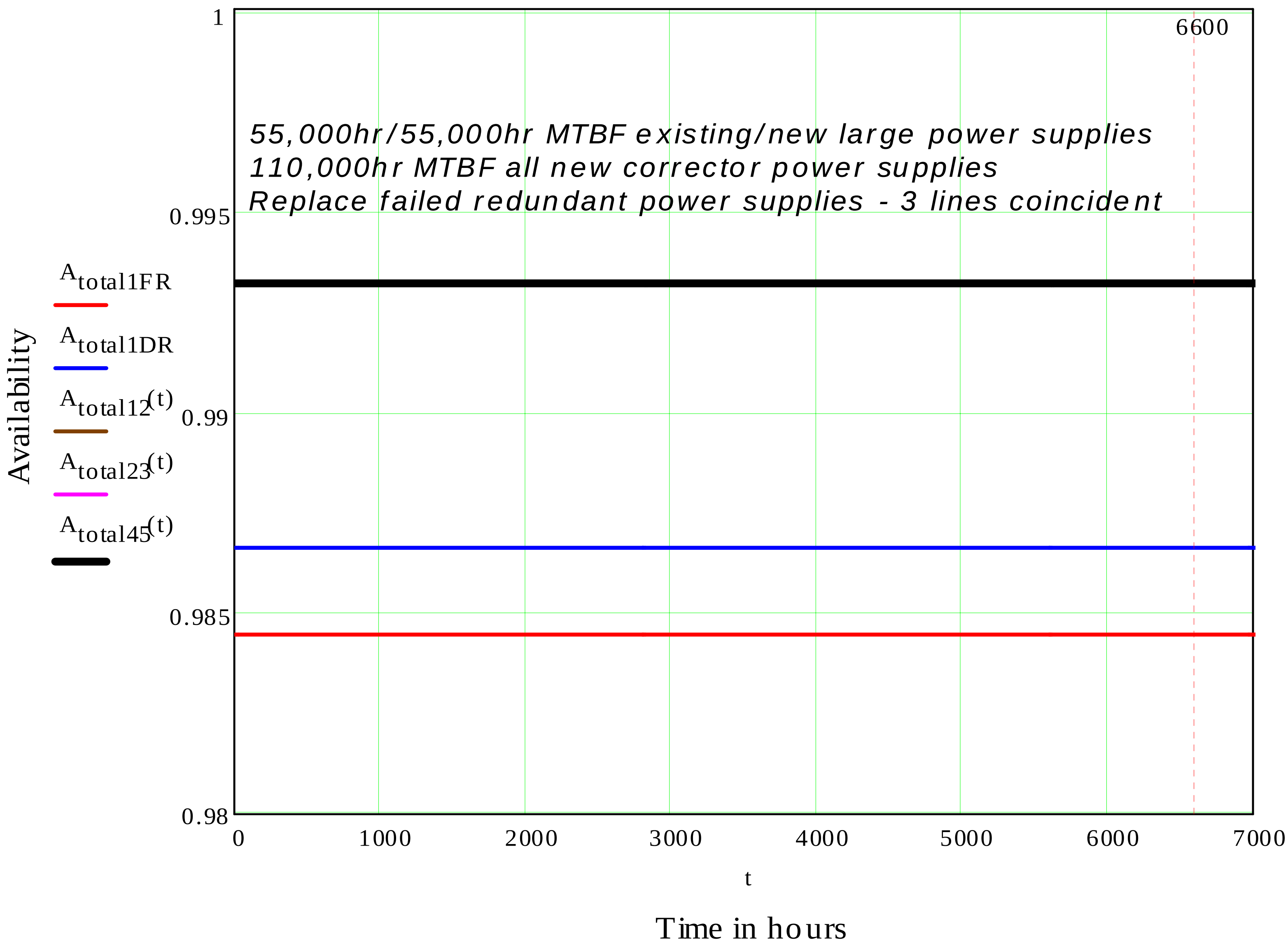

Number Failures 212 Large 310 Corrector
22 1FR failures + 33 corrector failures
18 1DR failures + 33 corrector failures
15 1/2 failures + 33 corrector failures
16 2/3 failures + 33 corrector failures
19 4/5 failures + 33 corrector failures
6600
Number of failures
$F_{total1FR}(t)$
$F_{total1DR}(t)$
$F_{total12}(t)$
$F_{total23}(t)$
$F_{total45}(t)$
0
5
10
15
20
25
30
35
40
45
50
55
60
0
1400
2800
4200
5600
7000
t
Time in hours


212 Large and 310 Corrector Availability
55,000hr/110,000hr MTBF existing/new large power supplies
55,000hr/110,000hr MTBF existing/new corrector power supplies
Replace failed redundant power supplies - 3 lines coincident
6600
1
0.995
0.99
0.985
0.98
Availability
$A_{total1FR}$
$A_{total1DR}$
$A_{total12}(t)$
$A_{total23}(t)$
$A_{total45}(t)$
0
1000
2000
3000
4000
5000
6000
7000
t
Time in hours

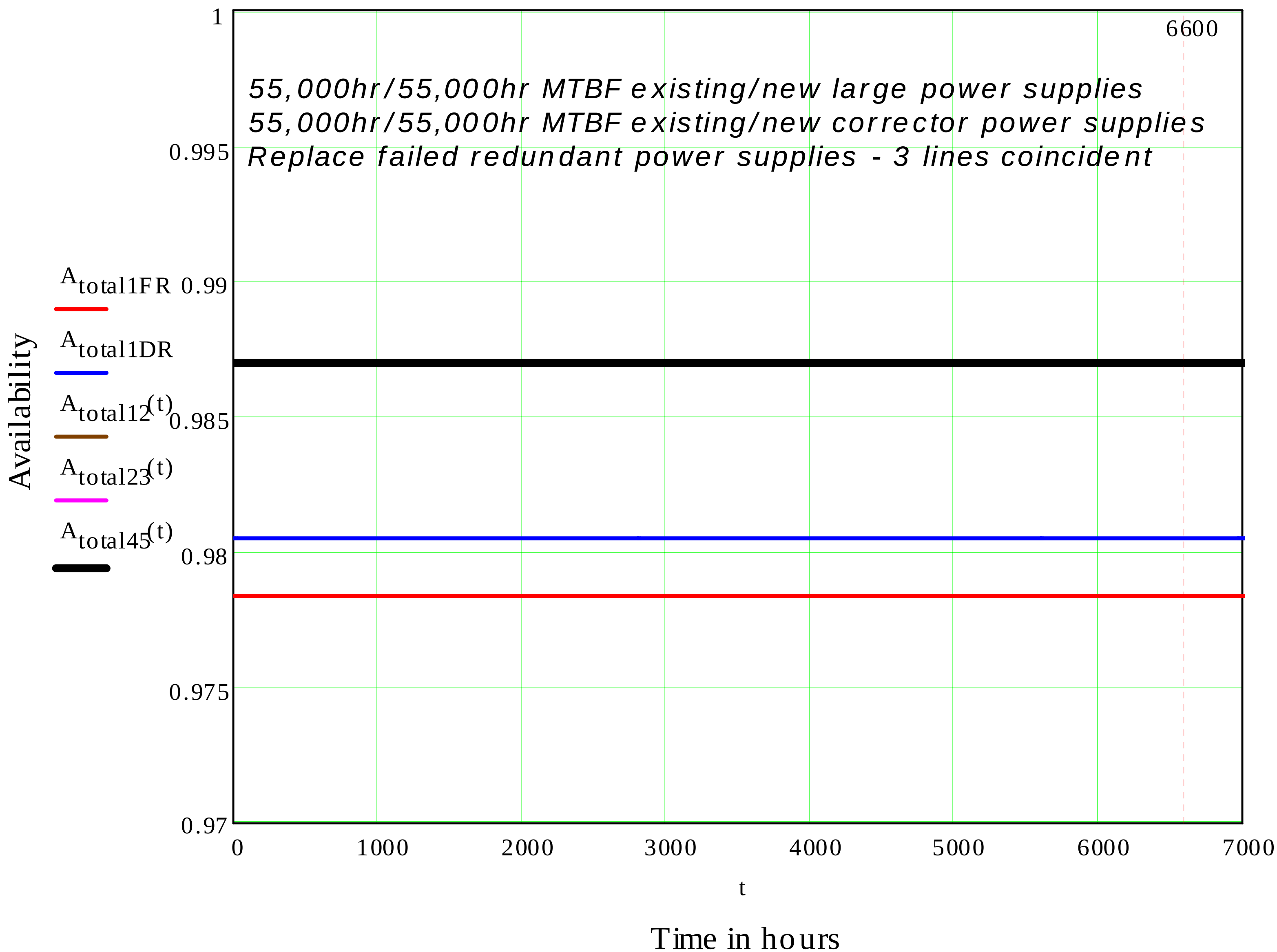
212 L/ 310 C - Replace Exist Correctors



212 L/310 C Pess Large + Replace Corr



212 L/310 C Most Pess Large and Corr



Large Corrector	55ke + 110kn 55ke + 110kn	55ke + 110kn 110k all new	55ke + 55kn 110k all new	55ke + 55kn 55ke + 55kn
1FR + correctors	0.983	0.987	0.984	0.978
1 DR + correctors	0.985	0.988	0.987	0.981
Redundant + correctors	0.990	0.994	0.993	0.987

Conclusions/Recommendations

1. The 0.98 availability criterion is reasonable. The 2% unavailability is not overly generous. The availability criterion is achievable with or without redundant power supplies

2. The overall availability is dominated by the corrector PS availability, simply because there are more of them

3. Redundant power supplies (power supplies are the weak link) provide availability improvement, even if they are not hot-swappable

4. Specify a minimum 100,000 hour MTBF in power supply purchase specifications. Require demonstrated compliance by analysis or empirical data before releasing power supplies for fabrication. The parts stress method described by MIL-HDBK-217 is appropriate