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U.S. Nuclear Regulatory Commission
Washington, D.C. 20555

ATTENTION: MR. R. W. BORCHARDT

SUBJECT: POSITION PAPER ON AP600-SPECIFIC TIME DELAY IN THE PHYSICALLY-BASED SOURCE TERM

Dear Mr. Borchardt:

The NRC has issued draft NUREG 1465 which describes a physically-based source term for accident dose evaluations. During a meeting held with the NRC on August 29 and 30, 1994, Westinghouse agreed to provide the Staff with a position paper for their consideration that details the time delay prior to fission product release that will be applied to the physically-based source term for AP600. The position paper is enclosed with this letter.

Please contact Brian A. McIntyre on (412) 374-4334 if you have any questions concerning this transmittal.

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Enclosure

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AP600 Specific Time Delay in the Physically-Based Source Term

The Nuclear Regulatory Commission (NRC) has issued NUREG 1465 (reference 1) which describes a physically-based source term for accident dose evaluations. The timing of the source term in reference 1 is based on current generation plant designs. The AP600 is a low power density light water nuclear reactor which employs passive systems to reflood the reactor vessel and quench the core in the event of a loss of coolant accident (LOCA). The response of the AP600 to a LOCA differs from that of a current generation nuclear power plant, and therefore, the timing of the physically-based source term defined in NUREG-1465 must be modified to properly credit the safety benefits of the AP600. This paper describes the features of the AP600 which delay the fission product source term compared to current generation nuclear plants and identifies the time delay to the onset of fission product release from the fuel (time of initial gap release). This time delay will be used in place of the value identified in reference 1 for AP600 accident dose evaluations.

1.0 Consideration of Systems Availability

The physically-based source term described in reference 1 for use in the evaluation of design basis accident doses is a severe fission product release which accompanies core melt accident sequences. To produce such a release, safety systems which are designed to prevent core damage must be assumed to have failed. Otherwise, no release of fission products beyond a small fraction of the gap inventory can be predicted. The selection criterion used in this analysis for systems to be credited in the source term timing is that the system must be passive or fail-safe to be included in the analysis.

1.1 Current Generation Plants (Basis for NUREG 1465 Timing)

In the current plant designs, the only passive or fail-safe emergency cooling system is the gas-charged accumulator tanks. The accumulators are filled with ambient temperature borated water and pressurized to approximately 600 psi. Under normal operating conditions, the accumulators are isolated from the RCS by check valves in lines connected to the cold legs of each of the loops in the reactor coolant system (RCS). In the event of a LOCA, the accumulators inject water into the cold legs. The water flows from the cold legs into the reactor vessel downcomer. Current plant accumulators are sized to refill the lower plenum and downcomer of the reactor vessel, considering spillage of injected water from the broken loop and entrainment of water through the break following a doubled-ended guillotine break of a cold leg pipe.

The ultimate water source for emergency core cooling in the current plant designs is the borated water from the refueling water storage tank (RWST). The RWST is a large tank of water outside the containment pressure boundary which is pumped into the reactor coolant system via the high/low pressure safety injection pumps. After the accumulators fill the lower plenum and downcomer, the pumped injection refills the reactor vessel and eventually quenches the core. The RWST water and high/low pressure injection pumps are not considered in the evaluation of the onset of core damage since operation of these pumps precludes core melt, and because these pumps are not passive and do not meet the system availability selection criterion.

1.2 AP600

In the AP600 design, the passive emergency core cooling systems consist of two gas-charged accumulators, two core makeup tanks (CMTs) which inject via gravity and the IRWST which injects via gravity. Both the accumulators and CMTs are filled with ambient temperature borated water and are injected via the direct vessel injection (DVI) lines into the reactor vessel downcomer.

The accumulators are pressurized to approximately 700 psi with nitrogen gas and, under normal operating conditions, are isolated from the RCS by check valves. In the event of a LOCA, the RCS pressure will fall, and the pressure in the accumulators will open the check valves and allow the borated water to be injected into the RCS. The AP600 accumulators are sized to refill the vessel and to reflood the core considering entrainment of injected water through the break following a double-ended guillotine break of an RCS pipe. Core quench occurs during blowdown for cold and hot leg break scenarios (reference 2).

The CMTs are initially pressurized to the RCS pressure by a normally-open balance line which connects the cold leg to the top of the CMT. Under normal operating conditions, the CMTs are isolated from the RCS by fail-open air-operated valves. In the event of a LOCA, the CMT discharge valves are opened by a high containment pressure or low pressurizer pressure signal. The CMTs drain via gravity into the vessel. During the pressurized injection of the accumulators, the CMTs do not inject since both inject through the same DVI lines into the vessel downcomer and the water head in the CMT cannot overcome the pressure of the accumulators. After accumulator injection, the CMTs inject, maintaining the vessel mixture level at the break elevation until the water in the CMTs runs out.

The ultimate water injection source for the AP600 is the in-containment refueling water storage tank (IRWST). The IRWST is at containment pressure and injects via gravity into the depressurized RCS. In the event of the postulated large break LOCA, the RCS is depressurized and IRWST injection would occur as a passive, fail-safe process. However, in this analysis of the delay time to initiate core damage, the injection of the IRWST water into the RCS is not considered since credit for this source of water would preclude core damage. This is an inconsistency in the application of the criterion developed above regarding equipment that can be credited for accident mitigation but, without this inconsistency, the accident would not address the requirement of 10 CFR 100 that a "substantial meltdown of the core" be considered.

The AP600 is a leak-before-break plant. Thus, the postulated large break LOCA goes beyond the plant design basis. However, using the large break LOCA as the basis for determining the time delay to onset of core damage is a conservative approach. In the event of a small break LOCA, the RCS is depressurized by operation of the automatic depressurization system (ADS). The ADS valves are a set of eight fail-closed, actively-operated valves which do not meet the selection criterion developed above. Assuming all of the passive, fail-safe systems are available (accumulators, CMTs, and IRWST injection) but that the ADS fails to operate, no core damage would be predicted for a LOCA unless the break size were small enough to prevent the RCS from depressurizing to the point at which the IRWST water could inject effectively. A LOCA of this size would have a significantly longer time to core damage than would a large break LOCA.

2.0 Accident Sequence Selection

The accident sequence for this analysis is chosen to minimize the time to core uncovery to bound the time to core damage for the possible RCS break sizes. The accident sequence must depressurize the RCS as rapidly as possible and spill injected water to the containment to minimize the amount of water which gets to the core. The time of core uncovery will be the shortest time for postulated RCS pipe break sizes. Therefore, the double-ended guillotine break of a hot leg pipe is chosen as the bounding sequence for this analysis. This break size is a very low probability event. The large break LOCA initiating event frequency is at least an order of magnitude less than the frequency of each of the other initiating events considered in the PRA, except for the vessel rupture initiating event.

In all calculations, the RCS pressure is assumed to be atmospheric pressure, and injection to the RCS is assumed to spill at the rate at which water is injected once it reaches the break elevation. The break elevation is assumed to be at the bottom of the hot leg which provides the least water volume available above the core.

3.0 Discussion of Accident Sequence Progression

This section provides a qualitative discussion of the processes that lead from accident initiation to core uncovery, heat up and fission product release for current generation plants and the AP600.

3.1 Current Generation Plants (Basis for NUREG 1465 Timing)

The accident is initiated by the double-ended failure of a cold leg pipe. Flashing and entrainment of coolant through the break voids the reactor vessel and coolant loops. The RCS pressure falls rapidly during blowdown and, within approximately 10 seconds, the accumulators begin to inject into the cold legs. A fraction of the accumulator injection "bypasses" the core due to spillage of water injected into the broken cold leg as well as entrainment of water in the downcomer flow exiting the break. After the blowdown is completed, the accumulator injection has refilled the reactor vessel lower head and downcomer. Due to the assumed failure of the pumped injection of RWST water, the top of the core remains uncovered and unquenched. The core heats up from decay heat generation, and gap release is expected to occur within minutes of the initiation of the accident.

3.2 AP600

The accident is initiated by the double-ended failure of a large RCS pipe. Flashing and entrainment of coolant through the break voids the reactor vessel and coolant loops. The CMT discharge valves are opened on a low pressurizer pressure signal, and the water injects via gravity into the reactor vessel downcomer through the DVI lines. The RCS pressure falls rapidly during the blowdown and, within approximately 10 seconds, the accumulators begin to inject into the vessel through the DVI lines. During accumulator injection, the CMTs cannot inject. A fraction of the injection flow is entrained during the blowdown from the downcomer through the break where it is lost to the containment. The accumulator injection refills the reactor vessel, and the core quenches early in the transient. After the accumulator flow is

completed, the CMTs resume injection via the gravity head of water in the tanks and maintain the vessel mixture level at the break elevation. After the CMT water runs out, decay heat boils away the water in the volume above the top of active fuel and below the break elevation to uncover the core. Subsequent to core uncovery, the fuel heats up from the saturation temperature of water to the temperature at which significant fission product release from the fuel occurs.

Additional AP600 design features which contribute to the longer time to fission product release are the low power density core and reactor vessel design which has a larger water volume above the core than is found in current generation plants.

4.0 Estimation of the Time to Core Damage for the AP600

For the purposes of this analysis, core damage is defined as the time that gap release of fission products begins. The gap release phase is assumed to begin when the temperature of the hottest fuel rod exceeds 1400°F (1033°K).

The time to core uncovery and core damage for a double-ended break of a RCS pipe can be broken down into several time frames. The sum of these time frames is the total time required to reach core damage in the AP600. The double-end LOCA provides the shortest time to core uncovery, and thus provides a core damage time estimate which bounds the core damage times for all other break sizes. The five time frames outlined in section 3.2 are summarized here:

- break initiation through beginning of accumulator injection
- duration of accumulator injection
- duration of core makeup tank injection
- boil off of water in the downcomer and upper plenum above the top of core
- heat up of core to core damage temperature.

The first time frame prior to accumulator injection is on the order of 10 seconds (reference 2).

4.1 Estimation of the Duration of the Accumulator Injection

In the large LOCA scenario, the AP600 accumulators inject as the reactor coolant system blows down to atmospheric pressure and then continue to inject to atmospheric pressure until they run out. Based on WCOBRA-TRAC analyses (reference 2), the RCS blowdown to atmospheric pressure occurs over approximately 30 seconds. The WCOBRA-TRAC analysis is concluded before the end of the accumulator injection since the core is quenched and the peak clad temperature has been determined. The calculation presented in this section conservatively estimates the duration of the accumulator injection.

This analysis assumes that the RCS pressure is atmospheric throughout the accumulator injection. This assumption is conservative since it causes the accumulators to inject faster during the initial interval during the blowdown when the RCS pressure is actually elevated.

To calculate the accumulator injection rate, the accumulator pressure is calculated from the isothermal expansion of the nitrogen which is assumed to behave as an ideal gas. This is a

conservative assumption since the isothermal expansion will overestimate the pressure in the accumulator and result in a faster discharge. The accumulator pressure is an inverse function of the volume of the gas:

$$\frac{P(t)}{P_0} = \frac{V_0}{V(t)}$$

where: P_0 = the initial pressure
V_0 = the initial volume of nitrogen
$P(t)$ = the time dependent pressure
$V(t)$ = the time dependent volume

A single-phase water flow algorithm (MAAP4 WFLOW subroutine, reference 3) is used to solve the injection flowrate, and the displaced volume of water determines the change in volume of the gas. The two accumulators are assumed to inject simultaneously, and the break is assumed to spill water at the injection rate, so the availability of two accumulators is not considered to extend the duration of time frame 2 over the time to inject one accumulator. The initial conditions and input parameters are chosen to minimize the duration of the accumulator flow.

The initial conditions of one AP600 accumulator are chosen conservatively as:

Initial water volume	= V_{W0}	= 1667 ft^3	= 47.2 m^3
Initial gas volume	= V_{G0}	= 333 ft^3	= 9.43 m^3
Initial pressure	= P_0	= 769 psia	= 5.3 MPa
Temperature	= T	= 120°F	= 322°K

Flow area of DVI line = 36.46 in^2 = 0.0235 m^2
Flow loss coefficient (K) from accumulator to reactor vessel downcomer = 16.1
RCS back pressure = 14.7 psia = 1.01 bar

The duration of the accumulator injection is calculated to be 145 seconds. The results of the calculation, presented as volume of water in the accumulator, pressure in the accumulator and the mass flowrate to the RCS, are shown in Figures 1 through 3, respectively.

4.2 Estimation of the Duration of the Core Makeup Tank Injection

The CMTs inject via gravity for several seconds after the safety injection "S-signal" and prior to accumulator injection. The pressurized injection of the accumulators shuts off the CMT injection since they both inject into the same DVI lines, and the CMT elevation head cannot overcome the pressure in the lines. After the accumulator injection is completed, the CMTs continue their injection via gravity into the DVI lines. Since the accumulator injection has quenched and recovered the core, the CMT injection maintains the water level at the break elevation until the CMTs are empty. In this calculation, the mass of water lost from the CMTs during the initial time frame of the blowdown is assumed to be negligible.

The analysis assumes that the pressures in the RCS and in the CMTs are exactly the same. This is a reasonable assumption given the open balance line from the cold leg to the top of the CMT. Since the assumption neglects possible condensation effects in the CMT steam space which could reduce the CMT flowrate and replenish the volume of liquid in the CMT, it is actually conservative. The two CMTs are assumed to inject simultaneously, and the break is assumed to spill water at the injection rate, so the availability of two CMTs is not considered to extend the duration of time frame 2 over the time to inject one CMT.

The duration of the CMT injection is determined by calculating the Bernoulli flowrate from the CMT to the RCS. The flowrate is driven by the elevation head of the water in the CMT. The water/steam mixture level in the RCS is assumed to be at the bottom of the hot leg, which is below the elevation of the DVI line, so no elevation head is assumed in the RCS back pressure at the DVI line exit into the reactor vessel downcomer.

The volumetric flowrate from the CMT derived from Bernoulli's equation is:

$$\dot{V} = A * \left[\frac{2g*z}{(K+1)} \right]^{1/2}$$

where: A = the flow area
g = the acceleration of gravity
z = the elevation head of water
K = the flow loss coefficient

The transient water elevation in the CMTs is solved, given the water volume, as a function of the geometric shape of the CMT which is a cylinder with hemispherical heads. The initial conditions and the parameters are chosen to minimize the time to inject the CMT water.

The initial conditions and parameters for the CMT injection calculation are:

CMT total volume (initially full of water) = 2000 ft^3 = 56.6 m^3
Elevation of the inside bottom of the CMT above DVI line = 7.58 ft = 2.31 m
Inner diameter of the CMT = 12.5 ft = 3.81 m

Flow area of the DVI line = 36.46 in^2 = 0.0235 m^2
Flow loss coefficient (K) from CMT to reactor vessel downcomer = 27.5
RCS and CMT pressure = 14.7 psia = 1.01 bar

The duration of CMT injection is calculated to be 1275 seconds. The results of the calculation, presented as volume of water in the CMT, height of water in the CMT and the volumetric flowrate to the RCS, are shown in Figures 4 through 6, respectively.

4.3 Duration of the Boil-Off of Water Above the Active Core

After the CMT injection is completed, the water level is initially at the break elevation, which is assumed to be at the base of the hot leg nozzles. The mixture which occupies the volume above the active fuel and below the base of the hot leg nozzles must be boiled away before the

core uncovers and begins to heat up. The coolant is assumed to be saturated, and therefore a void fraction of the hot side volume must be included in the determination of the inventory that needs to be boiled away to uncover the core. The volume in the AP600 reactor vessel between the active core and the base of the hot leg nozzles (V_{hot}) is 348 ft^3 (9.85 m^3). The volume in the downcomer above the core and below the bottom of the nozzles (V_{cold}) is 202 ft^3 (5.72 m^3).

The decay heat rate used to determine the boil off rate and the void fraction is determined from the ANS 1979 decay heat correlation at 1420 seconds. The time is determined from the sum of the accumulator and CMT injection durations. The void fraction at the core exit is calculated using the Yeh correlation (reference 4). The decay heat rate, the boil off rate and the void fraction are:

Decay heat rate: $Q = (100\%\ \text{Power}) * Q/Q_0 = 1940\ \text{MWt} * 0.01891 = 36.7\ \text{MWt} = 34786$ btu/s

Boil off rate: $w_B = Q/h_{fg} = (34786\ \text{btu/s})/(970.3\ \text{btu/lbm}) = 35.85\ \text{lbm/s}$

Void fraction at the core exit $= \alpha_e = 0.77$

The mass of water above the core is:

$$m_w = \frac{V_{cold} + V_{hot}(1-\alpha_e)}{v_f} = 16899\ lbm$$

The duration of the boil off of water above the core is:

$$\Delta t_{BO} = \frac{m_w}{w_B} = 471\ seconds$$

4.4 Duration of the Heat Up of Fuel Rods After Core Uncovery

After core uncovery, the fuel rods, which are initially near the water saturation temperature, heat up to the temperature at which the gap release is expected to occur. This temperature is assumed to be 1400°F (1033°K). The heat generation up to 1400°F is assumed to be due to decay heat only, chemical energy is assumed to be negligible at these temperatures. Chemical energy from exothermic reactions becomes important once the temperature is above approximately 2240°F (1500°K) where rapid zircaloy oxidation begins, and the chemical energy added by the reaction promotes melting of fuel and release of fission products. The heat up is assumed to be adiabatic, and only the thermal mass of the uranium dioxide is credited in the calculation of the heat up duration.

Average power density at full power = 78.82 kW/liter = 7.9E7 W/m^3
Hot rod peaking factor = 2.6
Axial peaking factor at top of core = 0.924
ANS 1979 Decay heat factor at 1895 seconds= $Q/Q_0 = 0.01743$

Volumetric heat rate = Q_V = 0.01743 (0.924) (2.6) (7.9E7) = 3.31E6 W/m^3

Average properties of UO_2 between 373°K and 1033°K:

density = ρ_{UO2} = 10859 kg/m^3

specific heat = Cp_{UO2} = 287 J/kg/K

The heat up rate of the core is given by:

$$\frac{dT}{dt} = \frac{Q_V}{(\rho C_p)_{UO2}} = \frac{3.31x10^6}{(10859)(287)} \frac{°K}{sec} = 1.06 \frac{°K}{sec} = 1.91 \frac{°F}{sec}$$

Therefore, the time required to heat up the hottest fuel rod to 1400°F is:

$$\Delta t = \frac{(1400 - 212)°F}{1.91 \frac{°F}{sec}} = 622 \ seconds$$

5.0 Leak-Before-Break Considerations

The AP600 is a leak-before-break plant, and therefore, according to reference 1, can credit a 10 minute delay in the beginning of the source term. The leak-before-break consideration limits the size of the LOCA which can be imposed on the reactor coolant system. For smaller LOCAs, the blowdown time (time frame one), accumulator and CMT injection times (times frames two and three) would be considerably longer than for a large LOCA and the spillage of water would be less, extending the time of core uncovery well beyond the time expected for large LOCA scenarios. After the operation of the automatic depressurization system after partial injection of the CMTs in most accident sequences, the RCS depressurizes much in the same way as a large break LOCA. The ten minute delay time is used as an estimate of the extension of the durations of time frames one, two and three. Therefore, the 10 minutes credited for leak-before-break added to the timing which has been developed for the AP600 large LOCA scenario is used to estimate the time delay for the leak-before-break case.

6.0 Results and Conclusion

The timing of the physically-based source term developed in NUREG 1465 (reference 1) is based on a current generation nuclear plant design. The response of a conventional nuclear plant and the AP600 to a double-ended loss of coolant accident leading to a large fission product source term have been compared. In the basis for NUREG 1465, pumped injection in current generation plant is not credited, and accumulator injection is not sufficient to quench the core. Gap release is expected to begin very quickly after accident initiation. In the AP600, the passive, fail-safe accumulators and core makeup tanks inject and quench and recover the core very early in the transient, minimizing heat up of the core. After CMT injection is completed, the water above the core must boil away and the core must heat up before gap release can occur. The low power density of the AP600 core and the increased volume of water above the core are additional design features which contribute to the delay of gap release.

The time to core uncovery and damage is determined in a series of five time frames which are summarized in Table 1. Also, leak before break is credited for delaying the time to gap release by 10 minutes. Based on the above conservative calculations, the minimum expected time to core damage and fission product release in the AP600 is 3123 seconds or 52 minutes. Therefore, to properly credit the safety benefits realized in the AP600, the 52 minute time delay prior to fission product release must be applied to the physically-based source term described by the NRC in reference 1.

7.0 References

1. Draft Final NUREG 1465, "Accident Source Terms for Light Water Nuclear Power Plants", August 1994.

2. Attachment to Westinghouse Letter NTD-NRC-94-4114, Additional Information in Support of Westinghouse Response to RAI 952.44 - 952.46, May 17, 1994.

3. EPRI Research Project 3131-02, "MAAP4 - Modular Accident Analysis Program for LWR Power Plants", May 1994.

4. Yeh, H. C., and Cunningham, J. C., "Experiments and Void Correlation for PWR Small Break LOCA Conditions", Trans. ANS, 17, p 369.

Table 1

Summary of the Time to Core Damage for the AP600

Description of Time Frame		Duration
Leak Before Break (10 minutes)		600 seconds
Time Frame 1:	Accident Initiation to Beginning of Accumulator injection	10 seconds
Time Frame 2:	Duration of Accumulator Injection	145 seconds
Time Frame 3:	Duration of CMT Injection	1275 seconds
Time Frame 4:	Boil-off of Water Above the Core	471 seconds
Time Frame 5:	Heatup of Fuel to Gap Release	622 seconds
	Total	3123 seconds

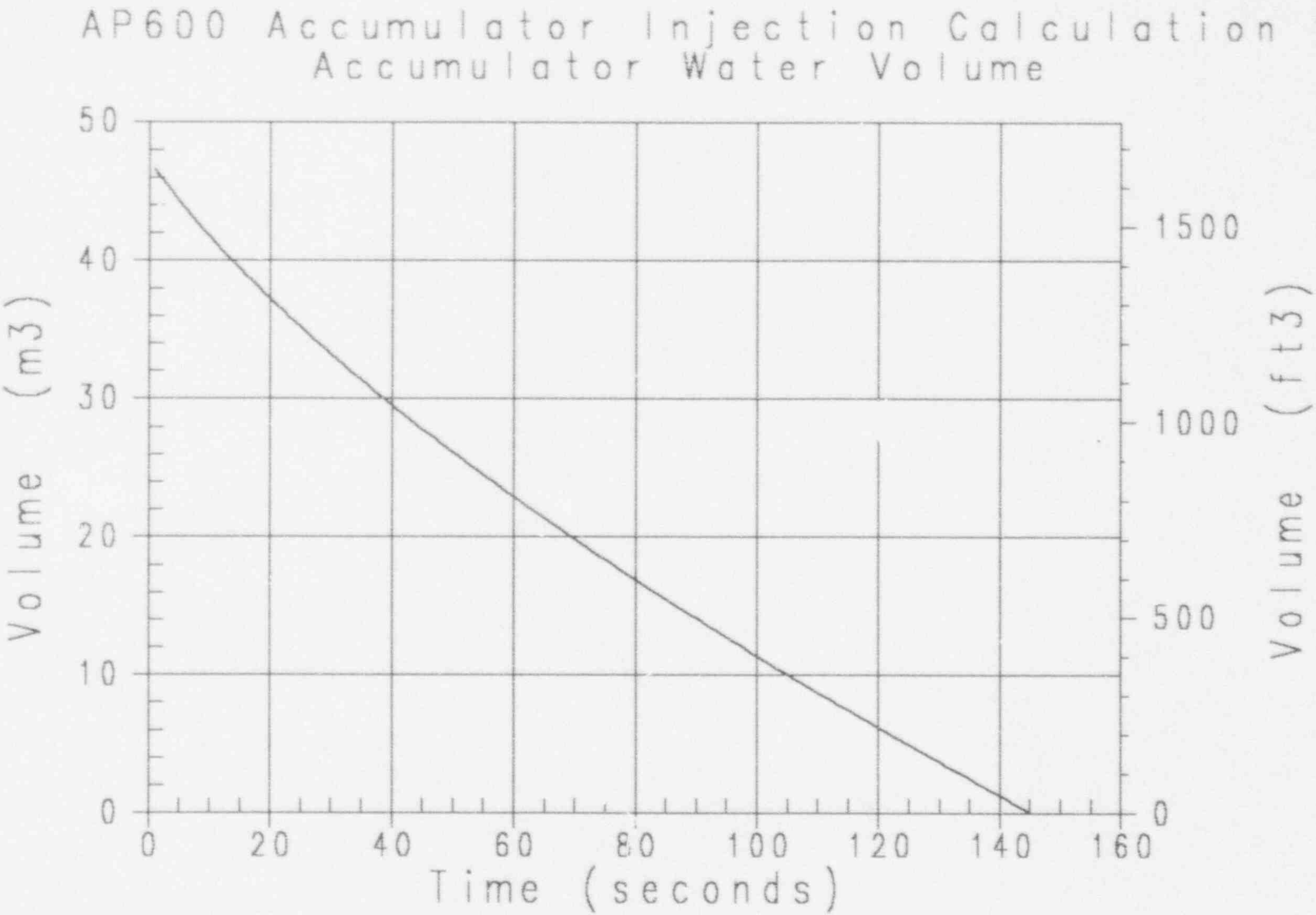
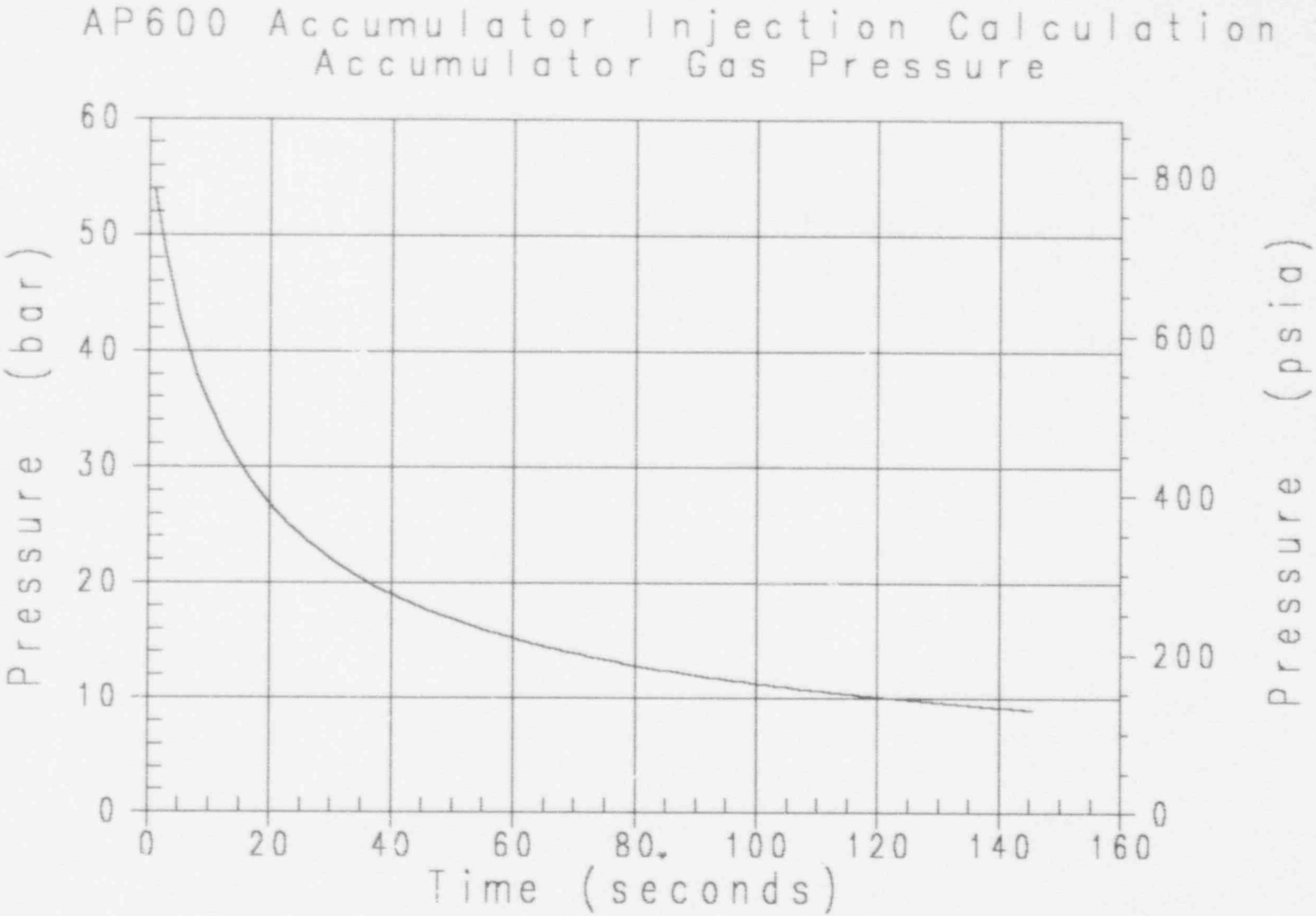
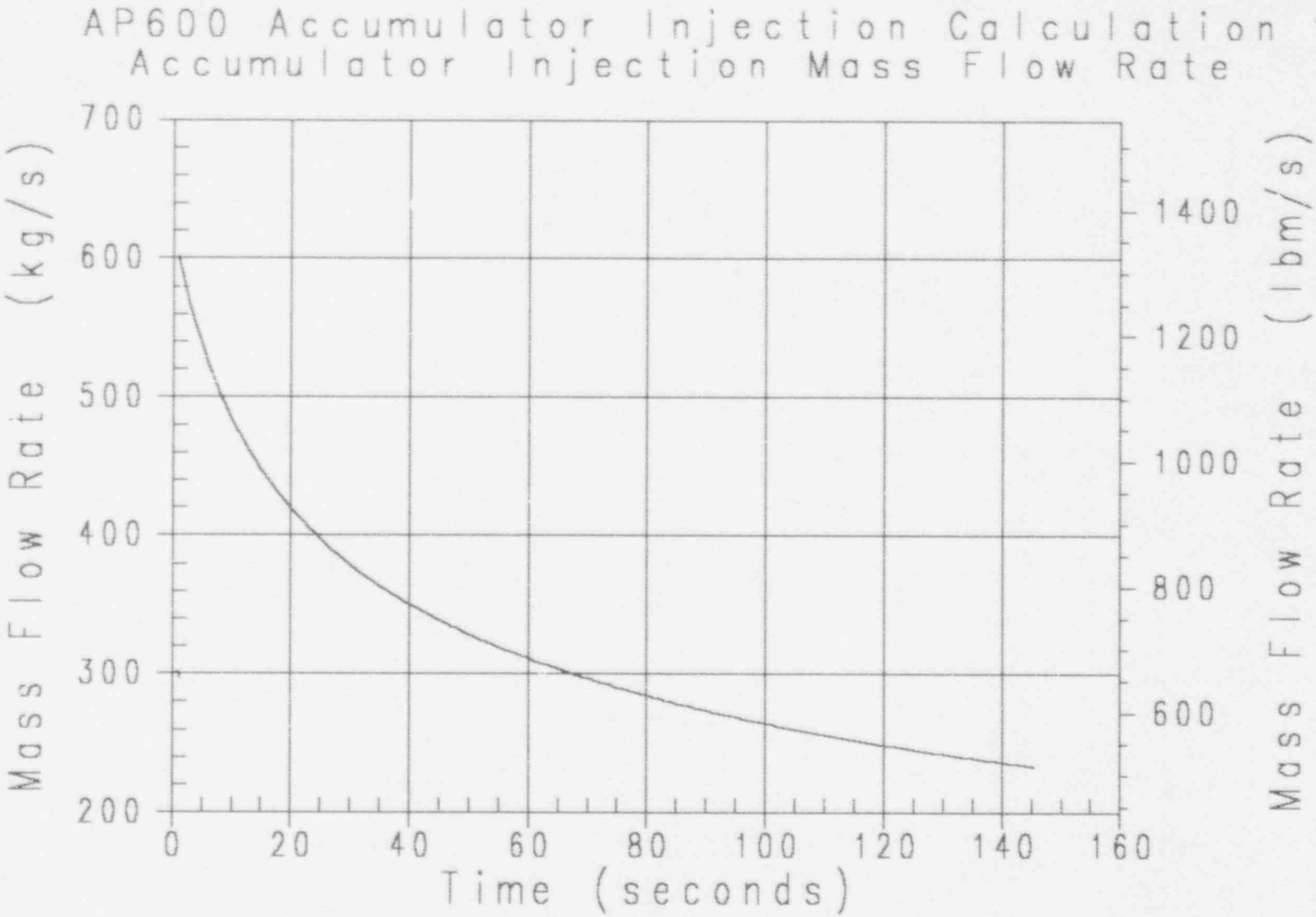

AP600 Accumulator Injection Calculation
Accumulator Water Volume
Volume (m3)
Volume (ft3)
Time (seconds)
0
10
20
30
40
50
0
500
1000
1500
0
20
40
60
80
100
120
140
160

Figure 1



AP600 Accumulator Injection Calculation
Accumulator Gas Pressure
Pressure (bar)
Pressure (psia)
Time (seconds)
0
10
20
30
40
50
60
200
400
600
800
80
100
120
140
160

Figure 2



AP600 Accumulator Injection Calculation
Accumulator Injection Mass Flow Rate
Mass Flow Rate (kg/s)
700
600
500
400
300
200
0
20
40
60
80
100
120
140
160
Time (seconds)
1400
1200
1000
800
600
Mass Flow Rate (lbm/s)

Figure 3

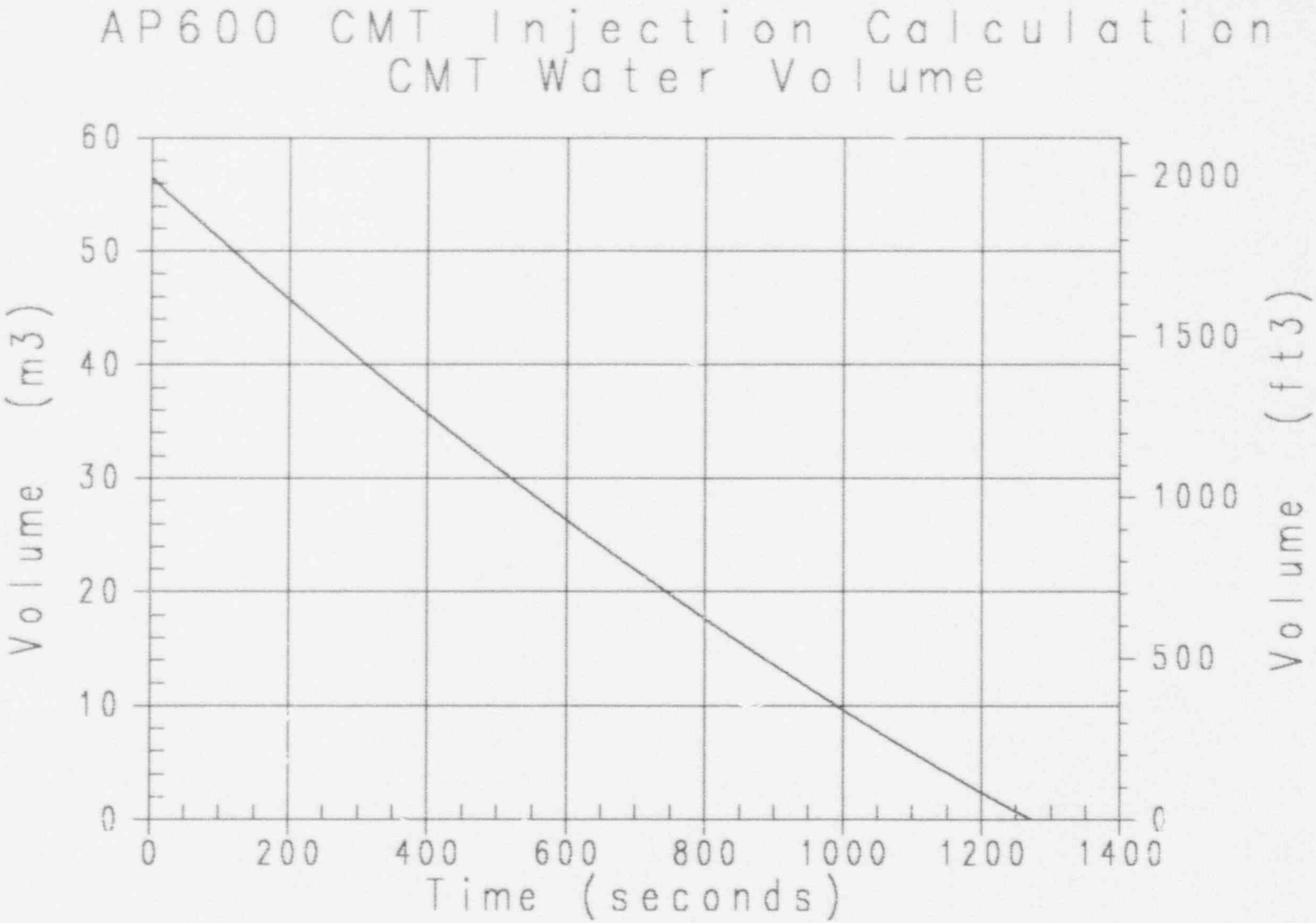

AP600 CMT Injection Calculation
CMT Water Volume
Volume (m3)
Volume (ft3)
Time (seconds)
0
10
20
30
40
50
60
0
500
1000
1500
2000
0
200
400
600
800
1000
1200
1400

Figure 4

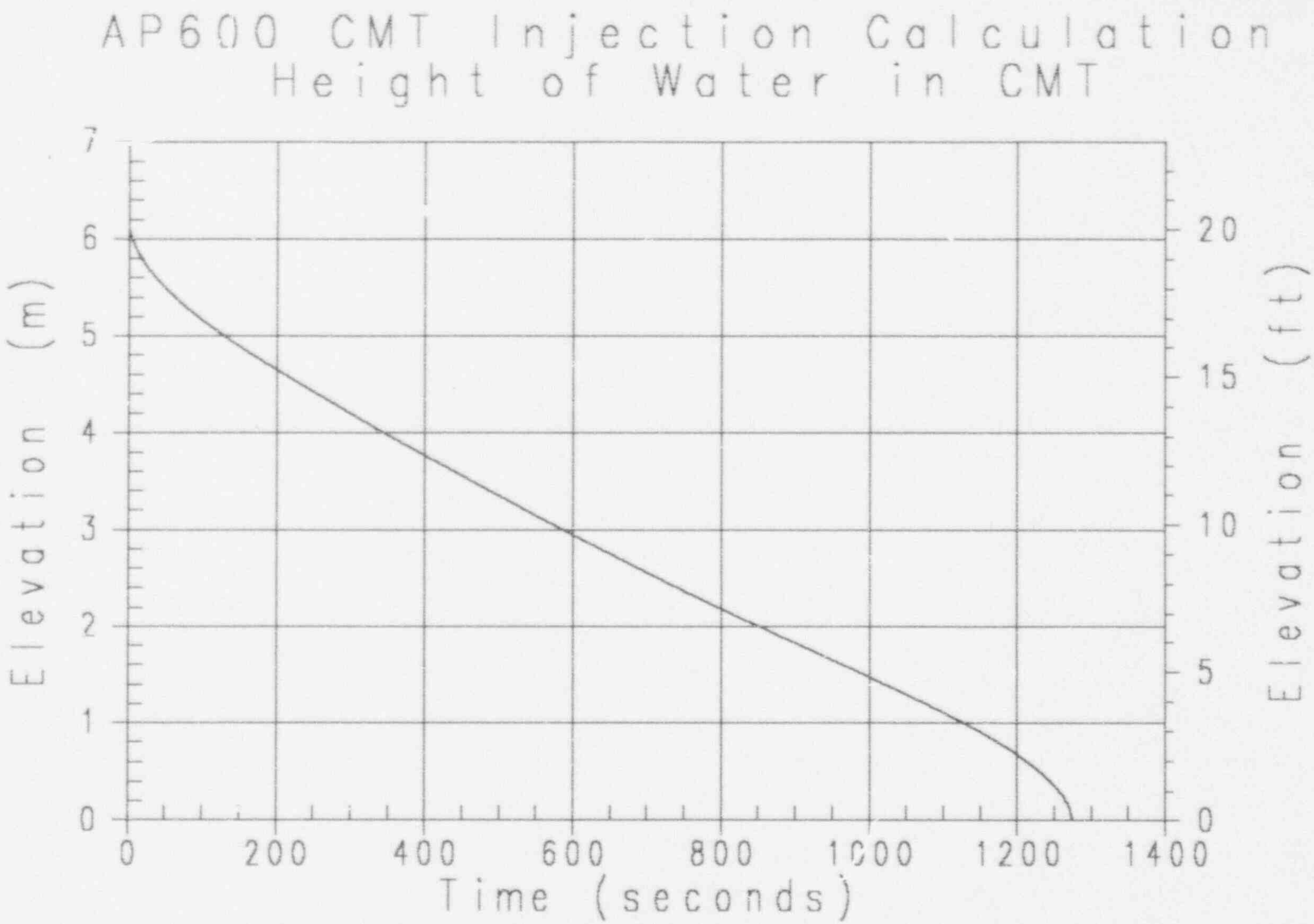

AP600 CMT Injection Calculation
Height of Water in CMT
Elevation (m)
Elevation (ft)
Time (seconds)
0
1
2
3
4
5
6
7
0
5
10
15
20
0
200
400
600
800
1000
1200
1400

Figure 5

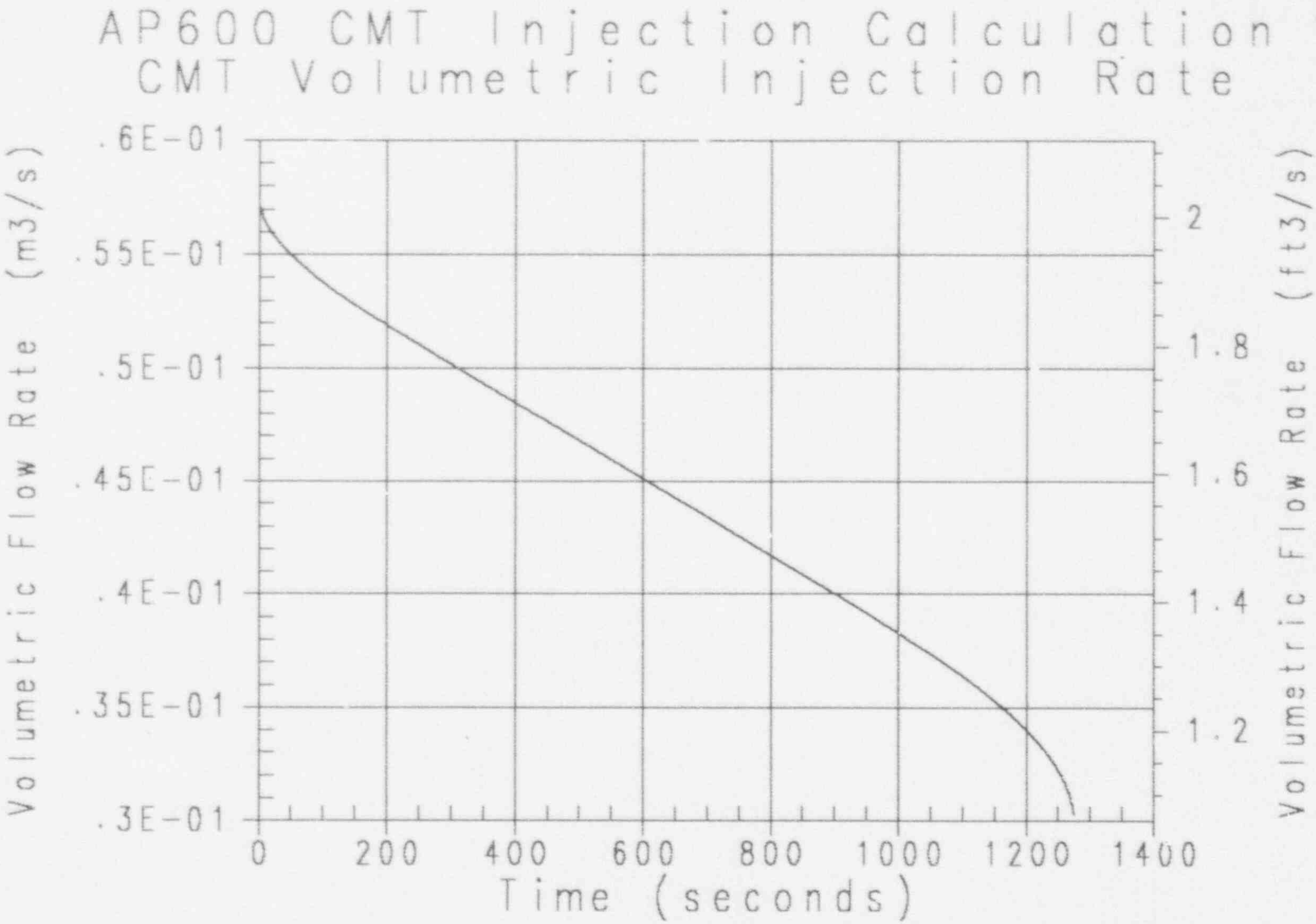

AP600 CMT Injection Calculation
CMT Volumetric Injection Rate
.6E-01
.55E-01
.5E-01
.45E-01
.4E-01
.35E-01
.3E-01
Volumetric Flow Rate (m3/s)
2
1.8
1.6
1.4
1.2
Volumetric Flow Rate (ft3/s)
0
200
400
600
800
1000
1200
1400
Time (seconds)

Figure 6