AP1000 Phase 2 review
Staff's meeting with Westinghouse

January 23, 2002

Suggested Agenda

Wednesday, January 23, 1:00p, O-10B4

Introduction/Overview........................ ADrozd (10 minutes)

Applicability of AP600 scaling and testing:
- Scaling... SBajorek (20) (1:30)
- Westinghouse response .... W (10) (1:40)
- Discussion .... All (20) (2:00)

Applicability of AP600 codes:
- Reactor codes .... WJensen (20) (2:20)
- WGOTHIC .... EThrom (10) (2:30)
- Westinghouse response .... W (10) (2:40)
- Discussion .... All (20) (3:00)

Break .... 15 minutes (3:15)

Design Acceptance Criteria and Exemptions:
- Introduction/Summary .... ADrozd (5) (3:20)
- Background .... JWilson (10) (3:30
- Relevant technical issues .... GBagchi/DTerao (15) (3:45)
- Westinghouse response .... W (10) (3:55)
- Discussion .... All (20) (4:15)

- Westinghouse summary of "other" (ACRS) concerns (15) (4:30)

Open forum .... All (45) (5:15)

Meeting closed

Background for AP1000 pre-application review

During several pre-May 2000 discussions with staff Westinghouse indicated interest in applying for AP1000 standard design certification.

New design based on AP600 design

April 27, 2000 meeting: staff discussed with Westinghouse three-stage approach for the AP1000 pre-application review:

Phase 1: identification of issues to be evaluate during the Phase 2
Phase 2: assessment of the applicability and/or acceptability of the AP600 scaling/testing, analysis codes, DAC and exemptions to AP1000 design
Phase 3: design certification review of AP1000

Background for AP1000 pre-application review (cnd)

May 4, 2000 letter: Westinghouse requests NRC to proceed with the Phase 1 (completed in July 2000)

August 28, 2000 letter: Westinghouse requests to proceed with the Phase Two review of the issues:

- Applicability of AP600 test program to AP1000
- Applicability of AP600 analysis codes to AP1000
- Acceptability of proposed AP1000 DAC
- Acceptability of certain exemptions for AP1000

Status of Pre-application review

Phase 1 completed in July 2000

Phase 2:

- technical review completed in January 2002
- SECY paper on DAC and exemptions in concurrence (due to EDO 3/20/2002)
- SECY paper on testing and codes being drafted (due to EDO 3/20/2002)
- discussion with ACRS sucommittees (New Rectors and T/H) 2/14-15/2002
- presentation to full ACRS 3/1-8/2002

Phase 3: possible Westinghouse application for DC: March/April 2002

Major points of SECY on scaling and codes

AP600 separate-effects and integral-system test programs may be appropriate for use in support of the AP1000 analysis

AP600 analysis codes may be applicable to AP1000

There are exceptions, e.g.,:

Liquid entrainment models in codes need to be validated, in particular in NOTRUMP for liquid entrainment in the upper plenum or from a horizontal stratified water level in the hot legs.

Penalty factor used with the NOTRUMP PRHRHX model needs to be qualified

Methodology used for calculating PCT when core becomes uncovered during SBLOCA needs to be justified

Comments regarding scaling of containment LST for AP600 (i.e., not properly scaled for transients) are also valid for AP1000

Major points of SECY on DAC and exemptions

10 CFR Part 52: application for design certification must provide complete, final design information in accordance with section 52.47(a)(2).

"Completeness" of design discussed in SECYs-90-377, 92-053, 92-196, and 92-299

DAC for I&C and control room design (i.e., human factors) is justifiable based on rapidly evolving technology.

Staff does not recommend use of DAC for the piping, seismic analyses and structural design.

Requested exemptions granted for AP600 are justifiable for AP1000 (plant safety parameter display console, auxiliary feedwater system, and offsite power sources).

DESIGN ACCEPTANCE CRITERIA (DAC)

Level of Design Information submitted for Design Certification

Design scope	ABWR	System 80+	AP600	AP1000
Instrumentation and control	insufficient (DAC used)	insufficient (DAC used)	insufficient (DAC used)	insufficient (proposed)
Human factors (control room)	insufficient (DAC used)	insufficient (DAC used)	insufficient (DAC used)	insufficient (proposed)
Radiation protection	insufficient (DAC used)	insufficient (DAC used)	sufficient	sufficient
Piping	insufficient (DAC used)	insufficient (DAC used)	mostly sufficient	insufficient (proposed)
Structures	sufficient	sufficient	sufficient	insufficient (proposed)
Seismic analysis	sufficient	sufficient	sufficient	insufficient* (proposed)

*except for the seismic analysis for hard rock sites

AP1000 DAC for Seismic, Structural, and Piping Design

Level of Design Information to be Submitted

Reference: WCAP15614, "AP1000 Seismic and Structural Design Activities" February 6, 2001

DAC Area	Design Certification	COL Application (Prior to Construction)	Post COL Issuance (During Construction)
Seismic Analysis	stick models for AP1000 <u>soil sites:</u> seismic analysis DAC <u>rock sites</u>: • fixed-base seismic analyses and ARS • overturning/stability	FE models for AP1000 **<u>soil sites:</u>** **• SASSI (soil-structure analyses) and ARS** **• overturning/stability**	
Structural Design	• preliminary assessment of key structural elements for soil/rock sites • *structural DAC*	*structural design/analyses for soil/rock sites*	as-built structural and seismic reconciliation
Piping Design	*piping DAC*	**analyses for LBB-qualified piping***	• *piping stress reports* • *pipe break analyses*

Notes:
bold - final safety determination cannot be achieved due to significant uncertainties
italics - benefits of standard design are eroded (level of detail issue)
* - Inconsistent with ALWR policy (SECY-93-087)

AP1000 Scaling Evaluation

January 23, 2002

Stephen M. Bajorek
Senior Technical Advisor
Safety Margins and Systems Analysis Branch
Division of Systems Analysis and Regulatory Effectiveness
Office of Nuclear Regulatory Research

Background

- RES performed independent review and evaluation of Westinghouse PIRT & scaling analysis
  - Agree with modifications of AP600 PIRT for AP1000. Most process rankings remained same. Requested that CIWH be added; otherwise no "new" processes identified.
- Independent scaling analysis consisted of:
  - "Top-down" evaluation of AP1000, AP600, ROSA, SPES and APEX to examine and compare global behavior of integral systems.
  - Single node transient calculations to examine ADS blowdown
  - "Bottom-up" evaluation of local processes.

"Top-Down" Scaling

- Top-down scaling methodolgy developed by INEL for AP600 applied. AP1000 transient: Subcooled blowdown, Intermediate (3 subphases), ADS-4 Blowdown, IRWST Injection (2 subphases), Sump Recirculation. Two scenarios considered: 1-inch CL break, DEG of DVI line.

- Acceptability defined as :

$$0.5 < \frac{\Pi_{test}}{\Pi_{AP1000}} < 2$$

  - Distortions (Π group ratios outside acceptable range), were considered acceptable if the test conditions were more conservative than those expected in AP1000.

Results of "Top-Down" Scaling

- Subcooled Blowdown - AP1000 scales acceptably with SPES
- ADS-1/2/3 Intermediate - AP1000 scales acceptably with SPES

- IRWST Injection & Draining - AP1000 scales acceptably with APEX
- IRWST / Sump Injection - AP1000 scales acceptably with APEX

Results of "Top-Down" Scaling, cont'd

- **ADS-4 Blowdown -**

- **Dominant dimensionless group is**

$$\Pi_{16-CMT} = \frac{\dot{m}_{CMT}}{\dot{m}_0} = \frac{\rho_l}{\dot{m}_0}\sqrt{\frac{g\Delta Y_{CMT,0}}{R'_{CMT,0}}}$$

which relates magnitude of the CMT flow to the ADS-4 discharge flow rate. It represents the rate at which the vessel inventory increases/decreases during the phase.

- **AP1000 scales acceptably with SPES, but not APEX while flow is critical.**

- **APEX has an important non-conservative distortion suggesting APEX results are not applicable for code validation (at high pressure, critical flow).**

- **AP1000 scales acceptably with both SPES and APEX when ADS-4 flow becomes non-critical.**

- **Same method used to verify that both SPES and APEX scale acceptably for both critical and non-critical flows for AP600.**

Simplified ADS Transient Calculation

- A single node model of AP1000 system was developed to investigate and compare transient depressurization characteristics of AP1000 to integral tests.

- Model considers mass balance and mechanical compliance of primary system, and was verified by comparison to ROSA data.

- Conclusions:

  - Depressurization rates of AP1000 and AP600 are similar. Transient time scales are about the same.

  - ADS-4 flow quality is a dominant uncertainty contributor. Low quality ADS-4 flow (i.e. high entrainment in upper plenum and/or hot leg) will deplete the AP1000 vessel inventory significantly faster than AP600 or test facilities.

  - Suggests that entrainment and carry-over from RCS to ADS-4 branch line is important effect on comparative results.

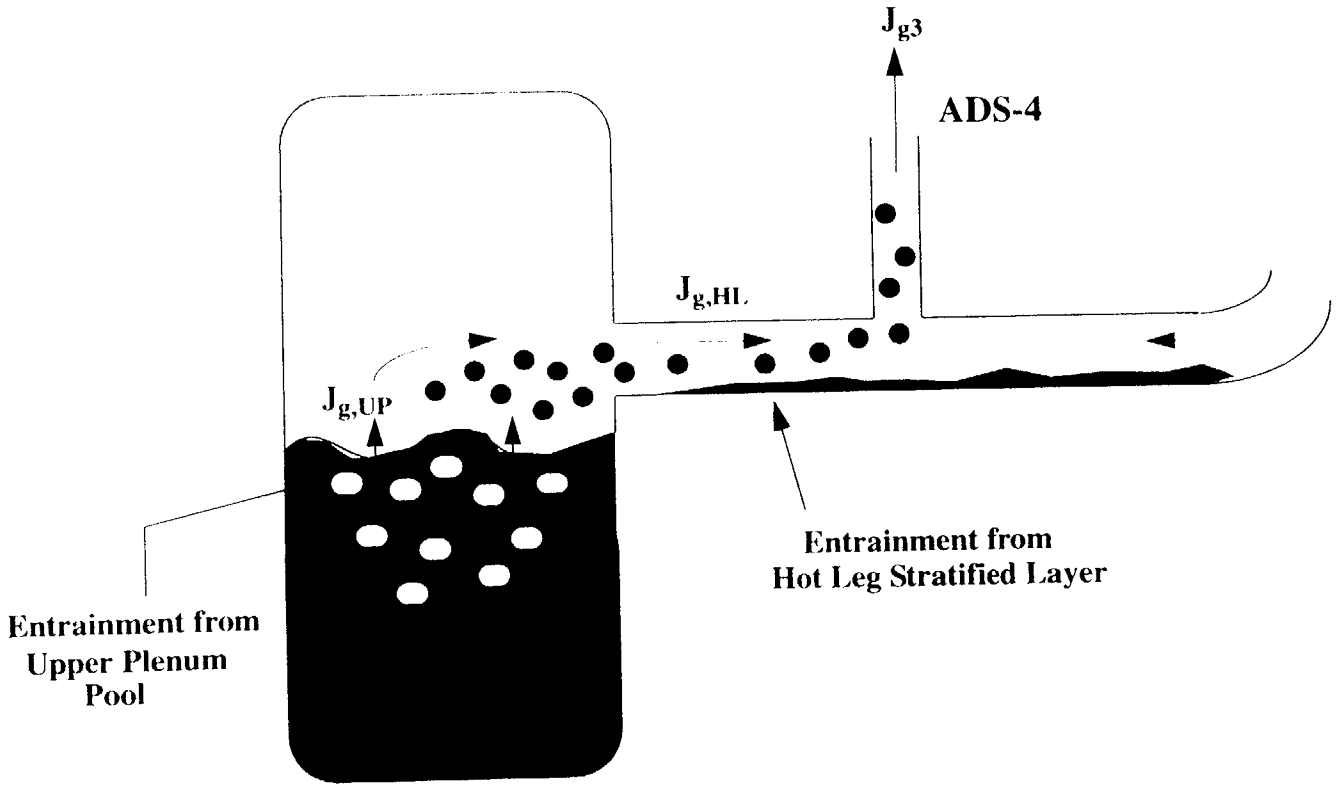
"Bottom-Up" Scaling

- **"Bottom-up" considers processes that may have large local effect, or may represent bifurcations in the top-down evaluation.**

- **AP1000 scaling relative to integral tests considered:**

Process	Scaling Parameter	Comment
Hot leg flow regime transition	Fr_m	**OK**
Cold leg flow regime transition	Fr_m	**OK**
Flooding	**Ku**	**OK**
Core exit void fraction	α	**OK**
Hot leg entrainment	(h_b/D) $J_{g,onset}$	
Upper plenum pool entrainment	E_{fg}	

Entrainment Processes

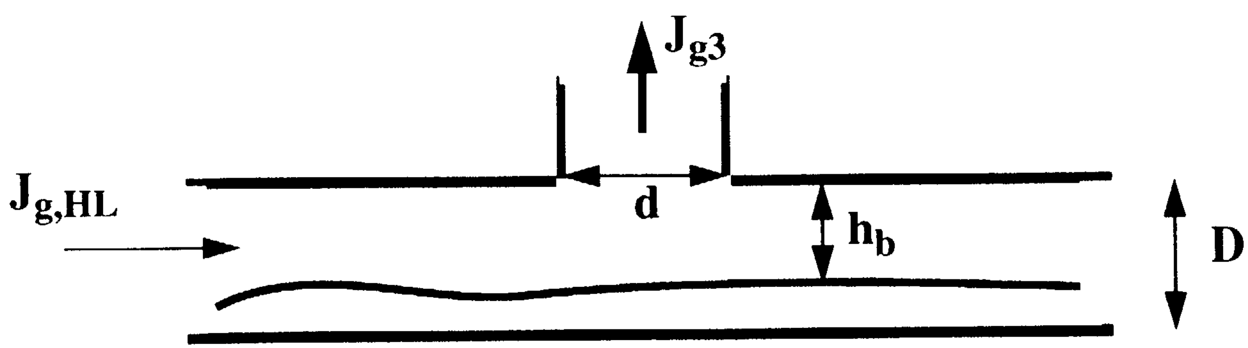


Results from “Bottom-Up” Scaling

- Entrainment from Hot Leg Stratified Layer

- Westinghouse approach used typical correlation for entrainment onset:

$$Fr_m = \frac{J_{g3}}{\sqrt{\frac{D_h g \Delta\rho}{\rho_g}}} = C\left(\frac{h_b}{d}\right)^m$$



- Assuming correlation is valid, what is non-dimensional entrainment onset height ? Alternately, to what level could water drop before entrainment stopped ?

Period	$\left(\frac{h_b}{D}\right)_{AP1000}$	$\left(\frac{h_b}{D}\right)_{AP600}$	$\left(\frac{h_b}{D}\right)_{ROSA}$	$\left(\frac{h_b}{D}\right)_{SPES}$	$\left(\frac{h_b}{D}\right)_{APEX}$	Branch Line
Intermediate (ADS-1/2/3)	0.095	0.065	0.082	0.063	0.061	Pzr Surge Line
ADS-4 Blowdown	0.298	0.228	0.245	0.194	0.232	ADS-4 Branch
IRWST Injection	0.323	0.247	0.260	0.206	0.240	ADS-4 Branch
Sump Injection	0.214	0.163			0.156	ADS-4 Branch

- **In all periods, entrainment onset could occur for a lower water level in AP1000 than in integral tests. (approx. 52% increase in h_b/D for ADS venting, 35% in IRWST)**

hard to judge [illegible] of [illegible] data based [illegible] these numbers

- Problems with horizontal-stratified onset correlation(s) of the form,

$$Fr_m = \frac{J_{g3}}{\sqrt{\frac{D_h g \Delta\rho}{\rho_g}}} = C\left(\frac{h_b}{d}\right)^m$$

- Correlations not based on data from prototypical geometry.

$$(d/D)_{AP1000} >> (d/D)_{data}$$

- Viscous effects, interfacial shear and suface tension is ignored. For high steam velocities, roll wave entrainment is expected to be an important process.

- Formulation is based on inviscid flow to a point sink. (Valid for only for small d/D ratios.)

◆ **Entrainment by roll wave entrainment - Typical correlation for critical entrainment velocity has form**

$$\frac{\mu_l J_{g,\,onset}}{\sigma}\sqrt{\frac{\rho_g}{\rho_l}} \ge C$$

Using C = 1.5x10^{-4} .

◆ **J_g in hot leg compared to $J_{g,onset}$; Entrainment assumed if** $\left(\frac{2}{3}\right)J_{g,\,HL} > J_{g,\,onset}$

(assumes single ADS-4 valve failure)

Period	AP1000	AP600	ROSA	SPES	APEX
Intermediate (ADS-1/2/3)	YES	NO	NO	NO	NO
ADS-4 Blowdown	YES	NO	NO	NO	NO
IRWST Injection	YES	NO	NO	NO	NO
Sump Injection	NO	NO			NO

- **Conclusions for HL Entrainment:**

- **Entrainment from horizontal stratified water levels in hot leg will occur at lower water levels in AP1000 than in AP600 or in test facilities.**

- **The higher J_g in AP1000 is expected to result in higher entrainment than what may have occurred in AP600 or in the integral test facilities.**

■ Upper Plenum Pool Entrainment

- ◆ **Tests in APEX facility following W and NRC AP600 test program showed high entrainment and carry-over from upper plenum pool to ADS-4 branch line.**

- ◆ **Relatively few data & applicable correlations. Correlations tend to be functions of gas velocity, physical properties & elevation that droplets must be carried.**

$$E_{fg} = \frac{\rho_f J_{fe}}{\rho_g J_g}$$

Rozen

$$E_{fg} = 0.37(J_g^*)^{4.2} N_{\mu g}^{0.7} \sqrt{\frac{\Delta\rho}{\rho_g}} \exp\left(-0.23\frac{h}{D_h}\right) \qquad (1)$$

Ishii & Kataoka (deposition controlled region)

$$E_{fg} = 3.18(J_g^*)^3 N_{\mu g}^{0.5} \qquad (2)$$

Ishii & Kataoka (momentum controlled, intermediate gas flux regime)

$$E_{fg} = (5.417x10^6)(J_g^*)^3 (h^*)^{-3} N_{\mu g}^{1.5} (D_h^*)^{1.25} \left(\frac{\rho_g}{\Delta\rho}\right)^{-0.31} \qquad (3)$$

- **Preserving geometry & with pressure similitude,,**

$$E_{fg} \propto (J_g)^3$$

so, for same UP:

$$\frac{(E_{fg})_{AP1000}}{(E_{fg})_{AP600}} \sim \left(\frac{q_{core,\,AP1000}}{q_{core,\,AP600}}\right)^3 = (1.75)^3 = 5.4$$

For AP1000 (assuming pressure similitude)

Equation	$\frac{\Pi_{ent,\,AP600}}{\Pi_{ent,\,AP1000}}$	$\frac{\Pi_{ent,\,ROSA}}{\Pi_{ent,\,AP1000}}$	$\frac{\Pi_{ent,\,SPES}}{\Pi_{ent,\,AP1000}}$	$\frac{\Pi_{ent,\,APEX}}{\Pi_{ent,\,AP1000}}$
(1)	0.095	0.235	0.0080	0.0064
(2)	0.187	0.693	0.292	0.030
(3)	0.187	0.060	0.006	0.010

- **For AP1000, upper plenum pool entrainment in intergal facilities may be significantly lower than entrainment in the full scale plant. This suggests that ADS-4 flow quality may be much lower in AP1000, than in the integral tests.**

Conclusions

- In general, integral tests performed to validate codes and confirm behavior of AP600 remain valuable and can be used AP1000 code validation.

- Entrainment and carry-over from vessel & hot leg to ADS-4 expected to have an important impact on vessel inventory during the SBLOCA periods when inventory is near a minimum. ADS-4 flow quality is a concern.

- Entrainment & carry-over processes are not well understood. Existing correlations are geometry & T/H range of condition dependent. Difficult to reliably extend these correlations to complex geometry in AP1000 UP and HL-branch line. They do however, suggest significantly higher entrainment in AP1000.

- It has not been demonstrated that entrainment data from integral test facilities is correct the range of conditions for AP1000, as is therefore not considered appropriately scaled to validate entrainment models in thermal-hydraulic codes. Alternate data or revised approach is necessary to validate entrainment modeling for AP1000.

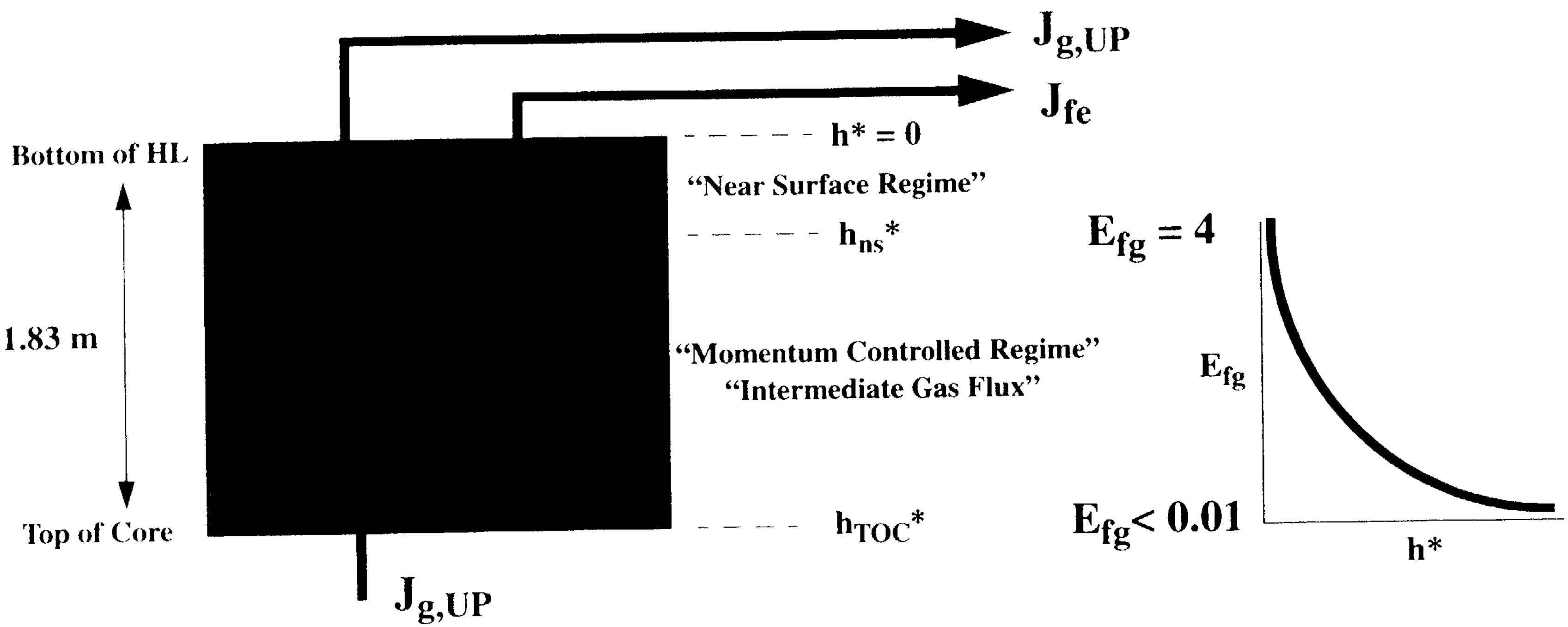
Possible Success Paths

- Range upper plenum and hot leg entrainment rates over sufficiently large range in plant & APEX simulations. Demonstrate that margin to core uncovery remains large even for "extreme" entrainment rates. Show that time to deplete UP mass >> ADS-4 transition time. Problem: How to establish range.

- Use experimental data from a SET facility with large d/D branch line, and upper plenum pool entrainment data from APEX or elsewhere to develop improved models and/or establish appropriate bound. Problem: Scaling issues, atypicalities in SET flow regimes (oscillations), APEX UP geometry.

- Incorporate DOE-NERI sponsored tests to be run in APEX at AP1000 scaled power & system configuration into code validation for AP1000.

Upper Plenum Drain Time



- May be possible to show that time to drain AP1000 upper plenum much greater than the ADS-4 - IRWST transition time.

NRC Staff Review of NOTRUMP and LOFTRAN for AP1000

- **Previous code reviews for operating plants and AP600.**
- **Additional capability requirements to model AP1000 systems and components. (Increased power, power density, and heat removal)**
- **Comparisons with RELAP5 analyses.**

LOFTRAN

- Used to evaluate non-LOCA transients and accidents in conjunction with other codes.
(RCS pressure, fuel temperature, DNBR)

- Approved for operating plants 1985 and for AP600 1998.

- Entire reactor system is modeled but two phase conditions are only allowed in the pressurizer and upper head.

AP1000 Considerations

- ADS actuation only for a limited period to assess DNBR.

No RCS void formation.

- PRHR heat transfer based on correlation of PRHR test data.

Test conditions extend to those of AP1000.

- LOFTRAN cannot evaluate asymmetrical flow conditions in split cold legs.

(Single RCP trip, locked rotor/sheared shaft)
The external cold leg flow model developed for AP600 should still apply.

- CMT draining is not expected.

No void formation expected in the pressure balance lines.

- Larger steam generators of AP1000 increase the likelihood that significant voiding may occur during MSLB.

Conclusion:

LOFTRAN is acceptable for analysis of non-LOCA transients and accidents for AP1000 including SGTR with the excepting one outstanding open issue.

Open Issue:

Westinghouse has not performed the analysis of a main steam line break to evaluate reactor system voiding. Voids might form in the reactor vessel head, CMT pressure balance line and reactor vessel upper head. The analysis and NRC review is deferred to Phase 3.

NOTRUMP

- **Used to evaluate small break LOCA. NOTRUMP is used in conjunction with the SBLOCTA code to calculate peak cladding temperature.**
- **Approved for operating plants in 1985 and for AP600 in 1998.**
- **Five conservation equations and a drift flux model are used to calculate liquid and vapor flows and thermodynamic states.**
- **Momentum flux from area and density changes in the flow links is not included in the present model.**

RELAP5 Comparisons

- NRC RELAP5 input deck produced based on an existing AP600 input and information supplied by Westinghouse.
- Results similar to NOTRUMP
    - Differences in break flow and depressurization rate because of segmented downcomer modeling
    - Higher core void fractions than for AP600
    - Higher core void fractions than NOTRUMP
    - Slight core uncovery for DVI line break
- NRC approval of AP1000 to be based on Westinghouse calculations

AP1000 Considerations

- **Accumulators same size as AP600.**

- **ADS1/2/3 are the same size.**

- **CMTs are the same height but with 24% more volume than AP600.**

- **PRHRHX is 22% larger but removes 72% more heat.**

NOTRUMP has a high heat flow limit (tube flow <= 1.5 ft/sec)

- **ADS4 is 76% larger and is designed for 89% more capacity. Entrainment of liquid including upper plenum and hot leg leading to the ADS4 is an open issue.**

Conclusions:

NOTRUMP is acceptable for analysis of small break LOCA for AP1000 with exception to the following outstanding issues.

1. Liquid entrainment from upper plenum, through hot legs and ADS4. Westinghouse proposes to benchmark NOTRUMP ADS4 against a modified WCOBRA/TRAC. Experimental verification remains an issue.

2. The conservatism of the PRHRHX model needs to be justified for high heat flows. Westinghouse proposes to reduce the heat transfer area by 50%. This penalty needs to be justified in a data comparison.

3. Westinghouse does not expect core uncovery during SBLOCA for AP1000. Only a limited number of breaks have been analyzed. If core uncovery is calculated, Westinghouse must seek approval of NOTRUMP and SBLOCA for this purpose.

WGOTHIC Computer Program

Presentation

January 23, 2002

Edward D. Throm
Senior Reactor Engineer

Plant Systems Branch
Division of Systems Safety and Analysis
Office of Nuclear Reactor Regulation
U.S. Nuclear Regulatory Commission

Telephone: (301) 415-3153

WGOTHIC Computer Program

WGOTHIC is described in WCAP-14407, "WGOTHIC Application to AP600," Revision 3, April 1998, Westinghouse Electric Corporation.

NRC Safety Evaluation is provided in NUREG-1512, "Final Safety Evaluation Report Related to Certification of the AP600 Standard Design," Volume 2, Section 21.6.5, September 1998.

Conservative models are used in the AP600 WGOTHIC Evaluation Model (EM) to address the following areas:

- Lumped-parameter network representation
- Non-condensable circulation and stratification
- PCS flow and heat transfer models

<u>W</u>GOTHIC Computer Program

PIRT and Scaling

AP1000 versus AP600

	AP600	AP1000
Core power level (MWt)	1,933	3,400
Design pressure (psia)	59.7	73.7
Containment height (ft-in)	189'-10"	215'-4"
Shell thickness (in)	1.625	1.75
Volume (ft^3)	1.73×10^6	2.07×10^6

Differences are modest or small, and PIRT ranking are unchanged - no new phenomena, but need to verify mass and heat transfer correlations.

WGOTHIC Computer Program

PIRT and Scaling (continued)

Large-Scale Test (LST) facility not properly scaled for transient situations but steady-state results used for development of mass and heat transfer correlations, with additional test data:

- W Small-scale test, W flat-plate test
- Separate effects tests for heat and mass transfer

Alternative to scaled facility test needed to justify the use of the WGOTHIC computer program for design basis accident evaluations.

WGOTHIC Computer Program

Evaluation of

Lumped-parameter network
Circulation and stratification

- WCAP-14407, Section 9
- NUREG-1512, Section 21.6.5.7.8

Application of GOTHIC program to international test problems, including the Battelle Model Containment (BMC) and the HDR (Heissdampfreaktor) experiments, combined with modeling conservatism to address uncertainties in circulation and stratification resulted in the approval of an Evaluation Model for using WGOTHIC for design-basis accident analyses.

WGOTHIC Computer Program

Results From Phase II Review

- No new phenomena identified, PIRT rankings unchanged
- Mass and heat transfer correlations are being used within their applicable ranges
- Using the approved modeling approach, WGOTHIC is applicable to the AP1000
- Phase III results need to be reviewed to confirm findings
  - Use of the "evaporated flow" model
  - SRP mass and energy releases
  - ADS4, IRWST and sump flows for AP1000

AP1000 Scaling

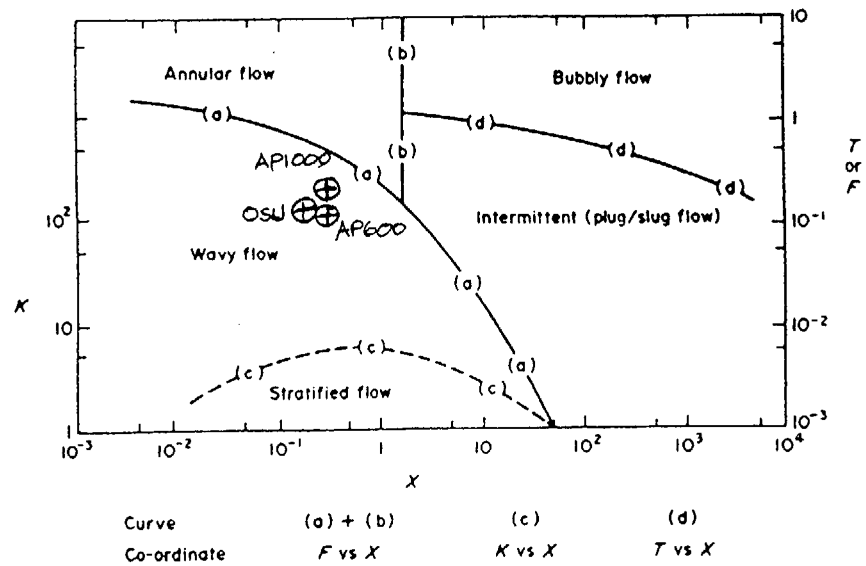
W. Brown

January 23, 2002

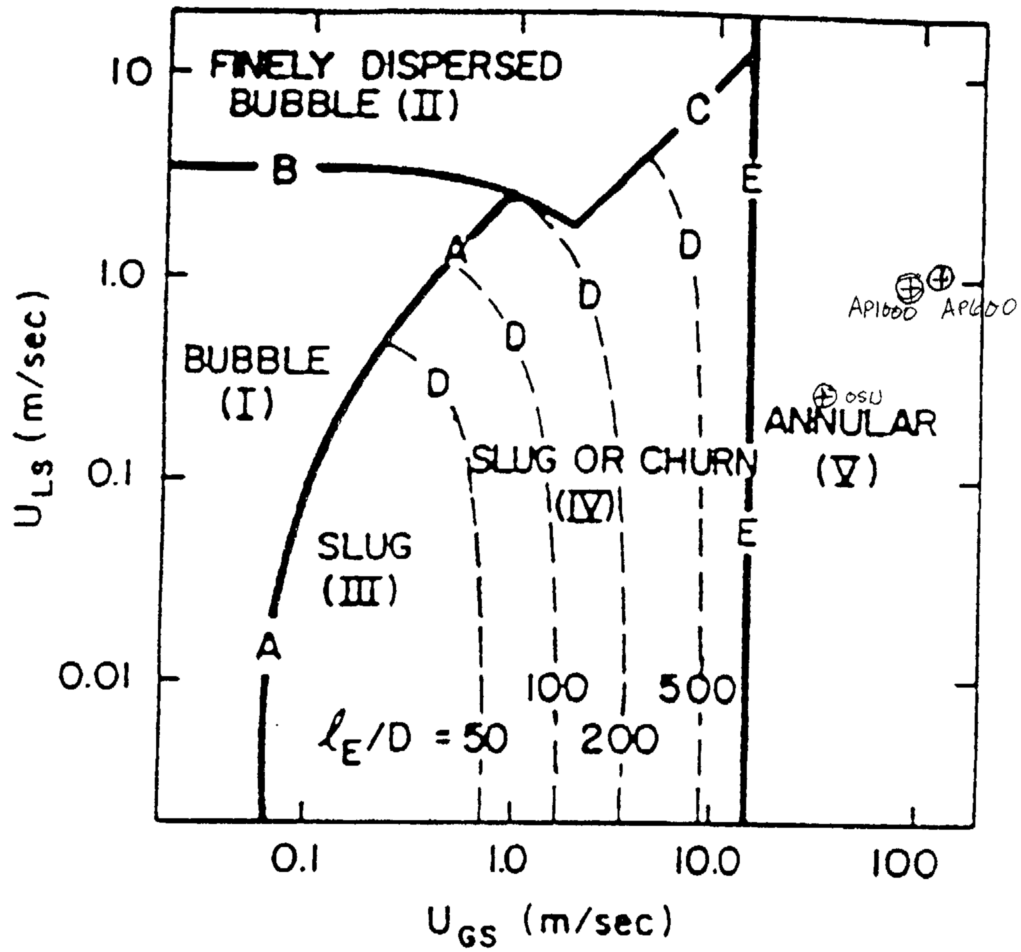
Impact of Slip on Core Exit Quality Scaling and Flow Regime during Low Pressure Two-phase Natural Circulation

- Dr. Wallis commented on flow regime in vent path and use of homogeneous model for scaling two-phase natural circulation at 3/15/01 ACRS T/H subcommittee meeting. At low pressure, such as during sump injection, slip between liquid and vapor phases is significant.
- Flow regime maps for vent path (hot leg and ADS4 piping) during sump injection phase generated.
- Separated flow model used to scale core exit quality during sump injection phase.

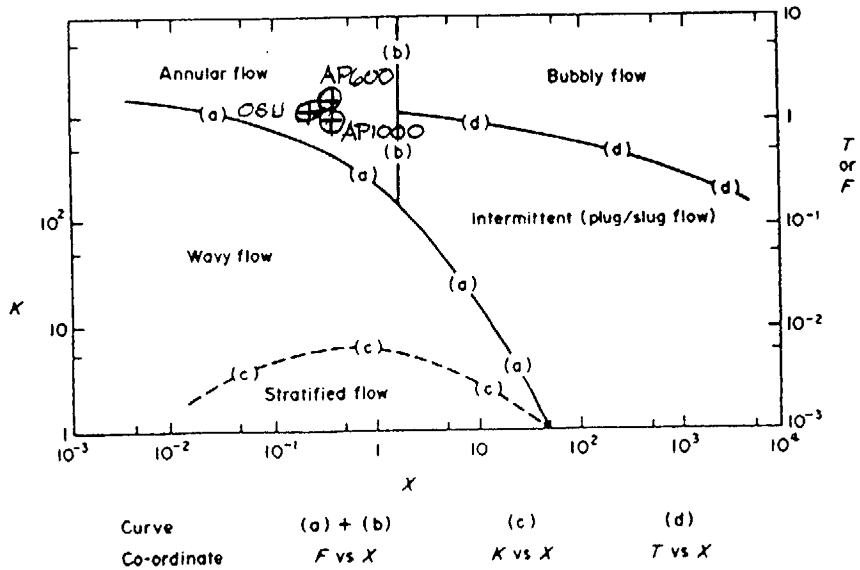
Sump Injection Phase - Hot Leg Horizontal Flow Regime Map (Taitel-Dukler)



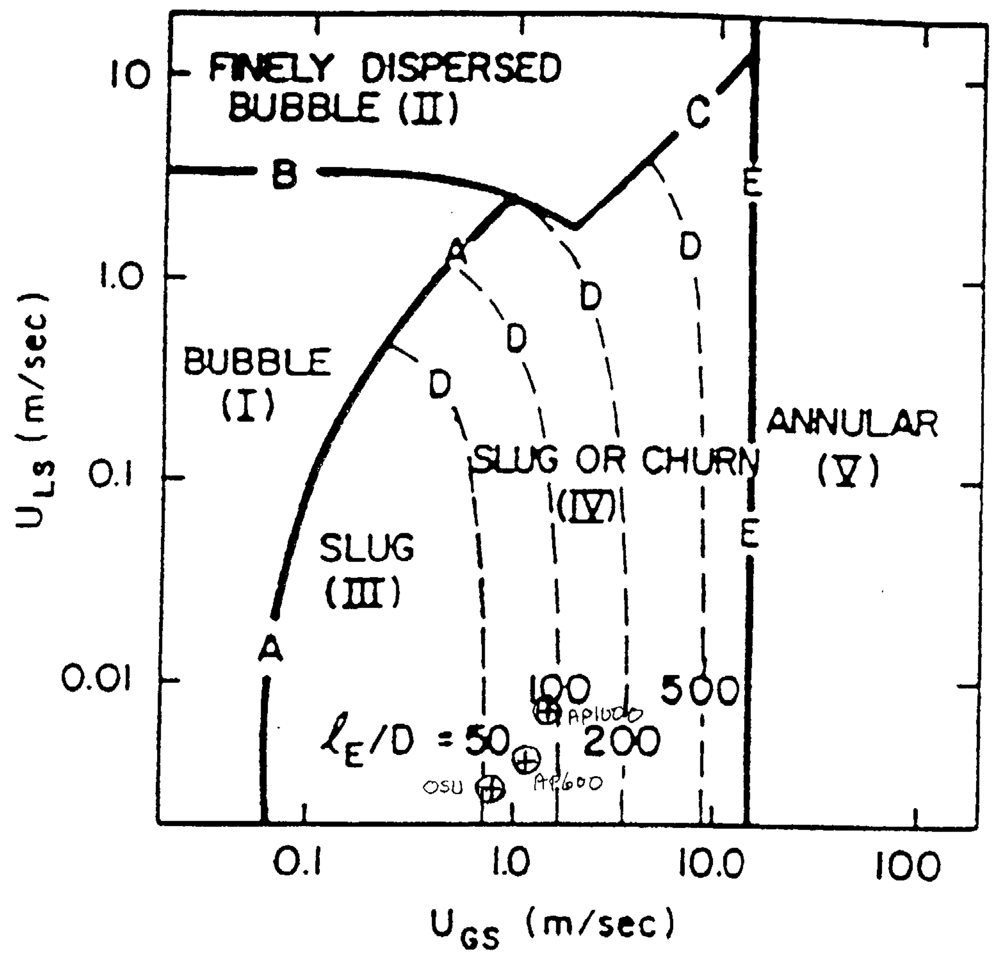
Sump Injection Phase - ADS4 Pipe (Vertical) Vertical Flow Regime Map (Taitel-Dukler)



Sump Injection Phase - ADS4 Pipe (Horizontal) Horizontal Flow Regime Map (Taitel-Dukler)



Sump Injection Phase - Upper Plenum Vertical Flow Regime Map (Taitel-Dukler)



Sump Injection Phase - Flow Regime Conclusions

- AP1000 and AP600 flow regime for hot leg and ADS4 piping well scaled in OSU test facility during Sump Injection Phase.

Sump Injection Phase Core Exit Quality Scaling

- Core exit quality scaling equation pressure drop model changed from homogeneous to separated flow model.
- Results:
  - Core exit quality significantly higher (~50%) with separated flow pressure drop model vs. homogeneous.
  - Scaling ratios still about the same.

Scaling Ratio	OSU AP600		OSU AP1000	
Two-phase Pressure drop model	Homogeneous	Separated	Homogeneous	Separated
$[x_{exit}]_R = (\pi_{x_e})_R$	1.19	1.15	1.08	1.11
Acceptance Criteria	$0.5 < \pi_R < 2$			

Sump Injection Phase Core Exit Quality Scaling Conclusions

- Core exit quality well scaled between OSU and AP1000. Therefore, OSU can be used for code validation during sump injection.

Liquid Entrainment Scaling

- Liquid entrainment is high ranked phenomena in SBLOCA PIRT for AP1000 during ADS-IRWST phase where minimum inventory typically occurs. Two regions of interest identified.
  - Upper Plenum
  - Hot Leg/ADS-4
- Entrainment ranking upgraded for AP1000 due to increased core power coupled with retention of upper plenum and hot leg size.
- Upper Plenum entrainment scaling not addressed in WCAP-15613. --
  - Addressed via recent work using Kataoka-Ishii pool entrainment.
- Hot Leg/ADS-4 entrainment inception scaling has been addressed in Section 4 of WCAP-15613.

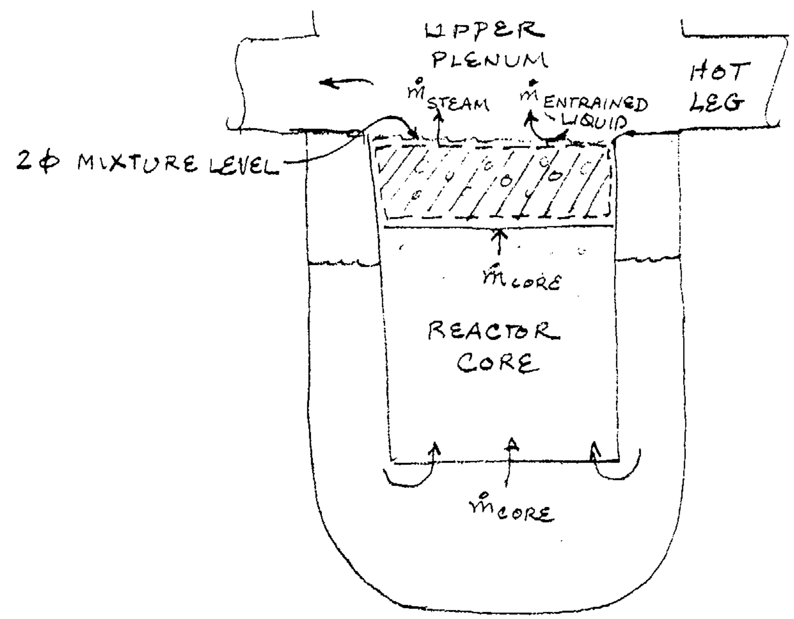
Liquid Entrainment Scaling

- Review of Kataoka-Ishii pool entrainment work (NUREG/CR-3304) identifies regions of entrainment
  - Near surface region
  - Momentum controlled region
- Near suface region entrainment dependent on density ratio.
- Momentum controlled region dependent upon:
  - density ratio
  - dimensionless diameter ratio (D_H*)
  - viscosity number
  - ratio of dimensionless superficial gas velocity (j_g^*) to dimensionless height (h*) above liquid surface.

Liquid Entrainment Scaling

- Basedupon Kataoka-Ishii pool entrainment work (NUREG/CR-3304)
  - As near suface region entrainment dependent on density ratio only, SBLOCAs where mixture level is in or near hot leg(most SBLOCA events) should be well scaled in test facilities as pressure (density) approximately preserved after ADS is actuated.
  - As momentum controlled region dependent upon dimensionless superficial gas velocity (j_g^*), liquid entrainment for SBLOCAs where mixture level goes below hot leg (i.e. DE DVI) may not be well scaled in AP600 test facilities for AP1000 due to the higher superficial gas velocity associated with higher AP1000 core power.

Upper Plenum Liquid Entrainment Evaluation



MOMENTUM-CONTROLED REGION LIQUID ENTRAINMENT
IN UPPER PLENUM (BELOW HOT LEG)

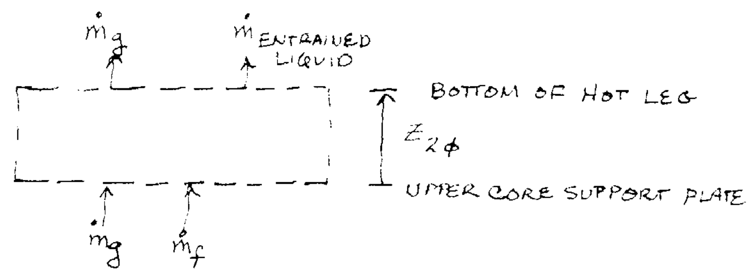
Upper Plenum Liquid Entrainment Evaluation

GOVERNING EQUATION SET

- CONSERVATION OF MASS – UPPER PLENUM

$$\frac{dM_{UP}}{dt} = \frac{d\left[\rho_m A Z_{2\phi}\right]_{UP}}{dt} = \dot{m}_{CORE} - \dot{m}_{STEAM} - \dot{m}_{\substack{ENTRAINED\\LIQUID}} = \dot{m}_f - \dot{m}_{\substack{ENTRAINED\\LIQUID}}$$

AS $\dot{m}_{CORE} = \dot{m}_f + \dot{m}_g$



$\dot{m}_f$ = LIQUID COMPONENT OF CORE EXIT MASSFLOW

$\dot{m}_g$ = VAPOR COMPONENT OF CORE EXIT MASSFLOW

- MIXTURE DENSITY DEFINED AS $\rho_m = \alpha \rho_g + (1-\alpha)\rho_f$

- VOID FRACTION MODELED USING YEH CORRELATION $\alpha = 0.925\left(\frac{\rho_g}{\rho_f}\right)^{0.24}\left(\frac{j_g}{V_{bcr}}\right)^{0.47}$

WHERE $V_{bcr} = 1.53\left[\frac{\sigma \cdot gr \cdot \Delta\rho}{\rho_f^{\,2}}\right]^{0.25}$

Upper Plenum Liquid Entrainment Evaluation

- ENTRAINMENT MODELED USING KATAOKA-ISHII CORRELATION FOR INTERMEDIATE GAS FLUX REGIME (MOMENTUM CONTROLLED).

$$E = \frac{\rho_f j_{fe}}{\rho_g j_g} = 5.417E6 \left(\frac{j_g^*}{h^*}\right)^3 \left(\frac{\rho_g}{\Delta\rho}\right)^{-0.31} N_{\mu g}^{1.5} D_H^{*1.25}$$

WHERE $j_g^* = \dfrac{j_g}{\left(\dfrac{\sigma g \Delta\rho}{\rho_g^2}\right)^{0.25}}$ $h^* = \dfrac{h}{\left(\dfrac{\sigma}{g\Delta\rho}\right)^{0.5}}$ $N_{\mu g} = \dfrac{\mu_g}{\left(\rho_g \sigma \sqrt{\dfrac{\sigma}{g\Delta\rho}}\right)^{0.5}}$ $D_H^* = \dfrac{D_H}{\sqrt{\dfrac{\sigma}{g\Delta\rho}}}$

- CONSERVATION OF ENERGY – CORE

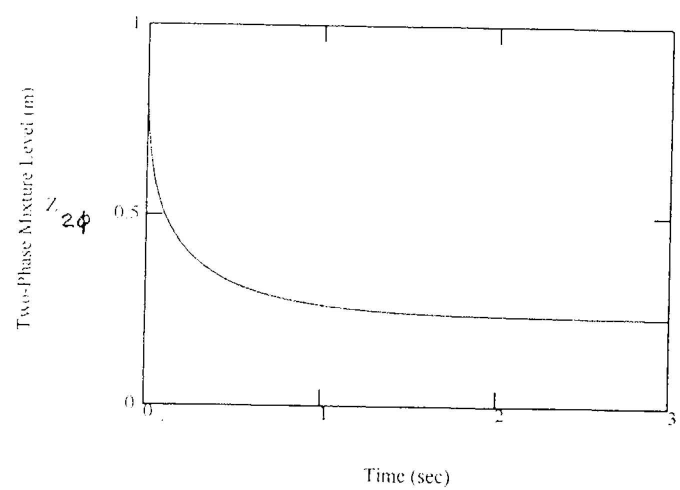
$$\dot{m}_{CORE} = \frac{q_{CORE}}{\Delta h_{sub} + x_{exit} h_{fg}}$$

W/O SUBCOOLING $\dot{m}_{CORE} = \dfrac{q_{CORE}}{x_{EXIT}\, h_{fg}}$

FOR QUASI-STEADY CONDITIONS IN CORE. ⇒ $j_g = \dfrac{q_{CORE}}{\rho_g \cdot h_{fg}\, A}$

Upper Plenum Liquid Entrainment Evaluation

- EQUATION SET SOLVED WITH MATHCAD, RESULTS SHOWN BELOW
- UPPER PLENUM 2ϕ MIXTURE LEVEL DROPS RAPIDLY BUT REACHES EQUILIBRIUM LEVEL WITHIN A FEW SECONDS
- ENTRAINMENT DIMINISHES RAPIDLY AS LEVEL IS REDUCED.
- TWO PHASE MIXTURE LEVEL STILL ABOVE TOP OF CORE.



Upper Plenum Mixture Level vs. Time

Liquid Entrainment Scaling Conclusions

- Near Surface region liquid entrainment in upper plenum sufficiently scaled in AP600 test facilities for AP1000.
- Momentum controlled region liquid entrainment rate may not be well scaled to AP1000. However, evaluation using conservative pool entrainment model indicates that impact of momentum controlled region liquid entrainment on two-phase mixture level in upper plenum not safety issue for AP1000. Therefore, AP600 integral effects test facilities sufficient for AP1000.

Ed Cart

AP1000
Preliminary HZP Steam Line Break Results

January 23, 2002

BNFL

Westinghouse

Purpose of Steam Line Break Core Response Analysis

- maximize cool down induced core power increase
- minimize DNBR

Steam Line Break Assumptions

- Transient initiated from Hot Zero Power Conditions
- Pressurizer & PRHR connected to Loop 1
- CMT connected to Loop 2
- Break is in steam line between SG and MSIV on Loop 2
- Full double ended rupture
- Dry steam blow down assumed
- Shutdown margin with stuck rod - 1.6 $\%\Delta\rho$
- No decay heat assumed
- Minimum Safeguards CMT performance characteristics
- Maximum Safeguards PRHR performance characteristics

BNFL Westinghouse

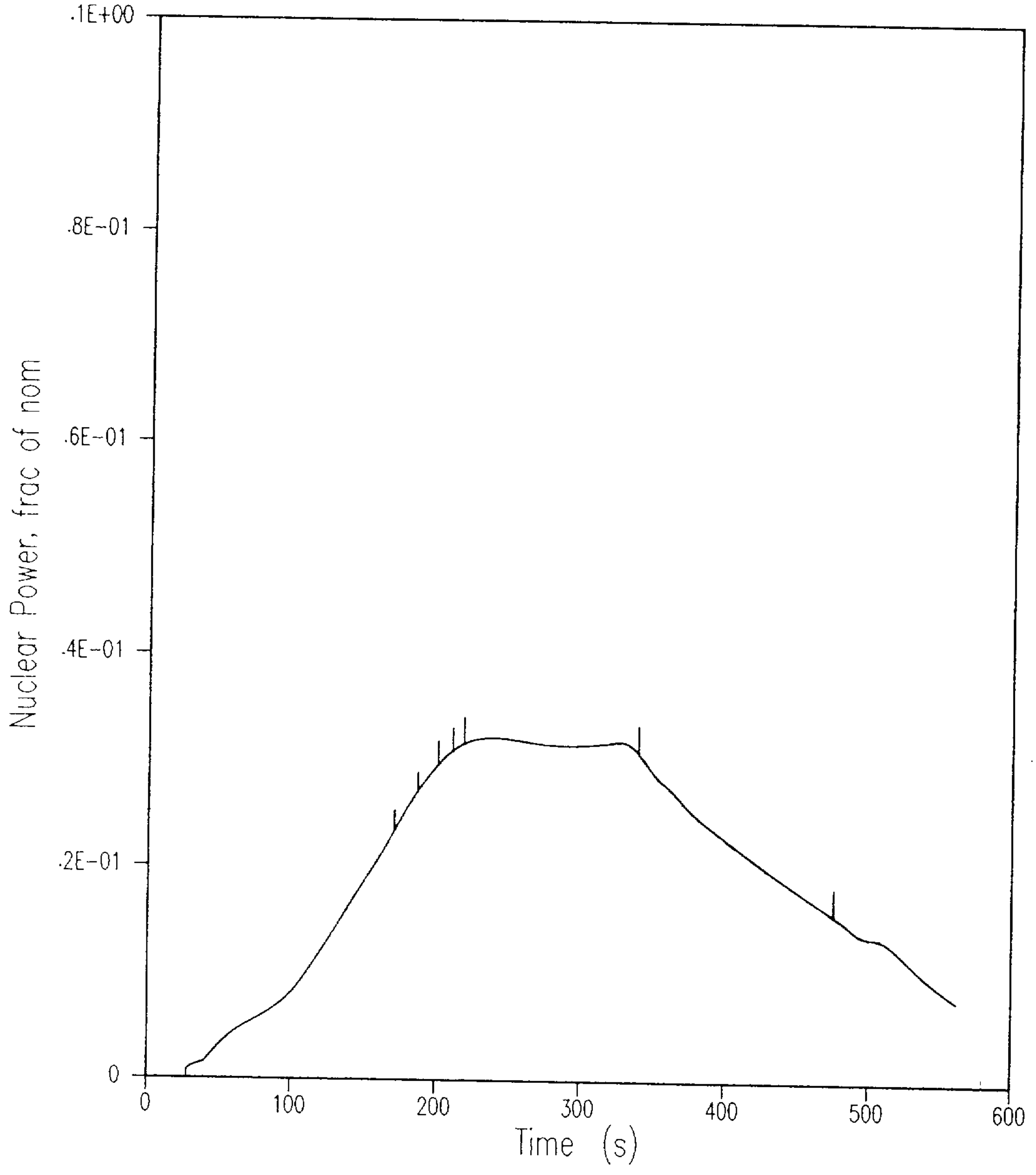
Sequence of Events

Time, sec	Event
0.0	Break initiated, startup feedwater started, PRHR started
1.4	Low steam line pressure setpoint reached
7.4	RCP's tripped on low steam line pressure signal
13.4	Main steam and main feedwater isolation valves close on low steam pressure signal
18.1	Low cold leg temperature setpoint reached
18.4	CMT's actuated on low steam line pressure signal
28.2	Criticality reached
30.1	Startup feedwater isolated on low cold leg temperature signal

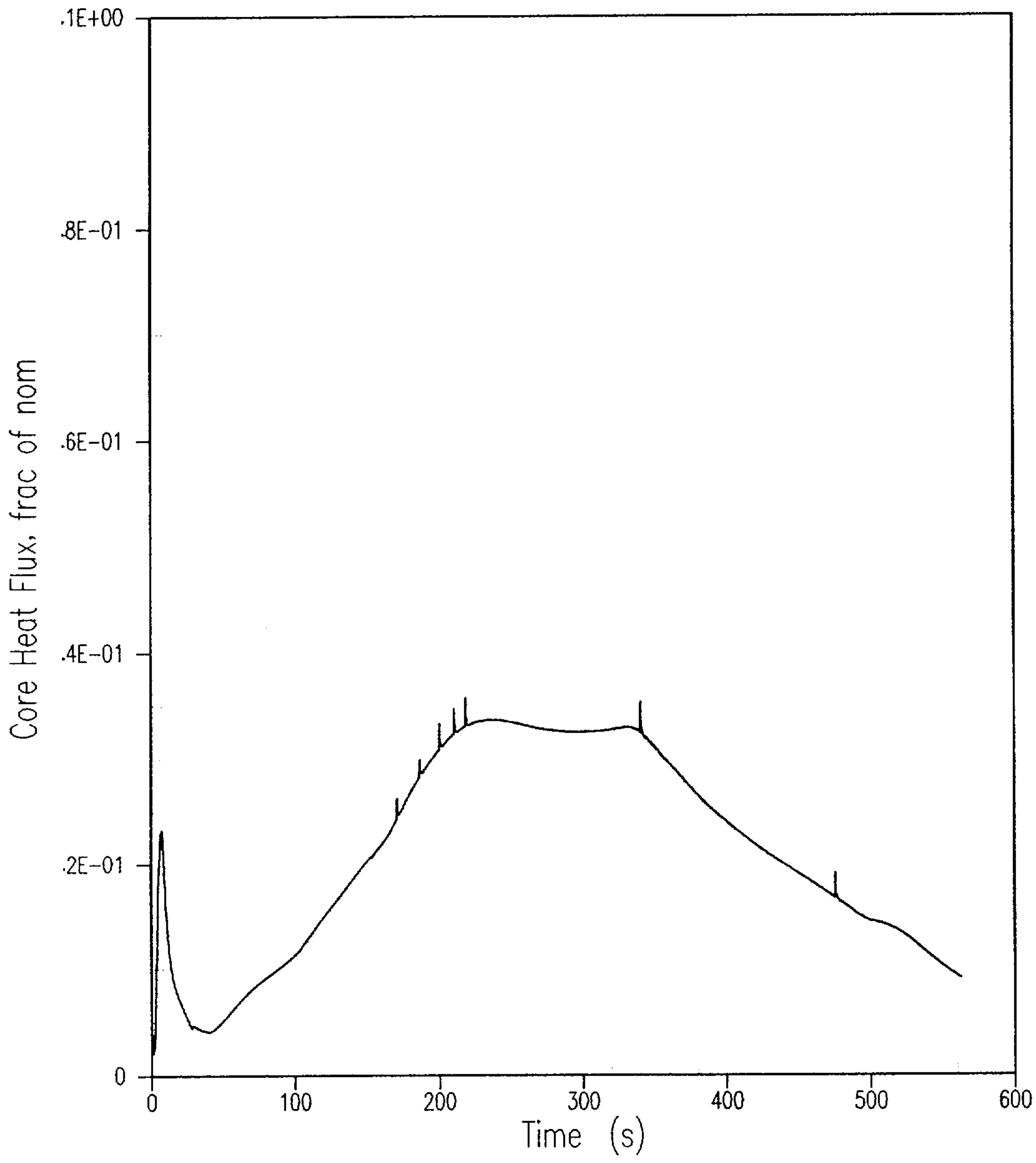
Sequence of Events (continued)

Time, sec	Event
105.	Pressurizer empties
152.4	Reactor vessel upper head reaches saturation
218.4	Peak core heat flux occurs
319.	Accumulators begin injecting

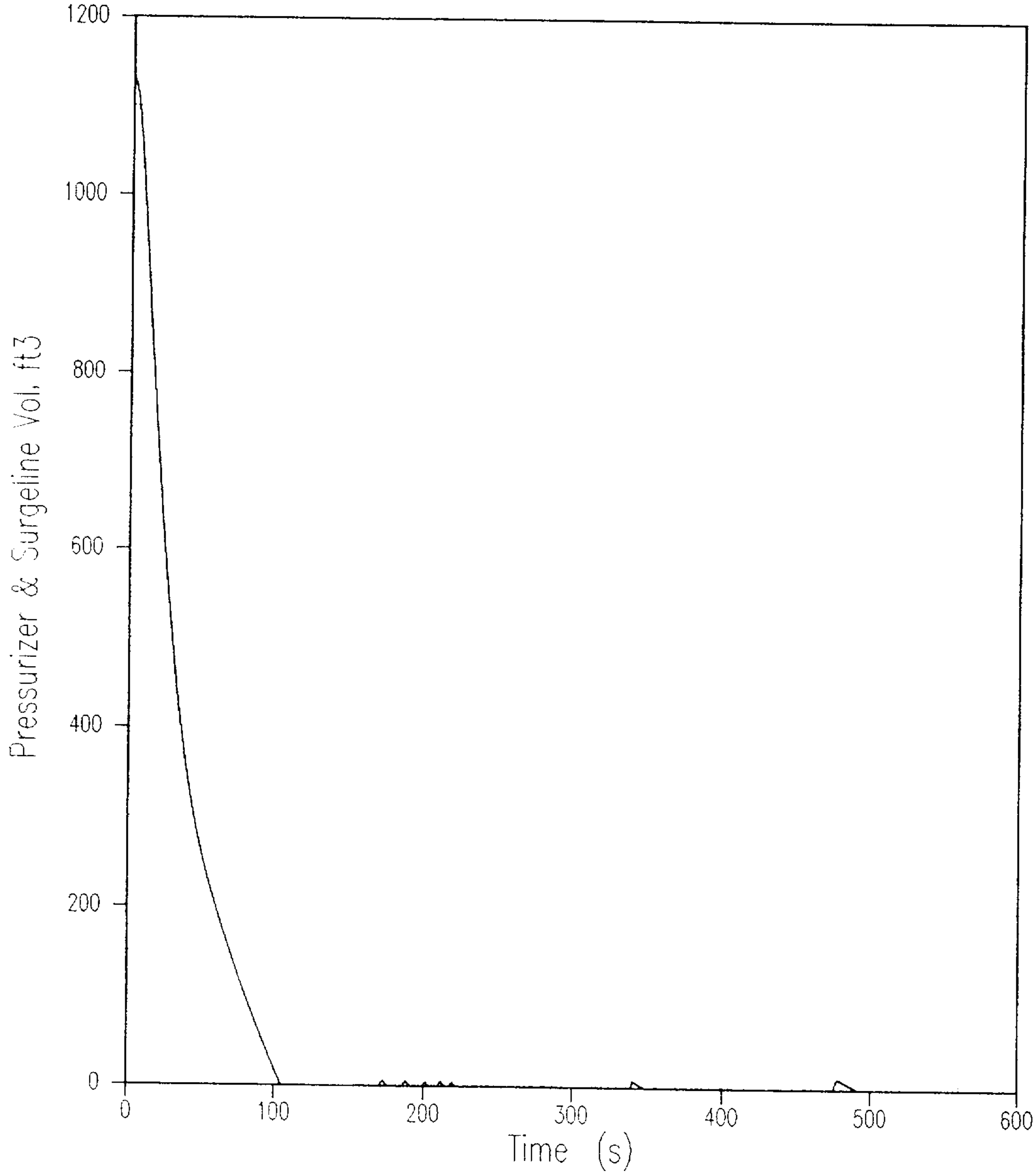
AP1000 Full DE Steam Line Rupture



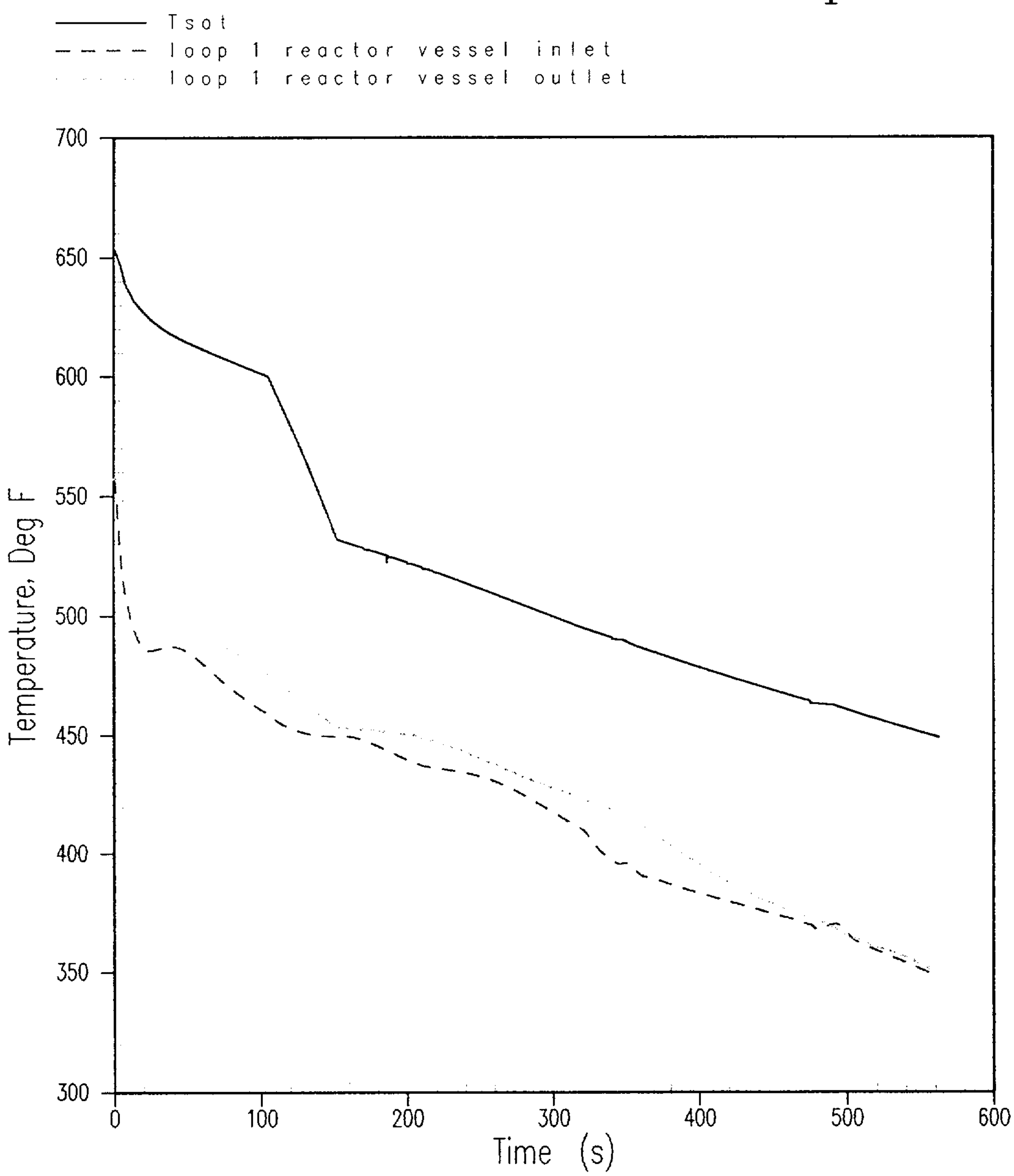
AP1000 Full DE Steam Line Rupture

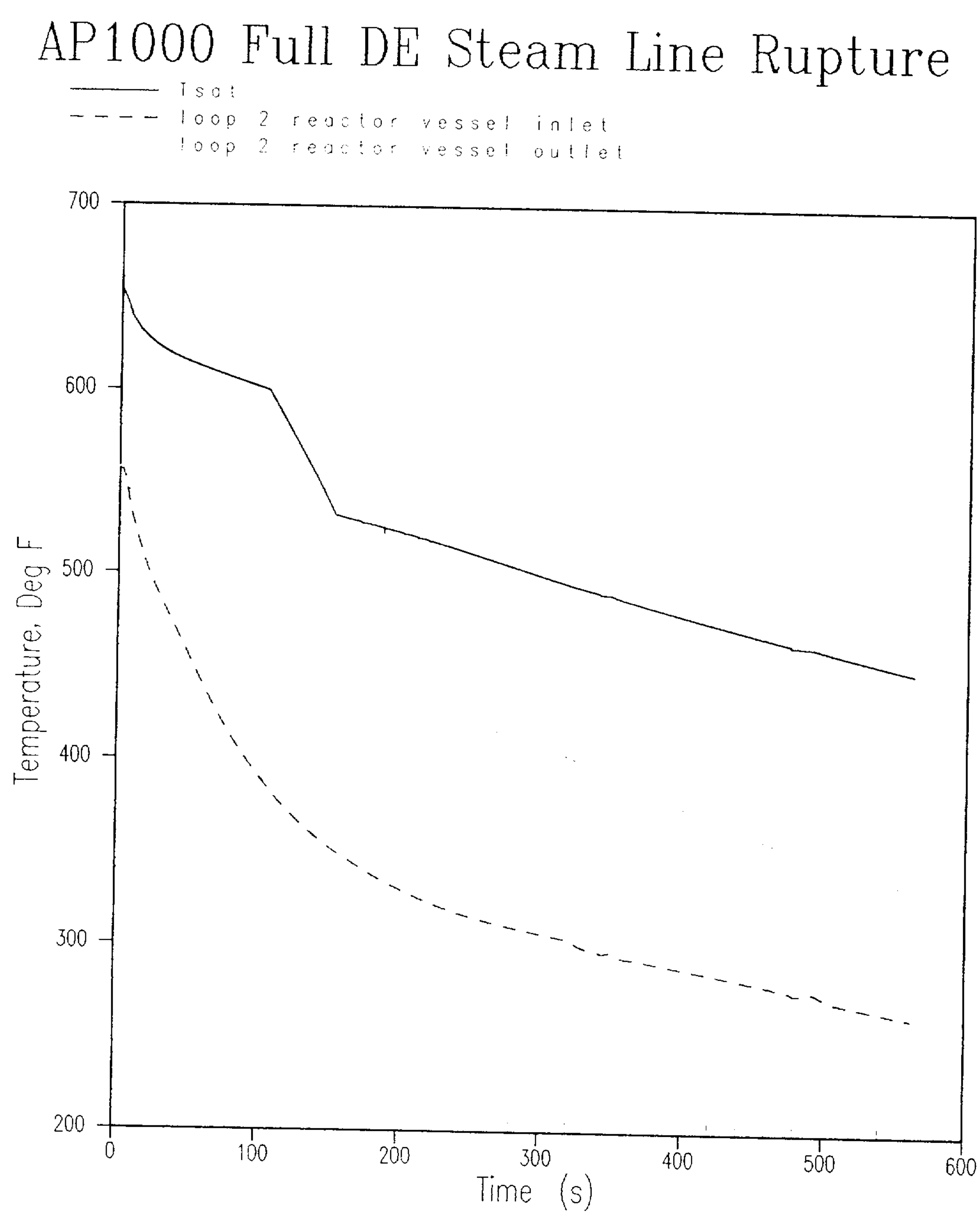


AP1000 Full DE Steam Line Rupture

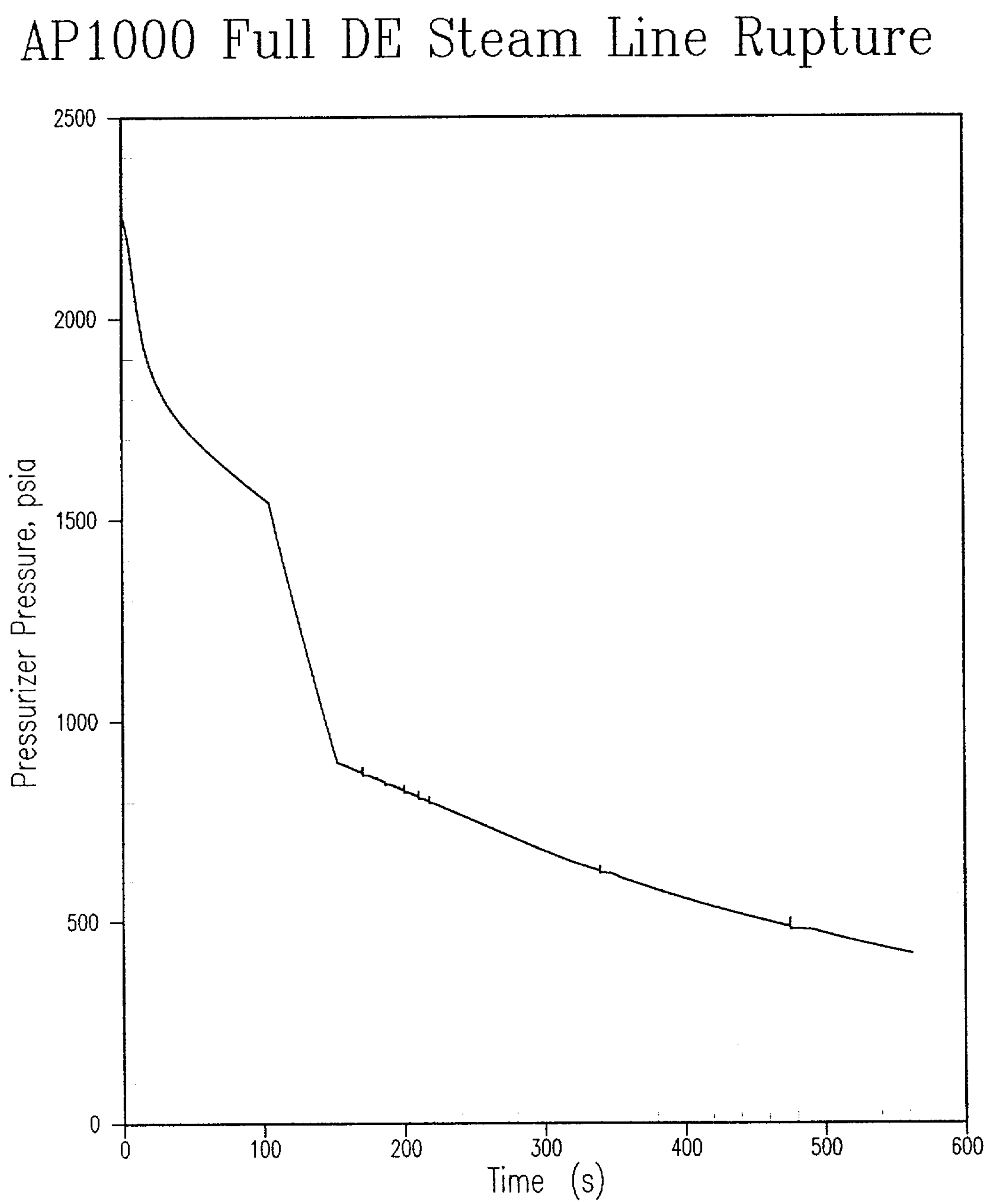


AP1000 Full DE Steam Line Rupture

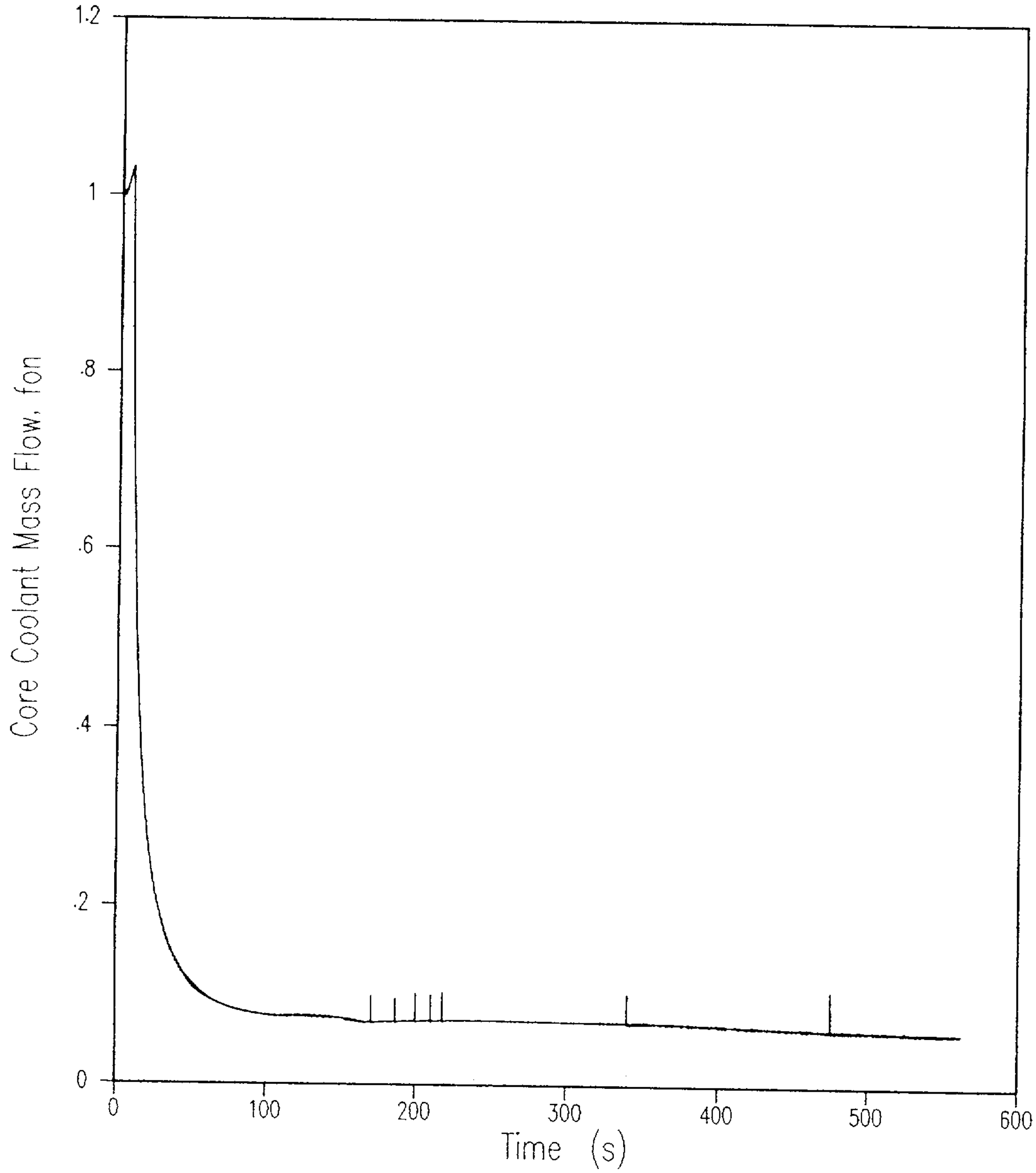




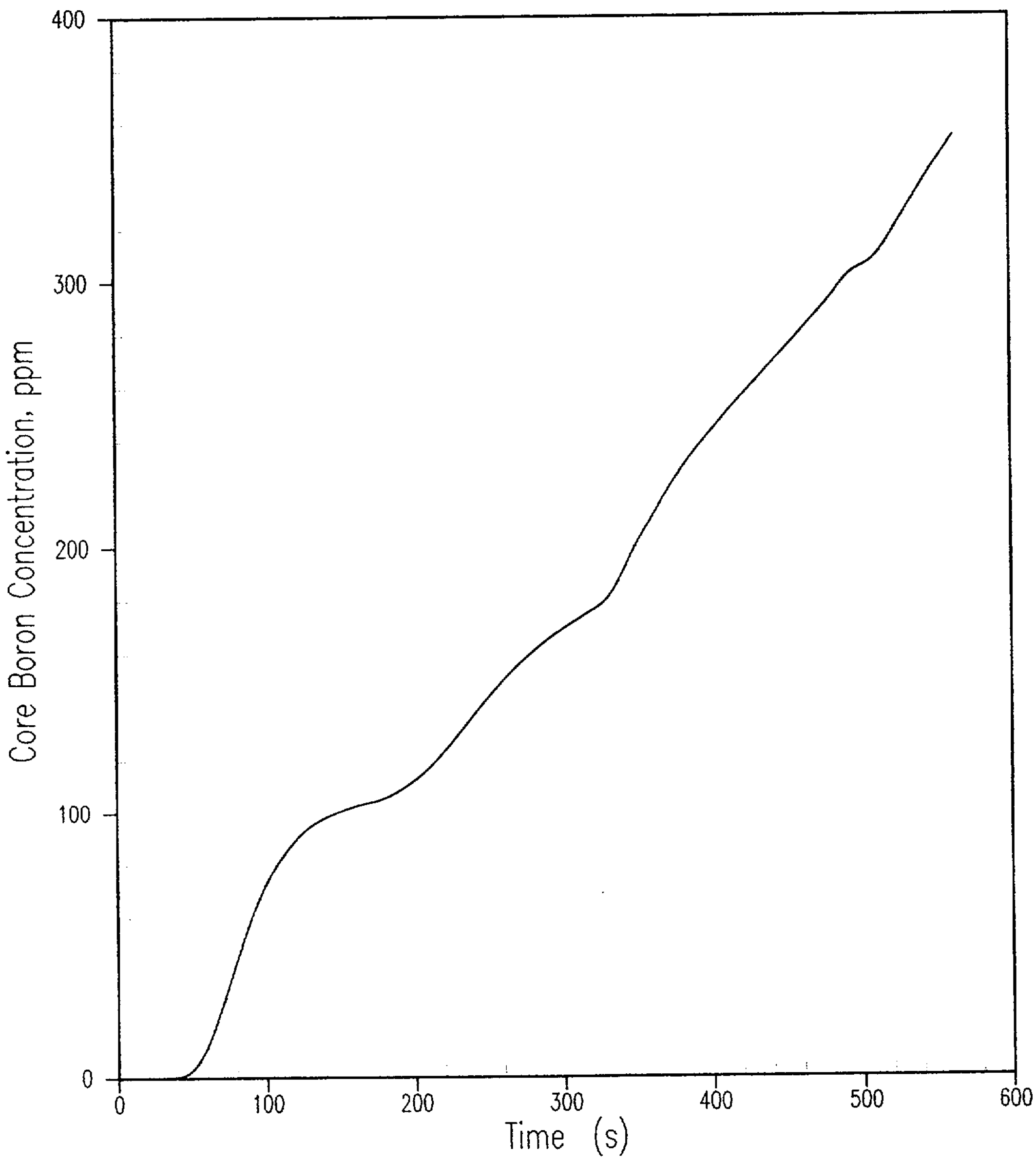
AP1000 Full DE Steam Line Rupture
Tsat
loop 2 reactor vessel inlet
loop 2 reactor vessel outlet
700
600
500
400
300
200
Temperature, Deg F
0
100
200
300
400
500
600
Time (s)

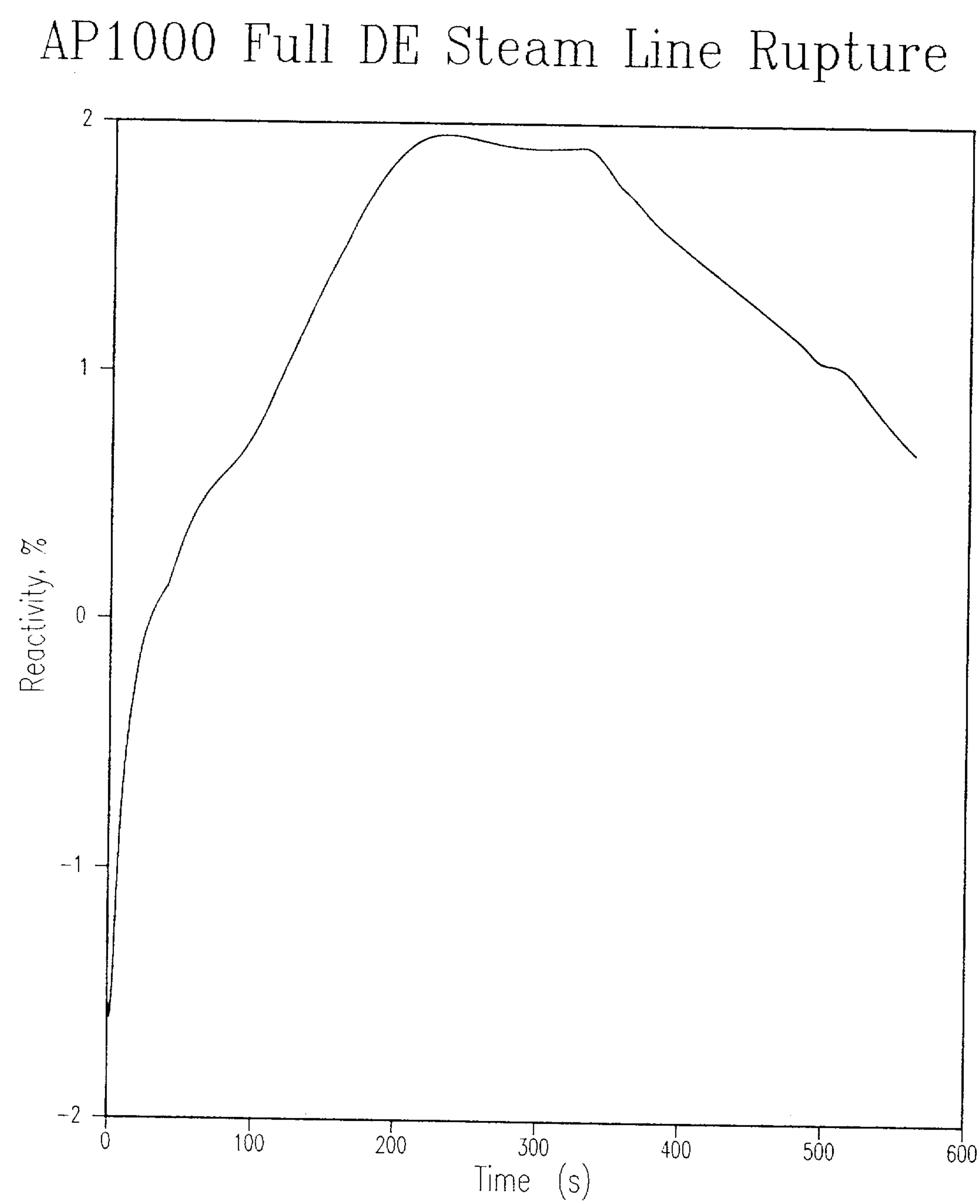

AP1000 Full DE Steam Line Rupture
Pressurizer Pressure, psia
2500
2000
1500
1000
500
0
0
100
200
300
400
500
600
Time (s)

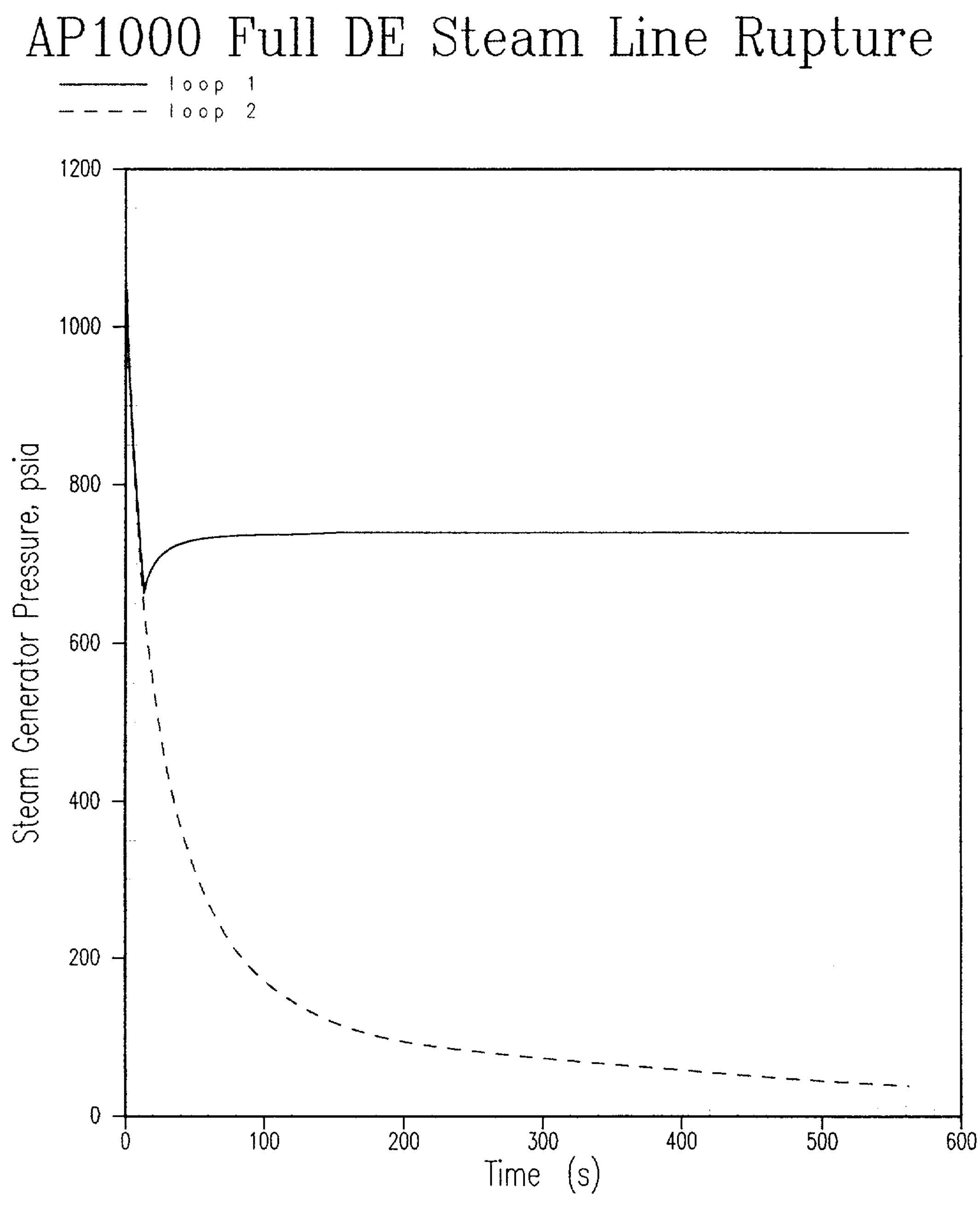
AP1000 Full DE Steam Line Rupture



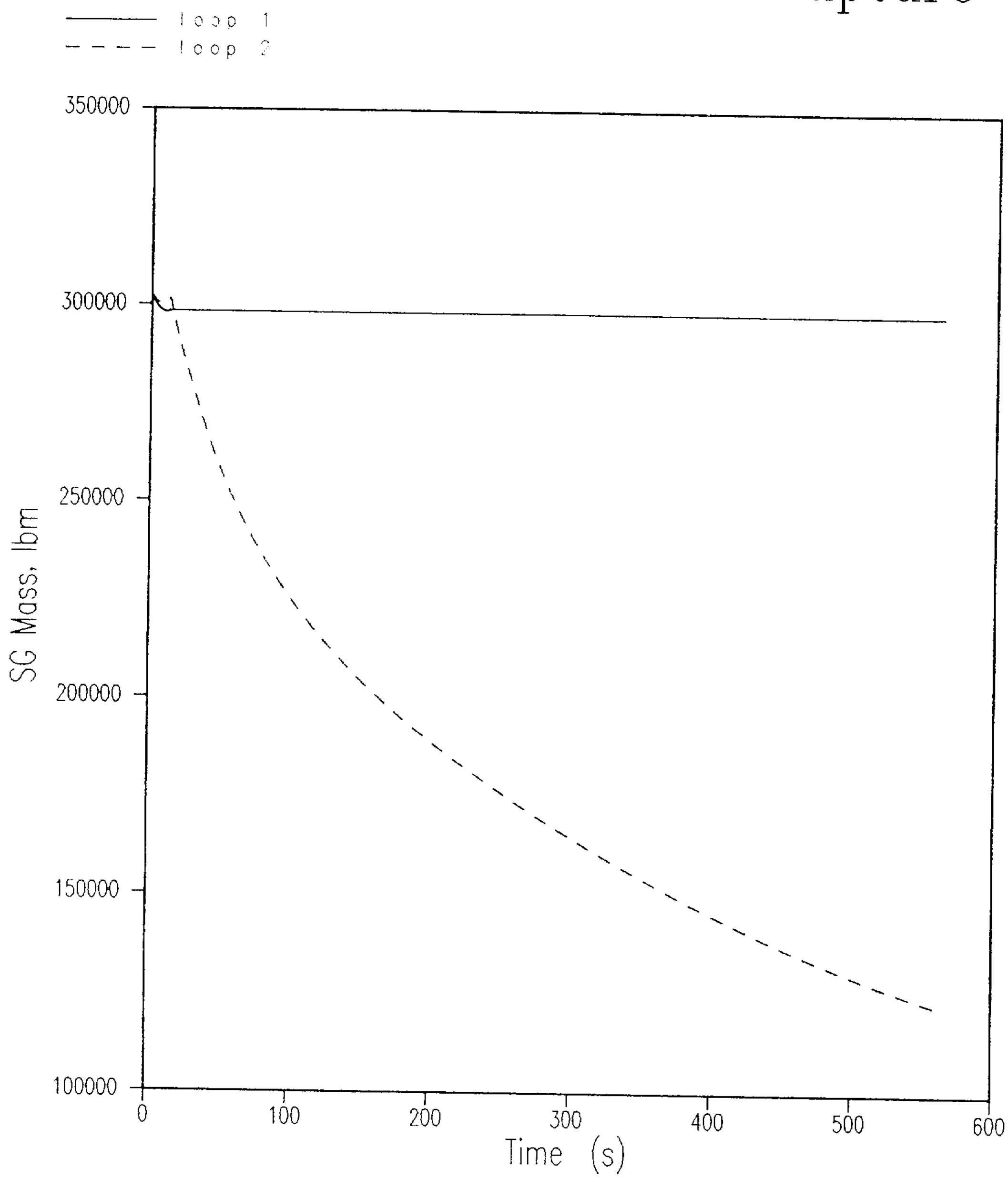
AP1000 Full DE Steam Line Rupture

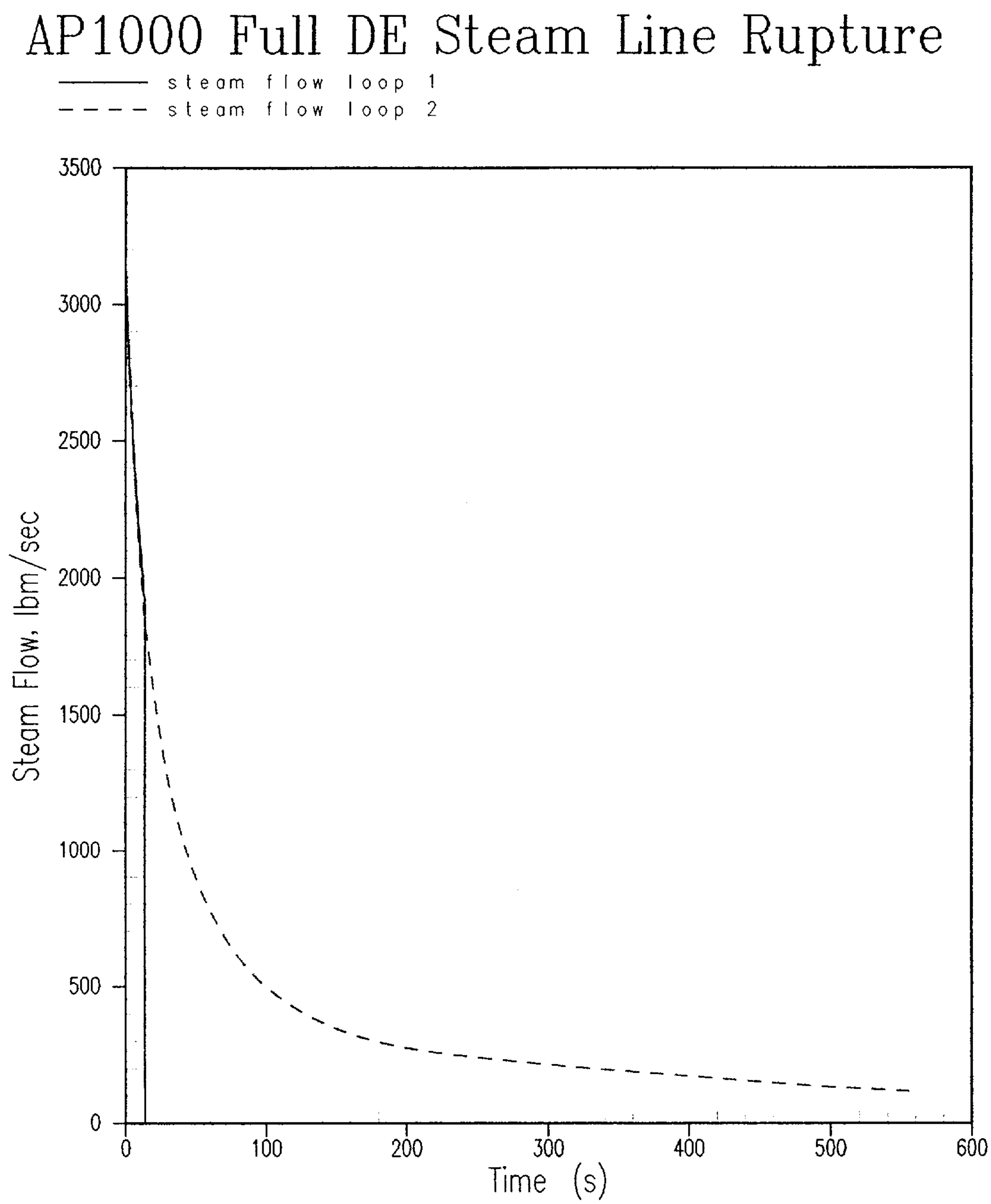



AP1000 Full DE Steam Line Rupture
2
1
0
-1
-2
Reactivity, %
0
100
200
300
400
500
600
Time (s)

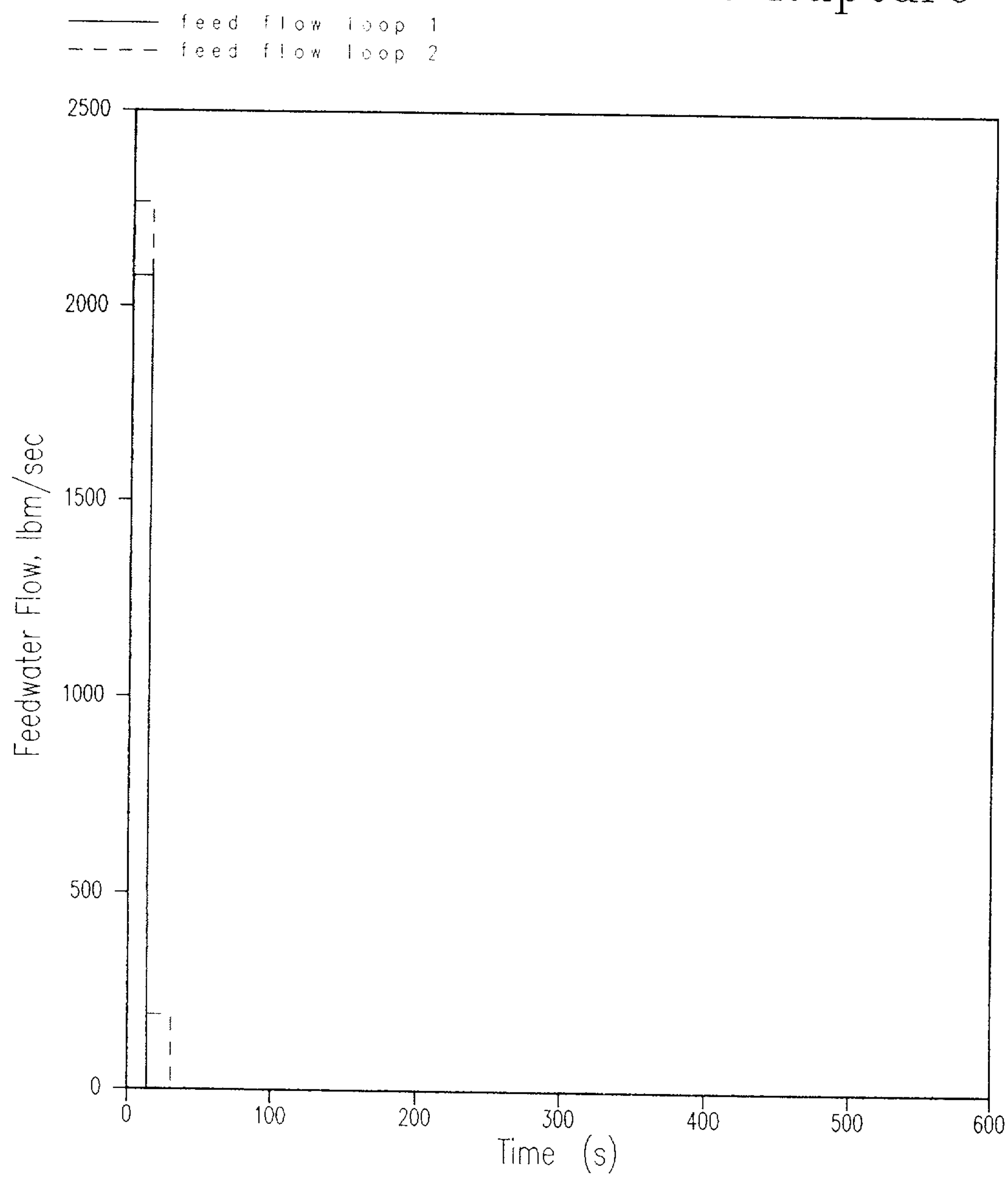

AP1000 Full DE Steam Line Rupture
loop 1
loop 2
1200
1000
800
600
400
200
0
Steam Generator Pressure, psia
0
100
200
300
400
500
600
Time (s)

AP1000 Full DE Steam Line Rupture

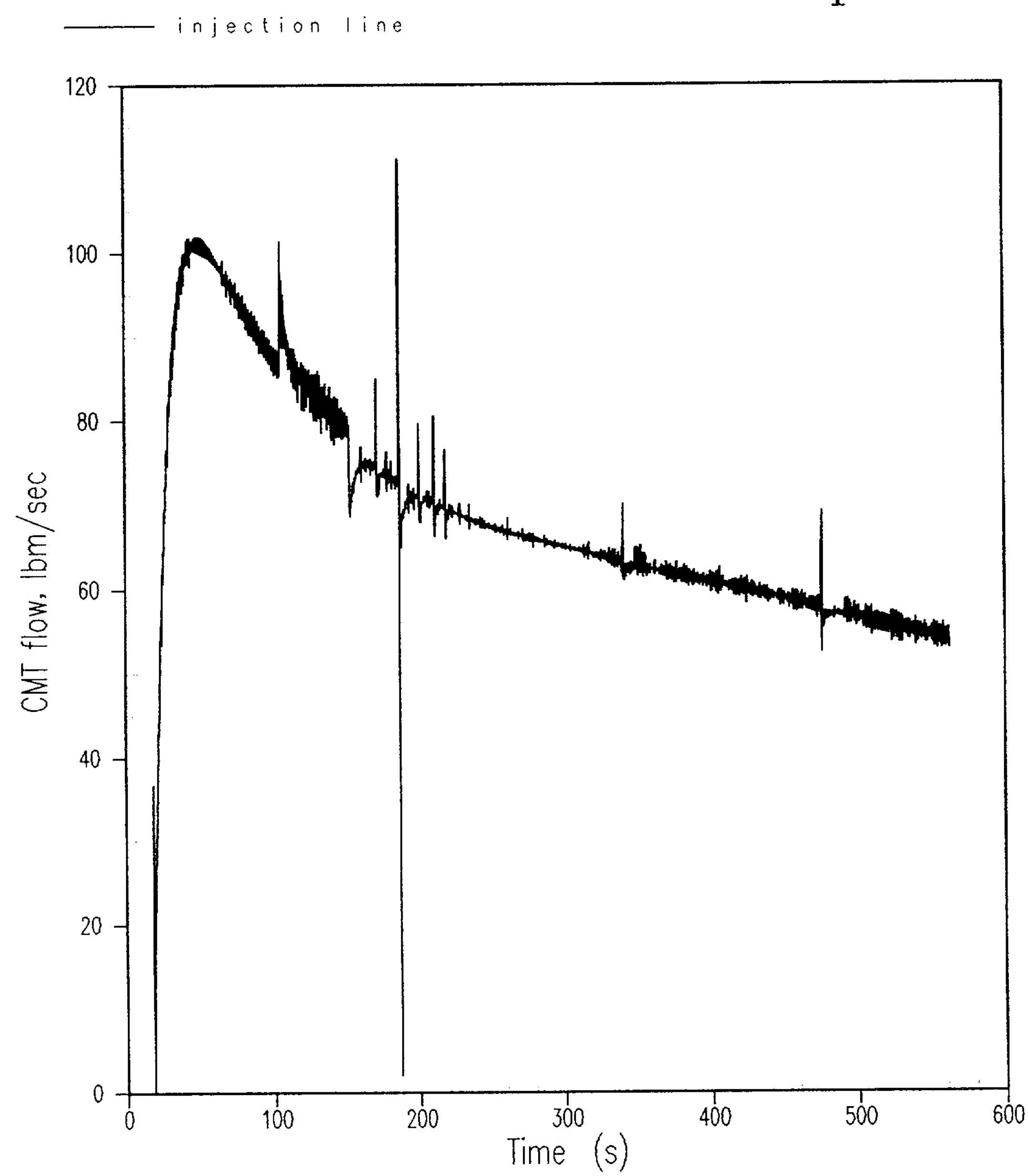



AP1000 Full DE Steam Line Rupture
steam flow loop 1
steam flow loop 2
3500
3000
2500
2000
1500
1000
500
0
Steam Flow, lbm/sec
0
100
200
300
400
500
600
Time (s)

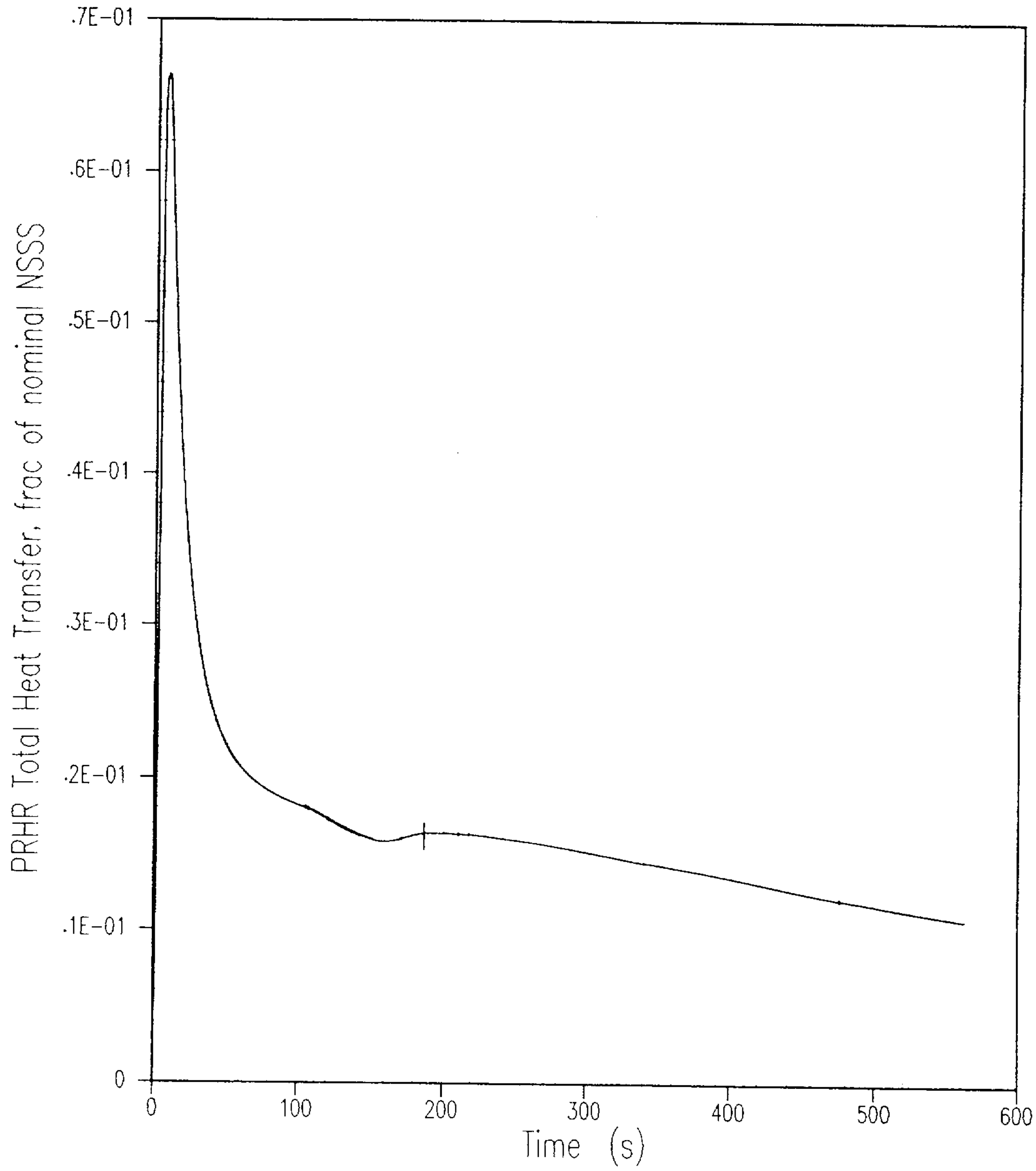
AP1000 Full DE Steam Line Rupture

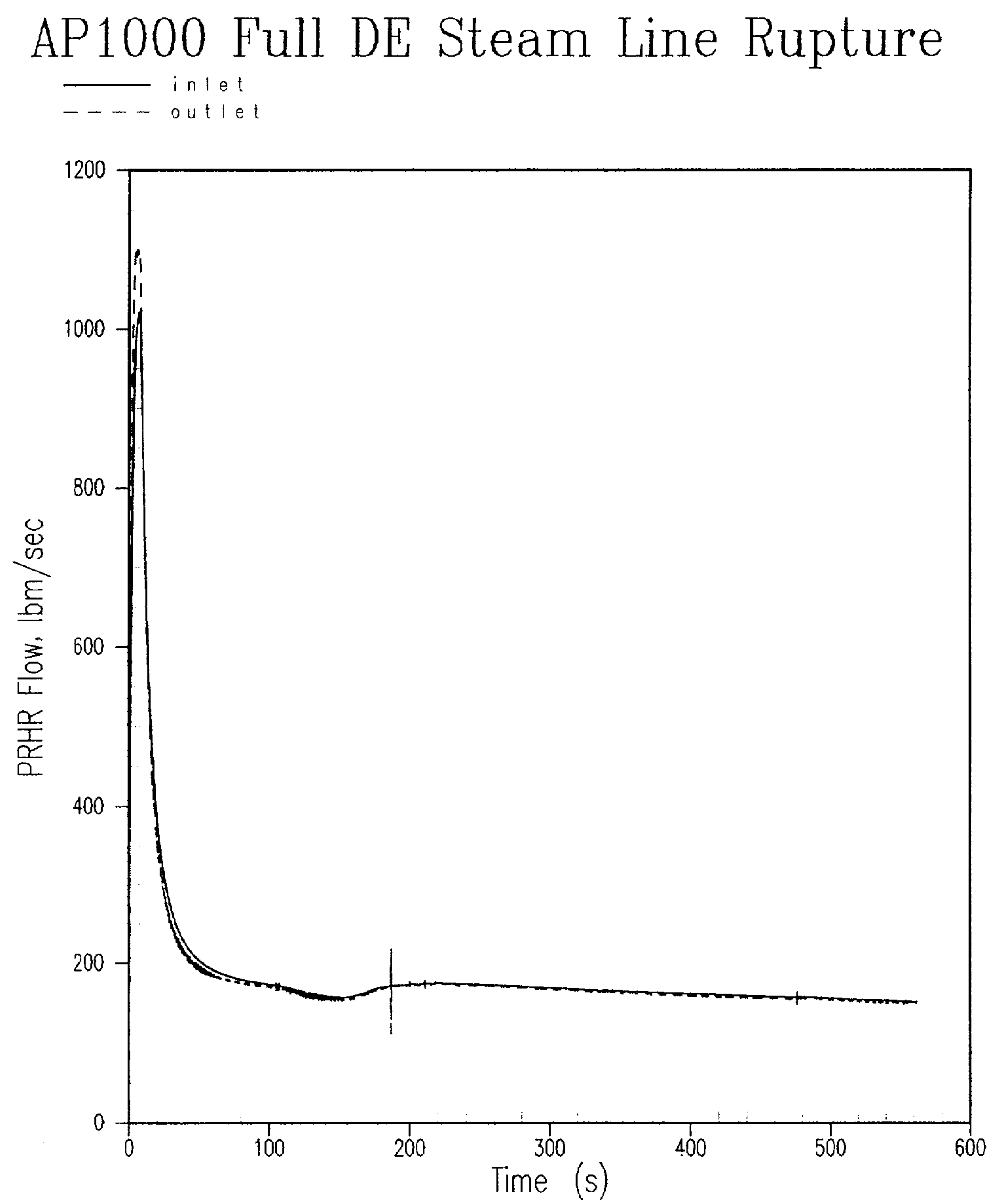


AP1000 Full DE Steam Line Rupture

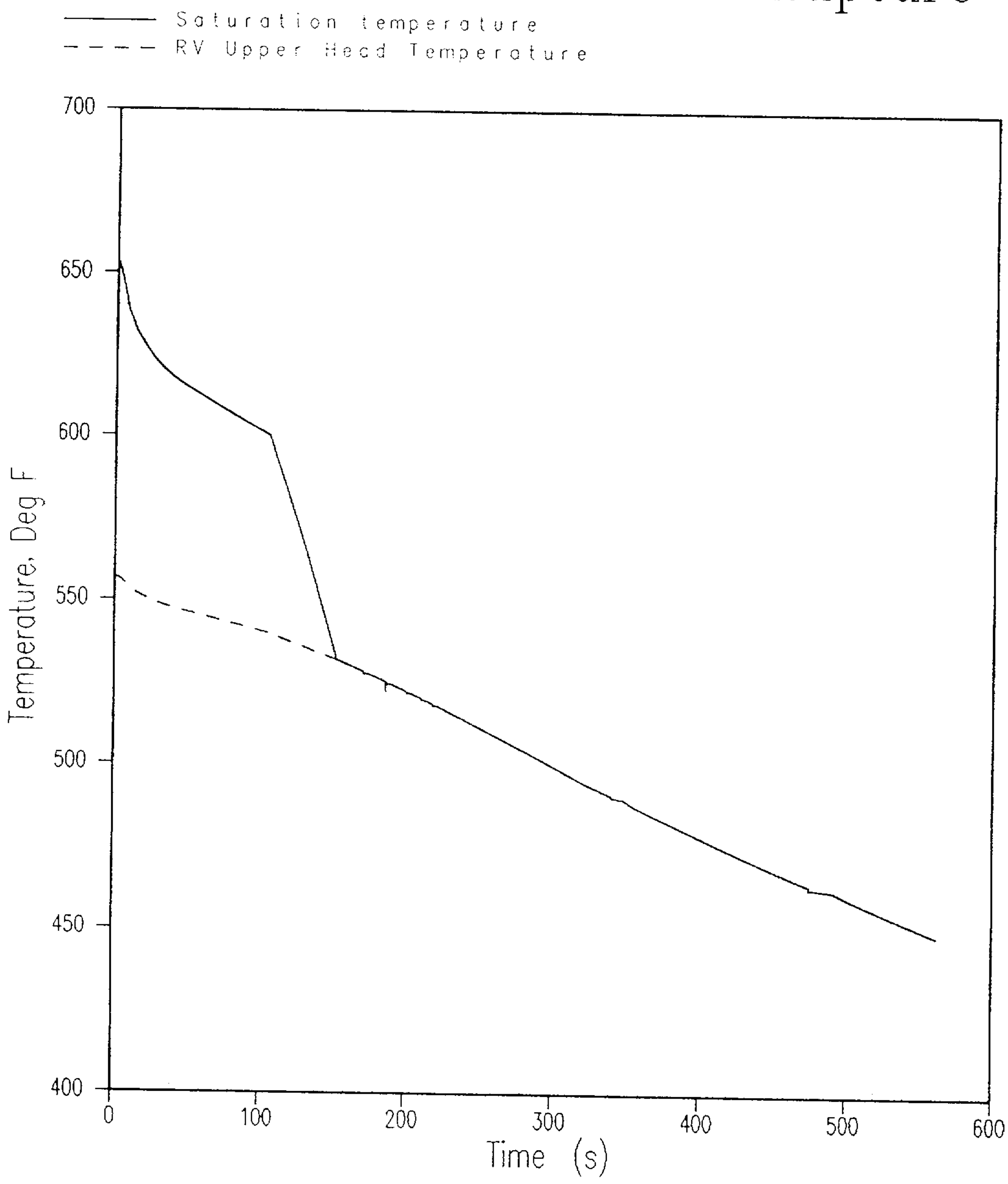


AP1000 Full DE Steam Line Rupture

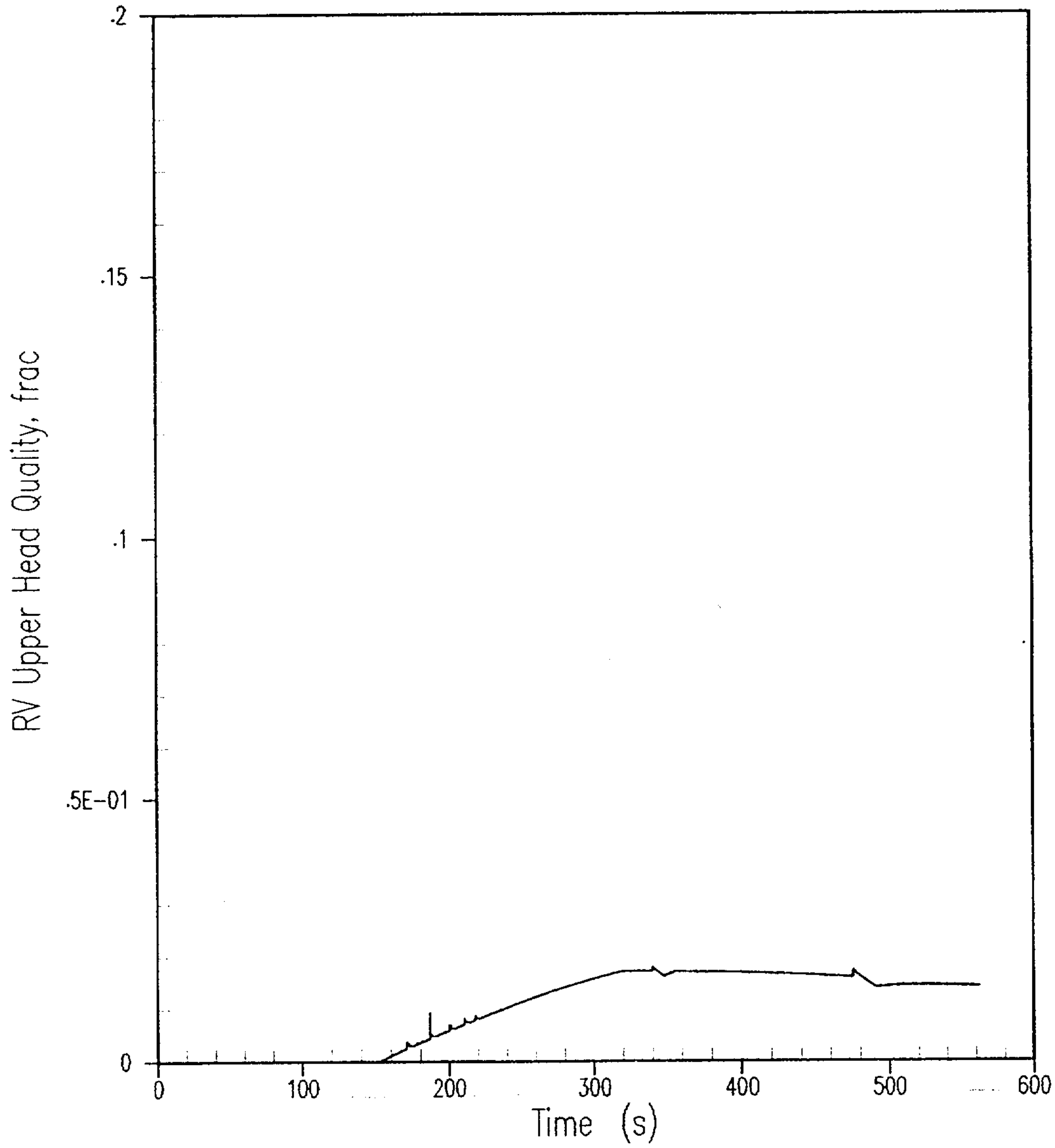



AP1000 Full DE Steam Line Rupture
inlet
outlet
1200
1000
800
600
400
200
0
PRHR Flow, lbm/sec
0
100
200
300
400
500
600
Time (s)

AP1000 Full DE Steam Line Rupture



AP1000 Full DE Steam Line Rupture



AP1000 NOTRUMP

January 23, 2002

Andre F. Gagnon
LOCA Integrated Services
Westinghouse Electric Company, LLC
(412) 374-5574; gagnonaf@westinghouse.com

AP1000 NOTRUMP

Background

- Preliminary cases performed to compare the AP600 and AP1000 plant performance in Dec. 2000
  - Documented in WCAP-15612
- Models continue to undergo refinement in preparation for SAR Analysis
- Cases re-performed with later model
  - Reference 2-Inch Cold Leg Break
    - 50% PRHR HTA reduction sensitivity

AP1000 SBLOCA Model Refinements

- Model more accurately reflects design than scoping study
  - –Actual model geometrical information
  - –Actual PRHR HT and piping configuration
  - –Core axial power shape based on 14 foot core designs
    - –Scoping study used scaled AP600 shape

2-Inch Break Results Comparisons

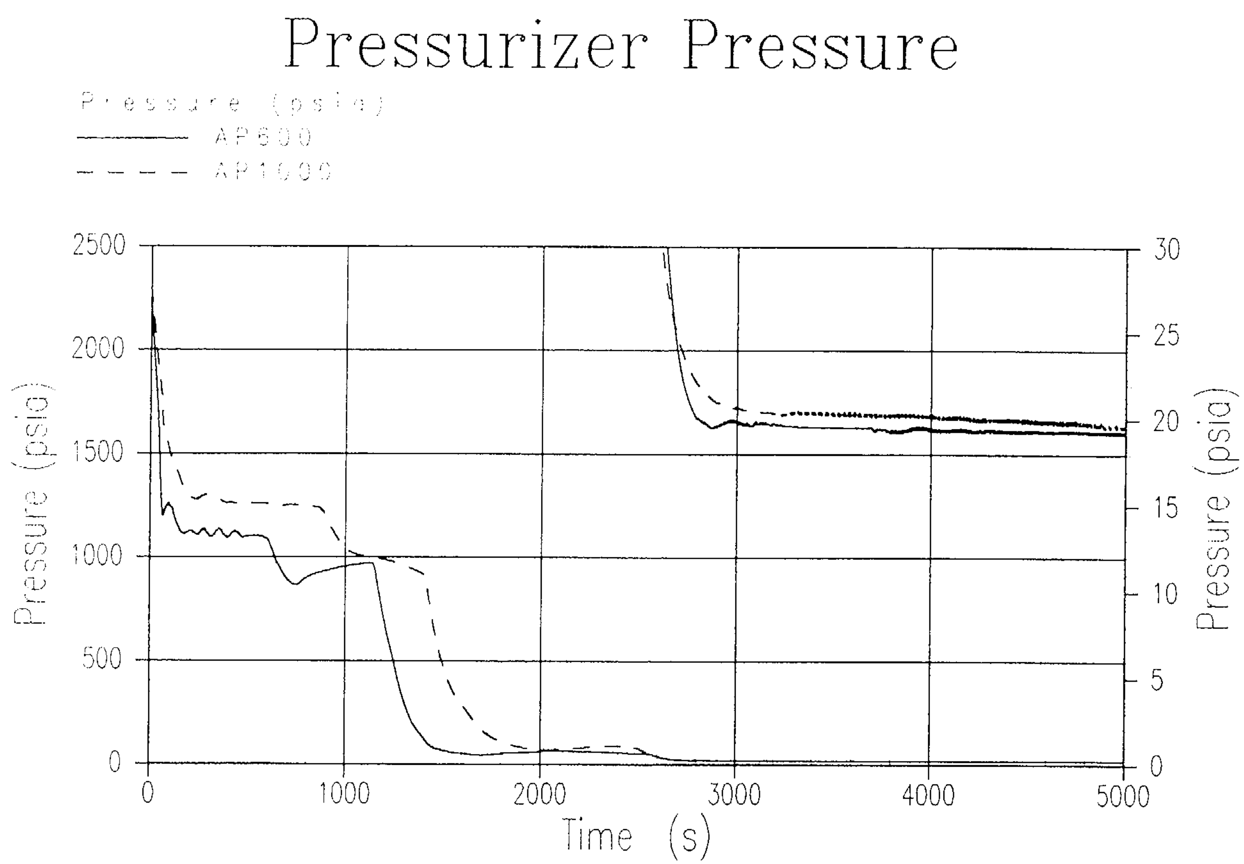
Event	AP600	AP1000 (WCAP)	AP1000 (SAR)
Break opens	0.0	0.0	0.0
Reactor trip	33.3	58.3	55.5
"S" signal	39.5	64.9	62.0
MFW Isolation	44.5	69.9	67.0
RCP Trip	55.7	81.1	67.2
ADS 1	1138	2720	1397
ACC Injection	1200	2760	1447

2-Inch Break Results Comparisons

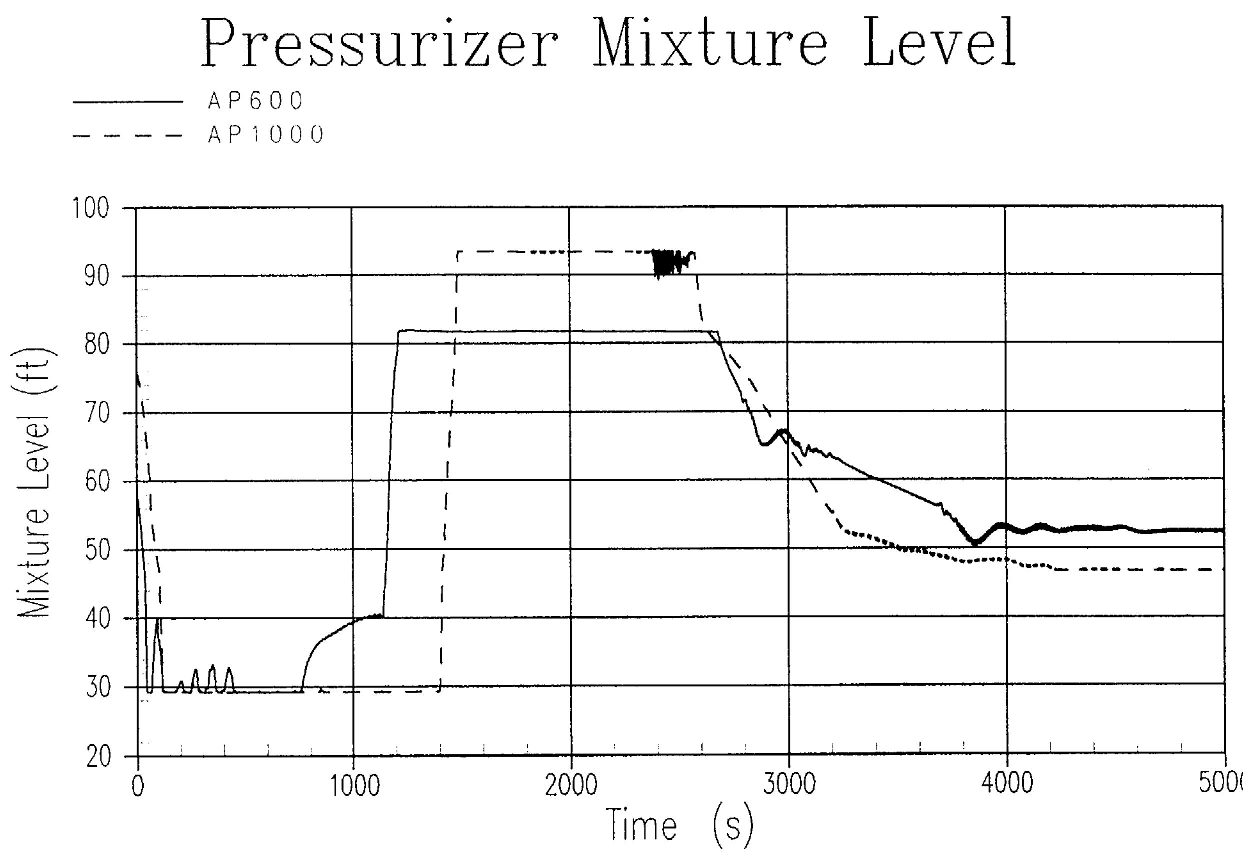
Event	AP600	AP1000 (WCAP)	AP1000 (SAR)
ADS 2	1208	2790	1467
ADS 3	1328	2910	1587
ACC Empty	1575	3183	1983
ADS 4	2522	3941	2490
CMT empty	2920	4240	2890
IRWST Injection	3560	4500	3300[1]

[1]Conservative ADS-4 Modeling

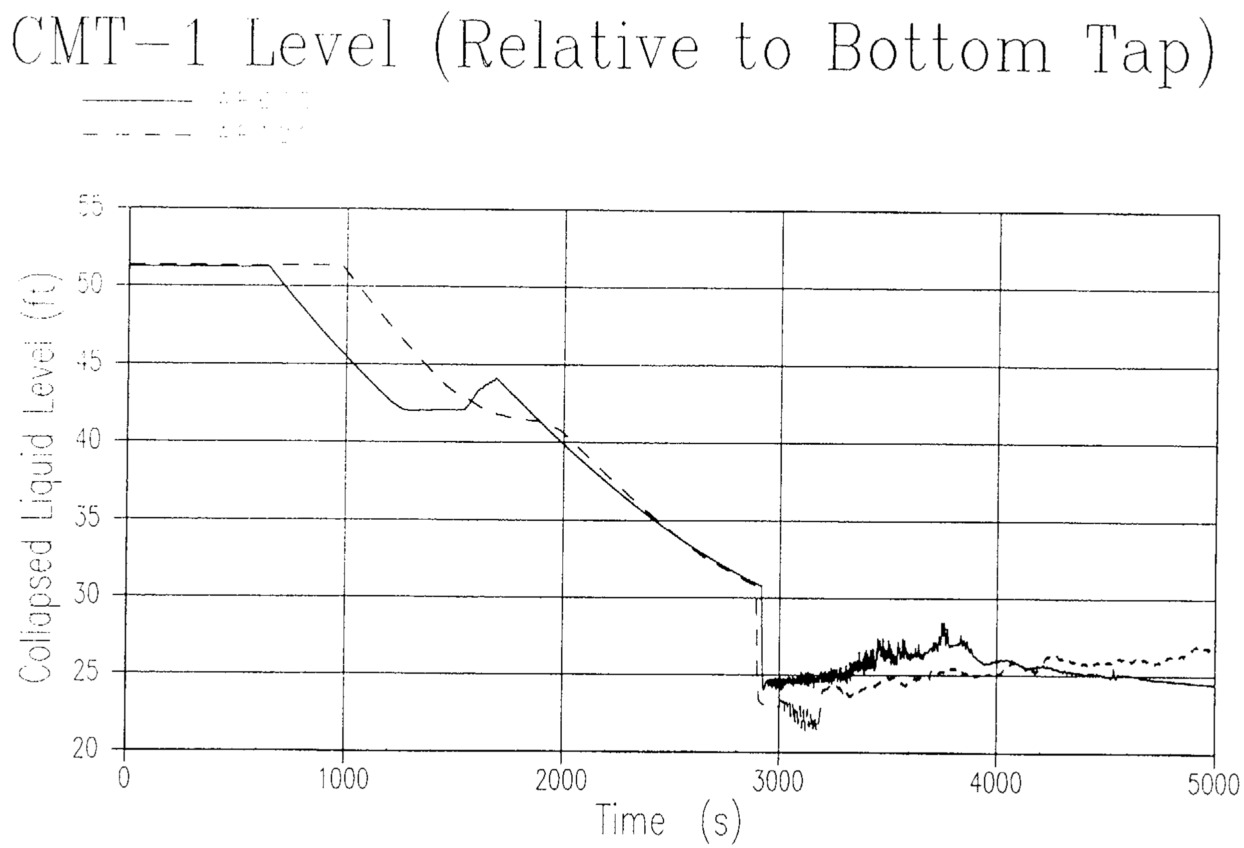
2-Inch Break Results (AP600 vs. AP1000)



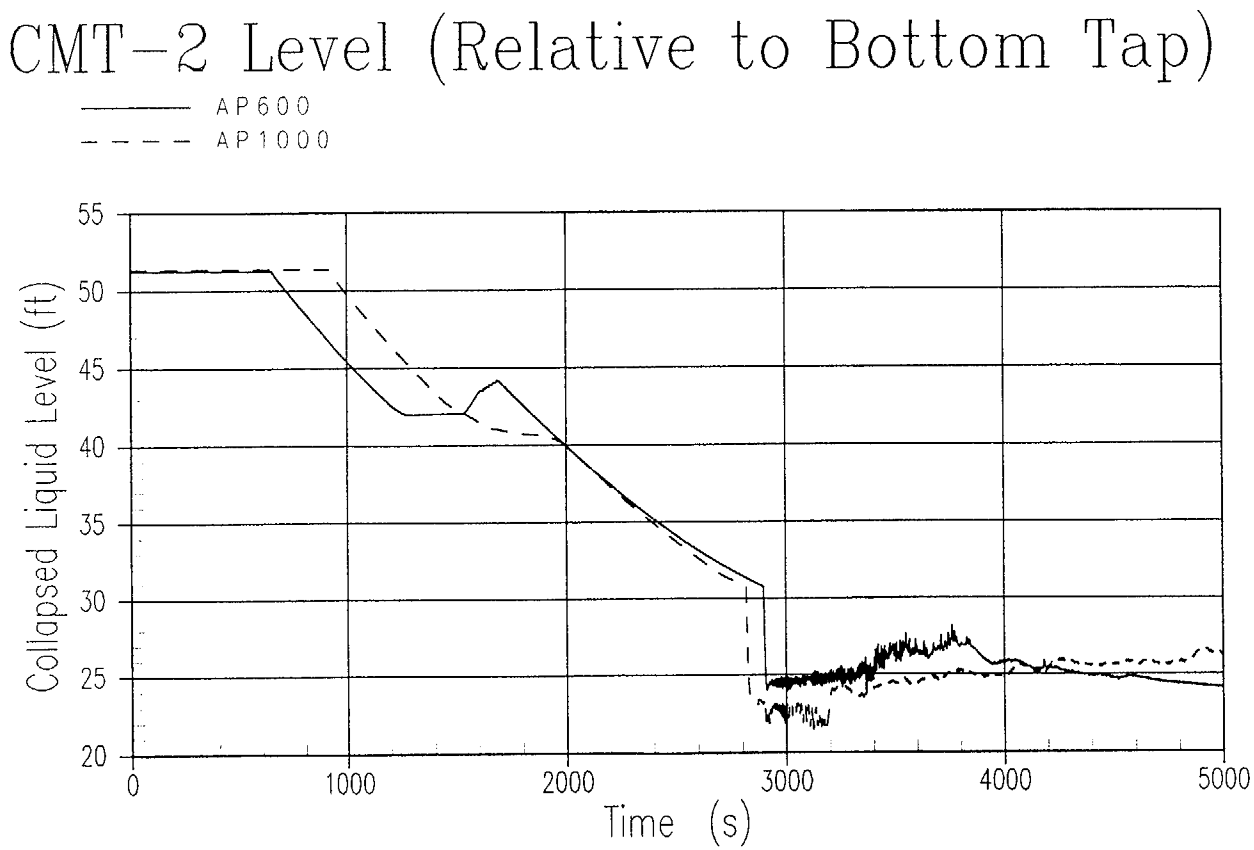
2-Inch Break Results (AP600 vs. AP1000)



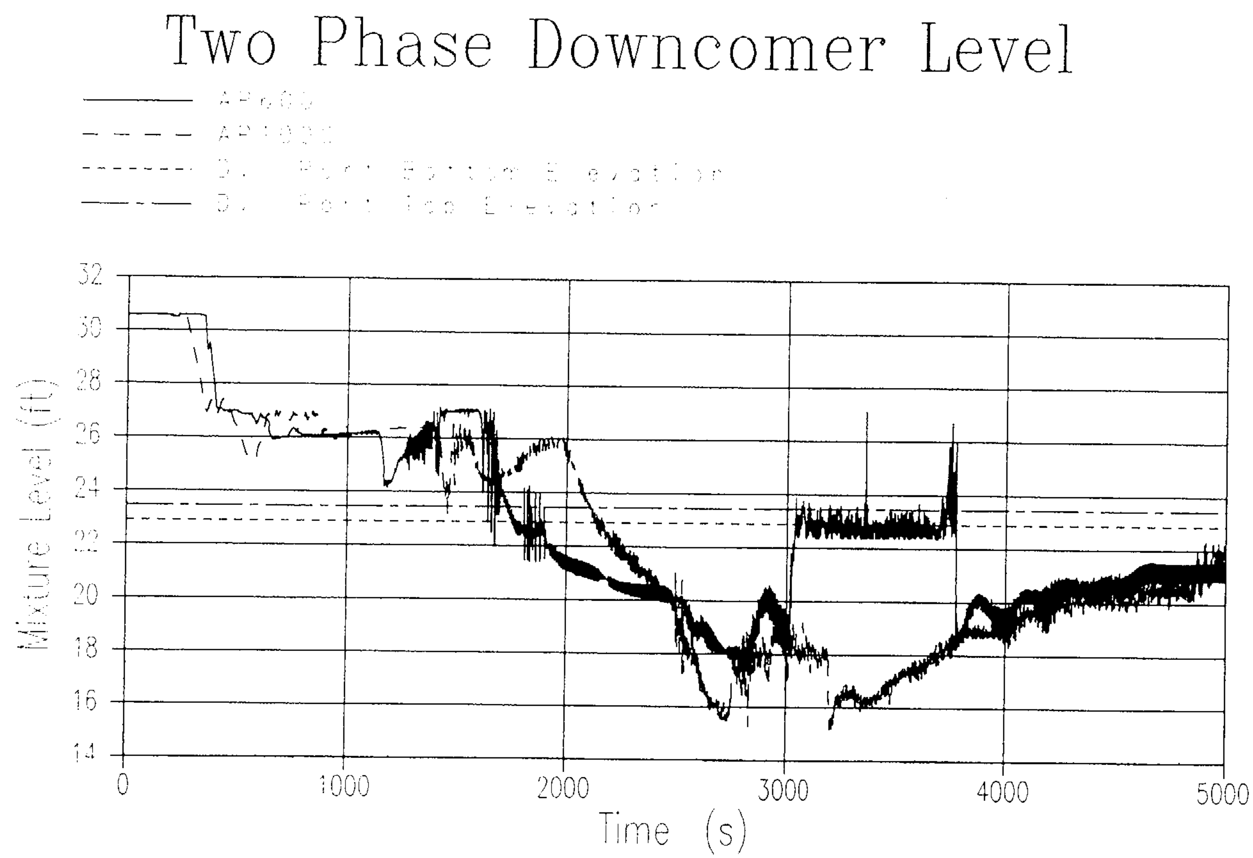
2-Inch Break Results (AP600 vs. AP1000)



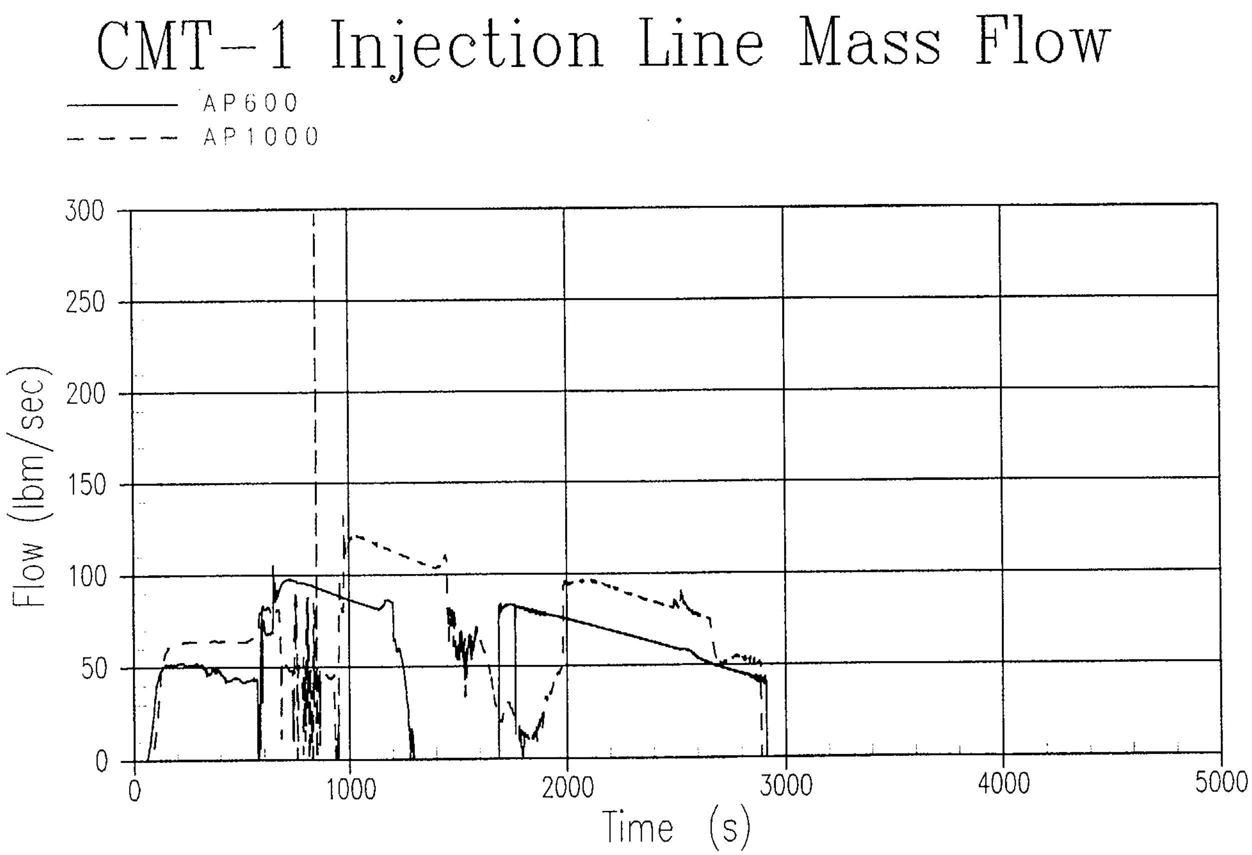
2-Inch Break Results (AP600 vs. AP1000)



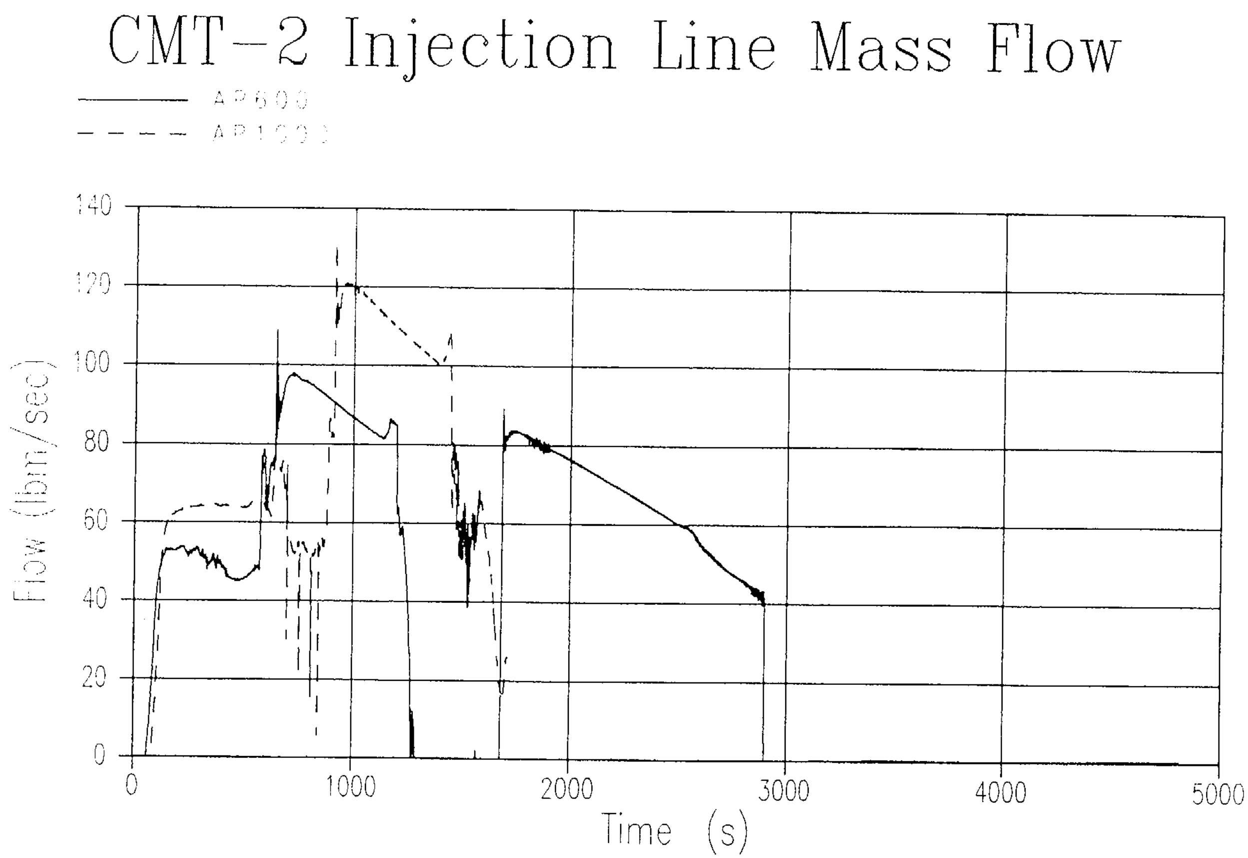
2-Inch Break Results (AP600 vs. AP1000)



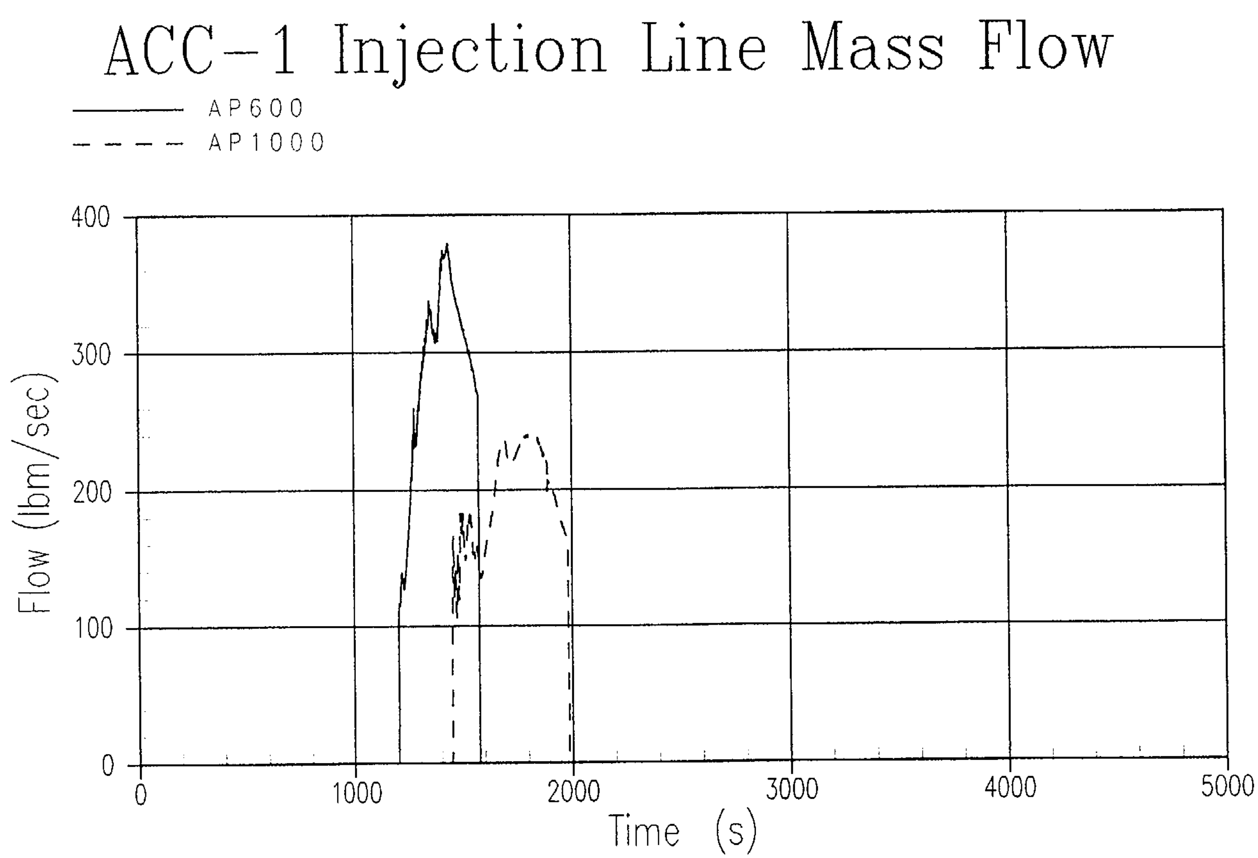
2-Inch Break Results (AP600 vs. AP1000)



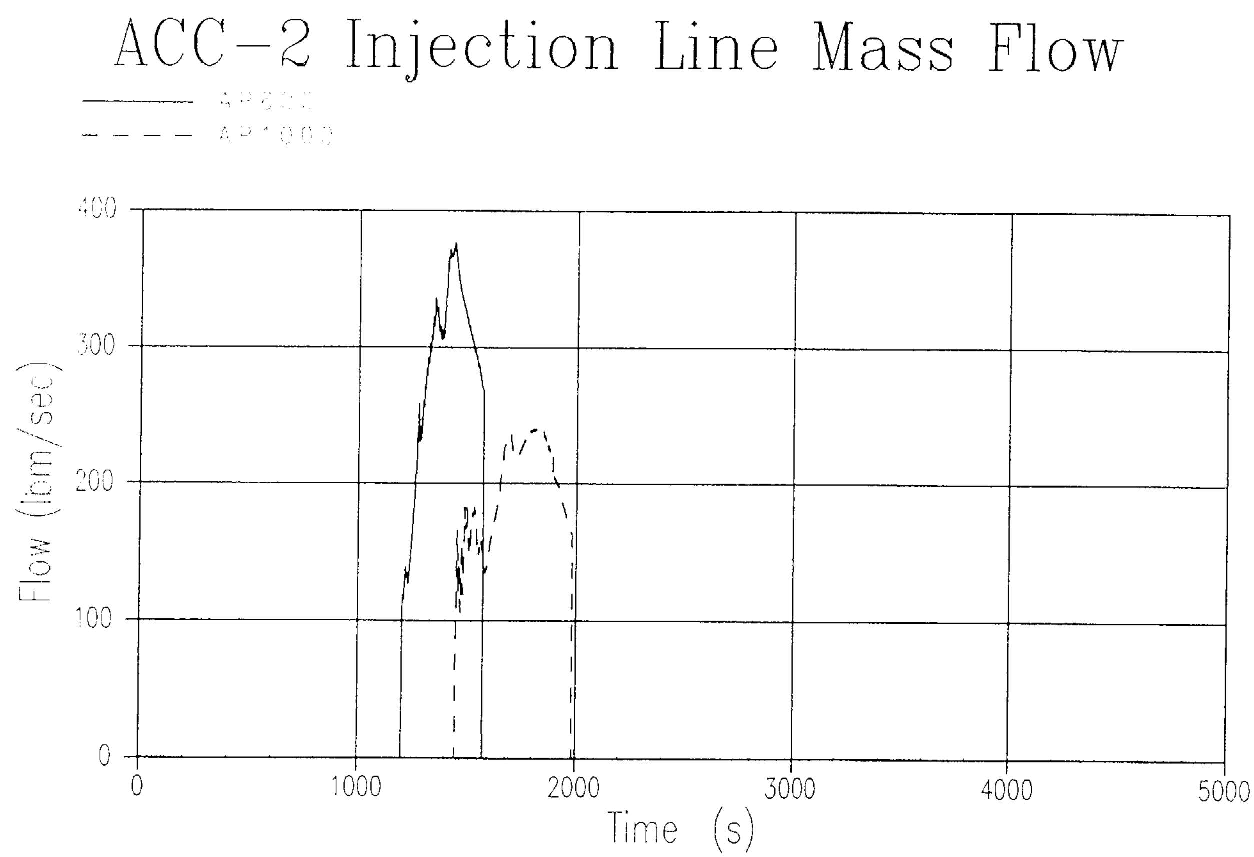
2-Inch Break Results (AP600 vs. AP1000)



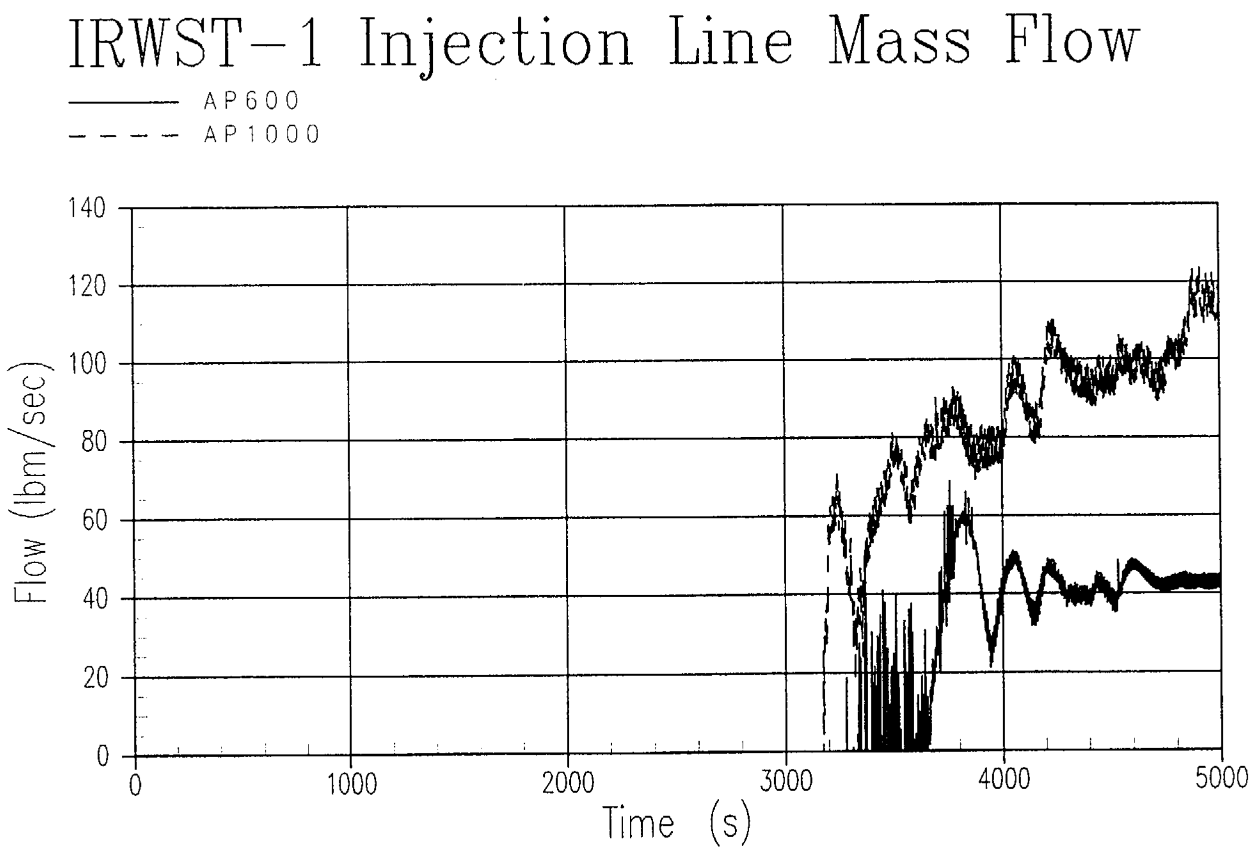
2-Inch Break Results (AP600 vs. AP1000)



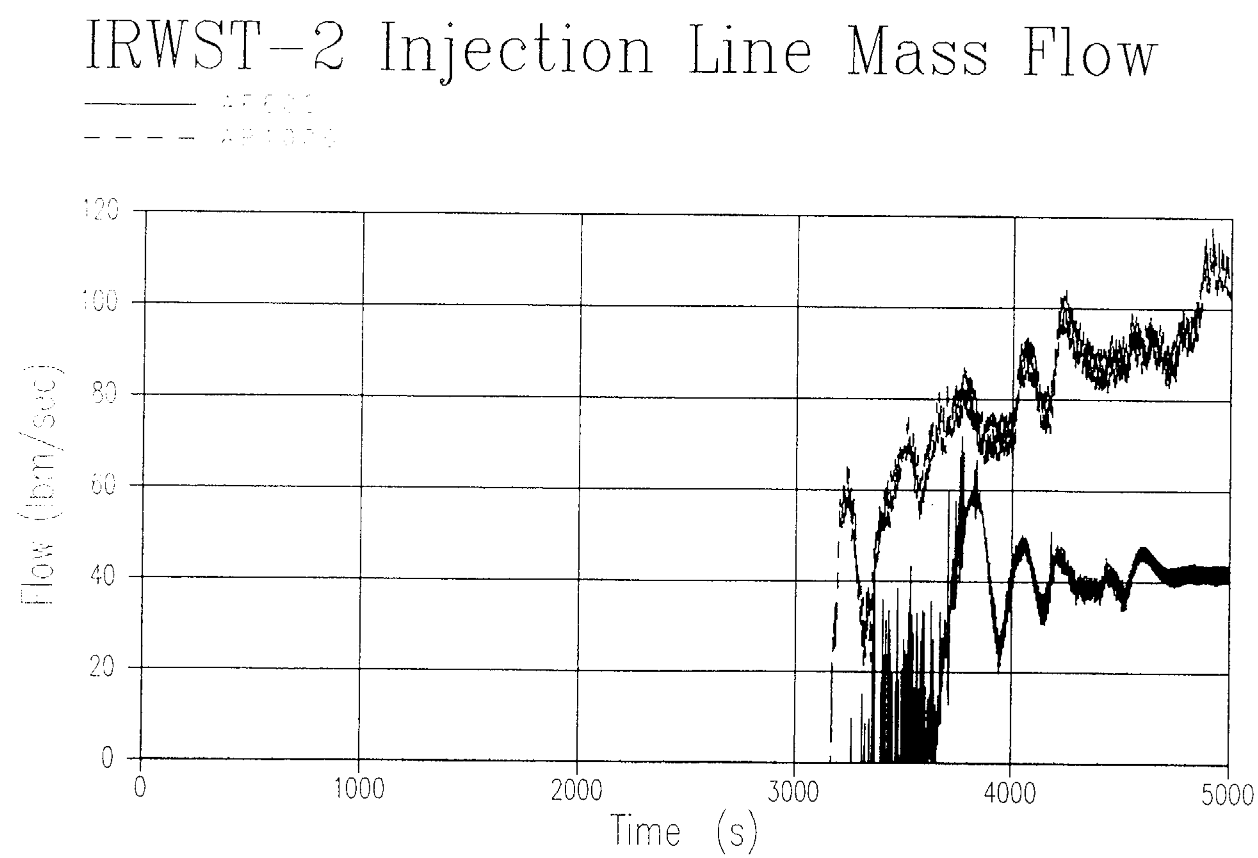
2-Inch Break Results (AP600 vs. AP1000)



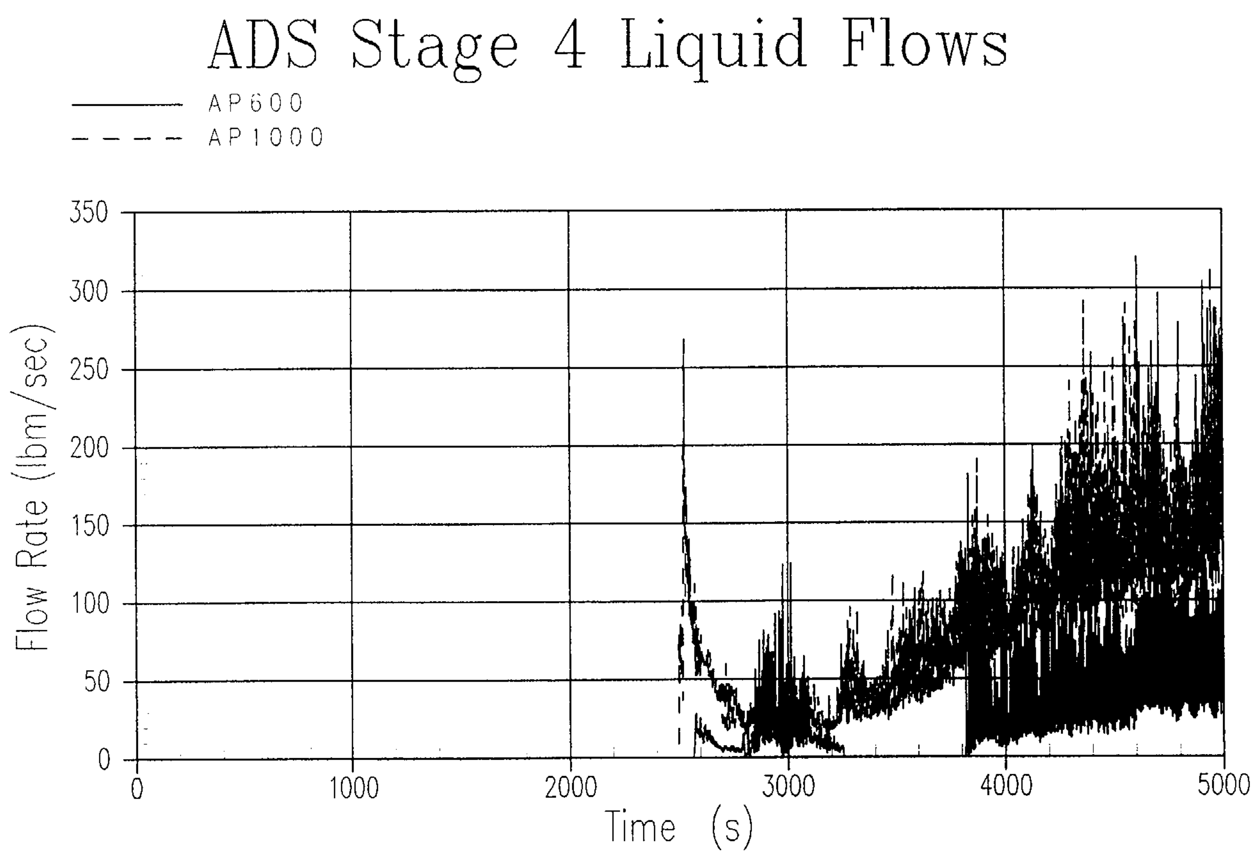
2-Inch Break Results (AP600 vs. AP1000)



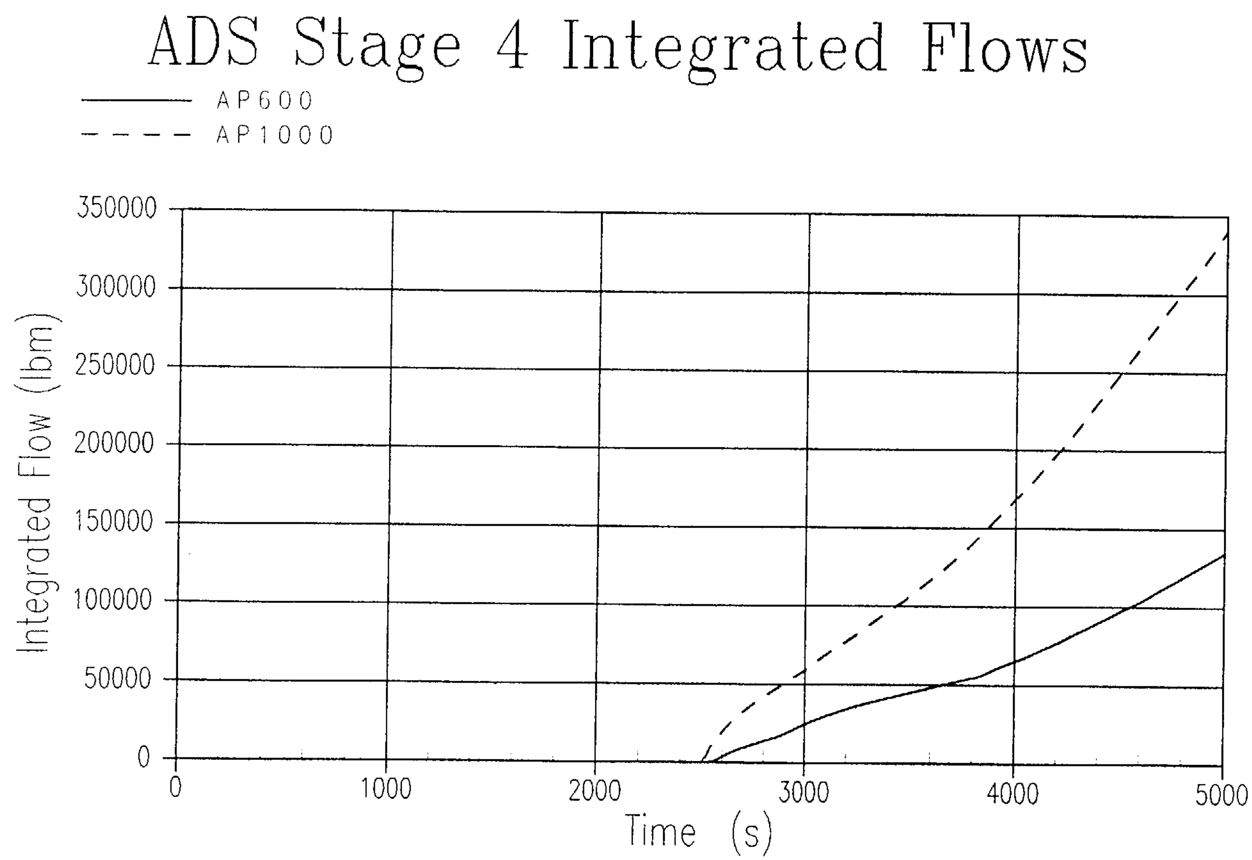
2-Inch Break Results (AP600 vs. AP1000)



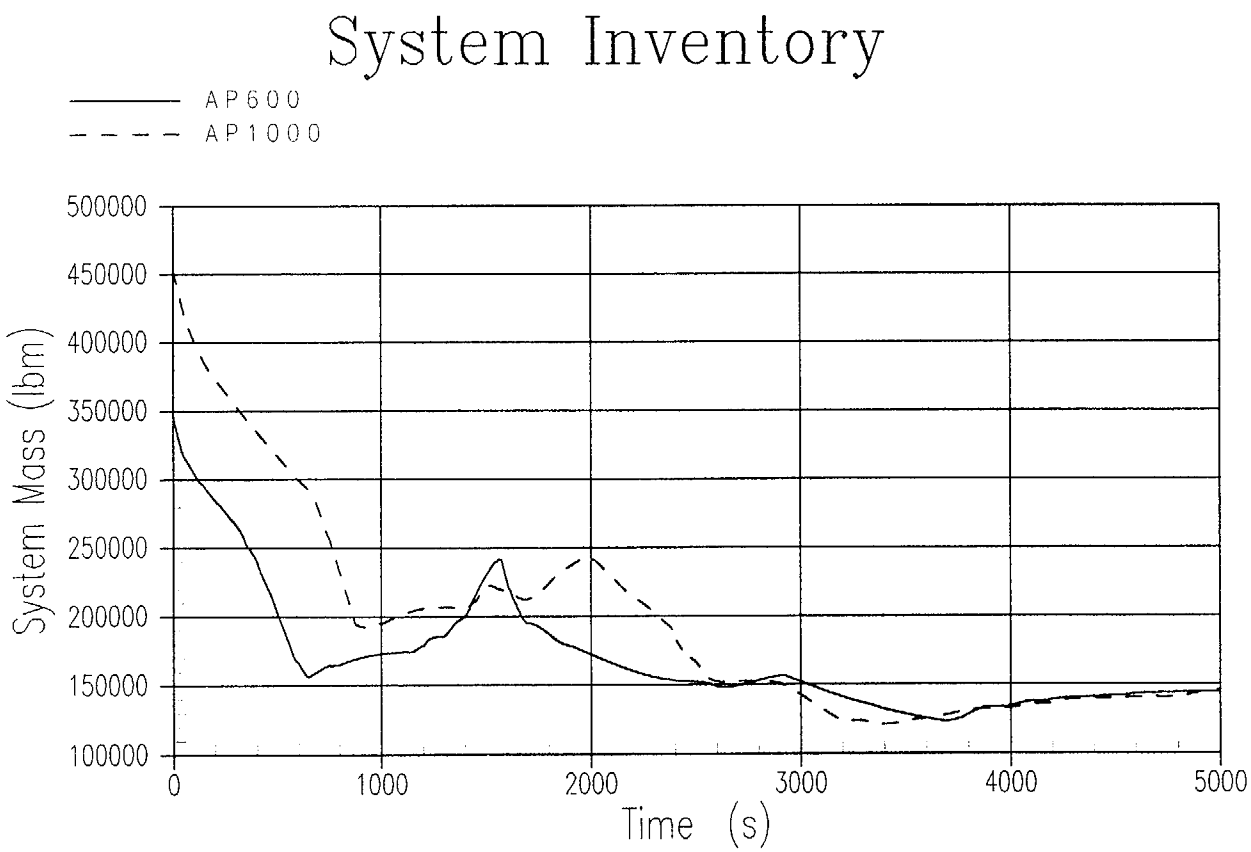
2-Inch Break Results (AP600 vs. AP1000)



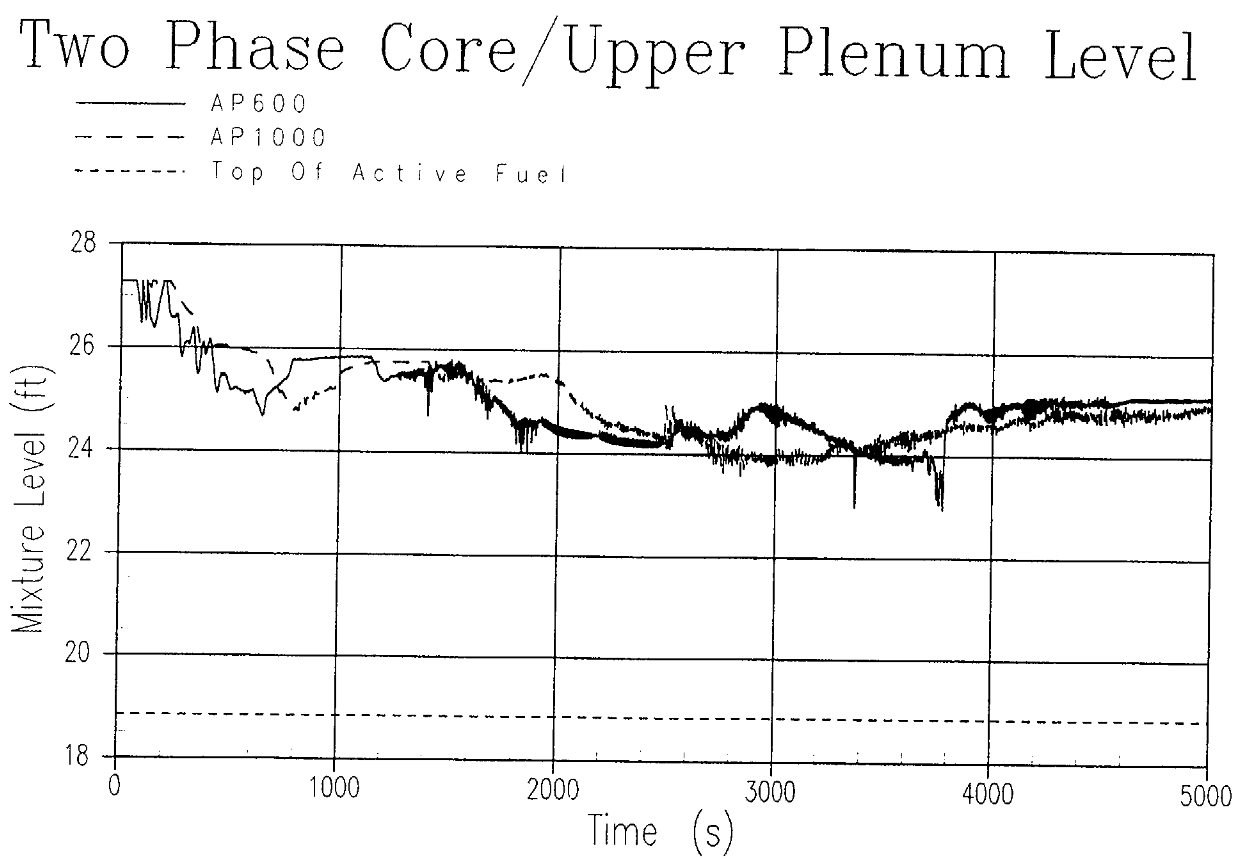
2-Inch Break Results (AP600 vs. AP1000)



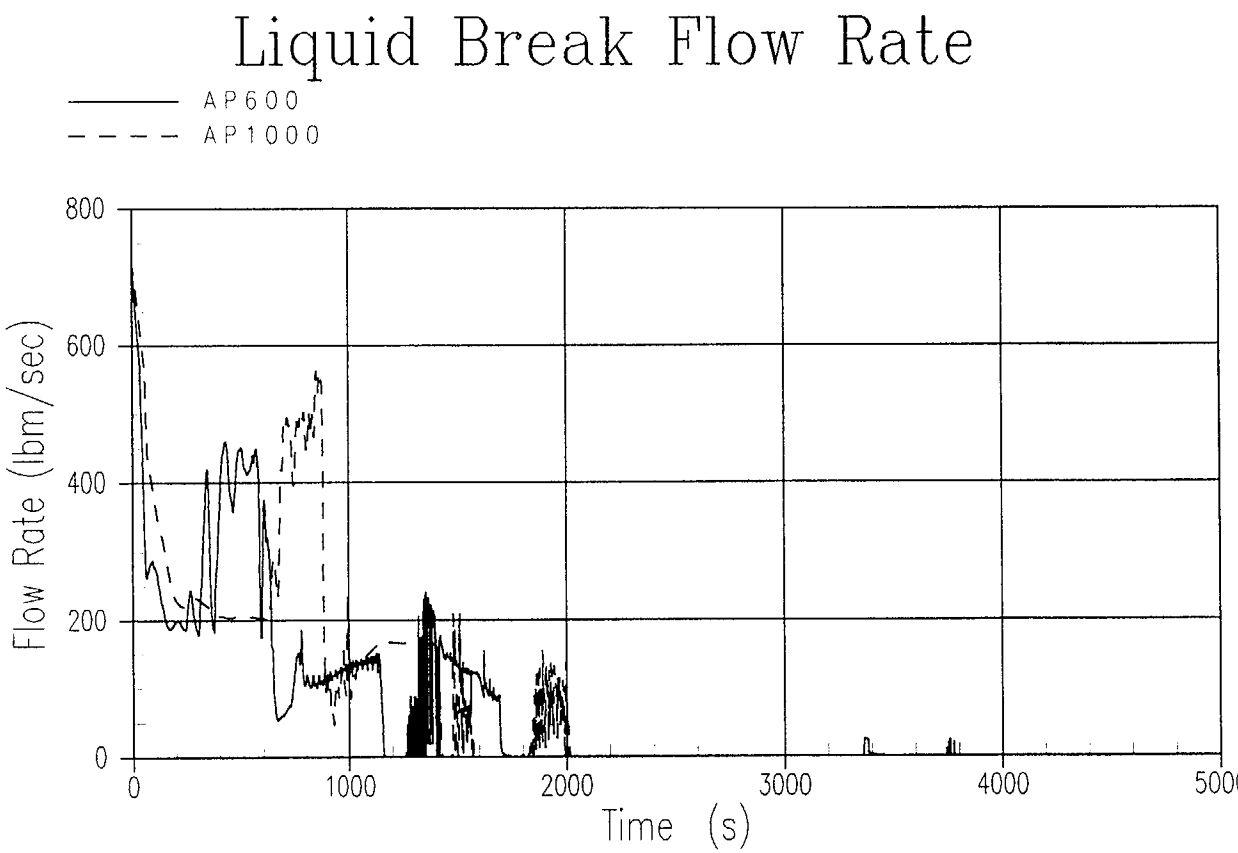
2-Inch Break Results (AP600 vs. AP1000)



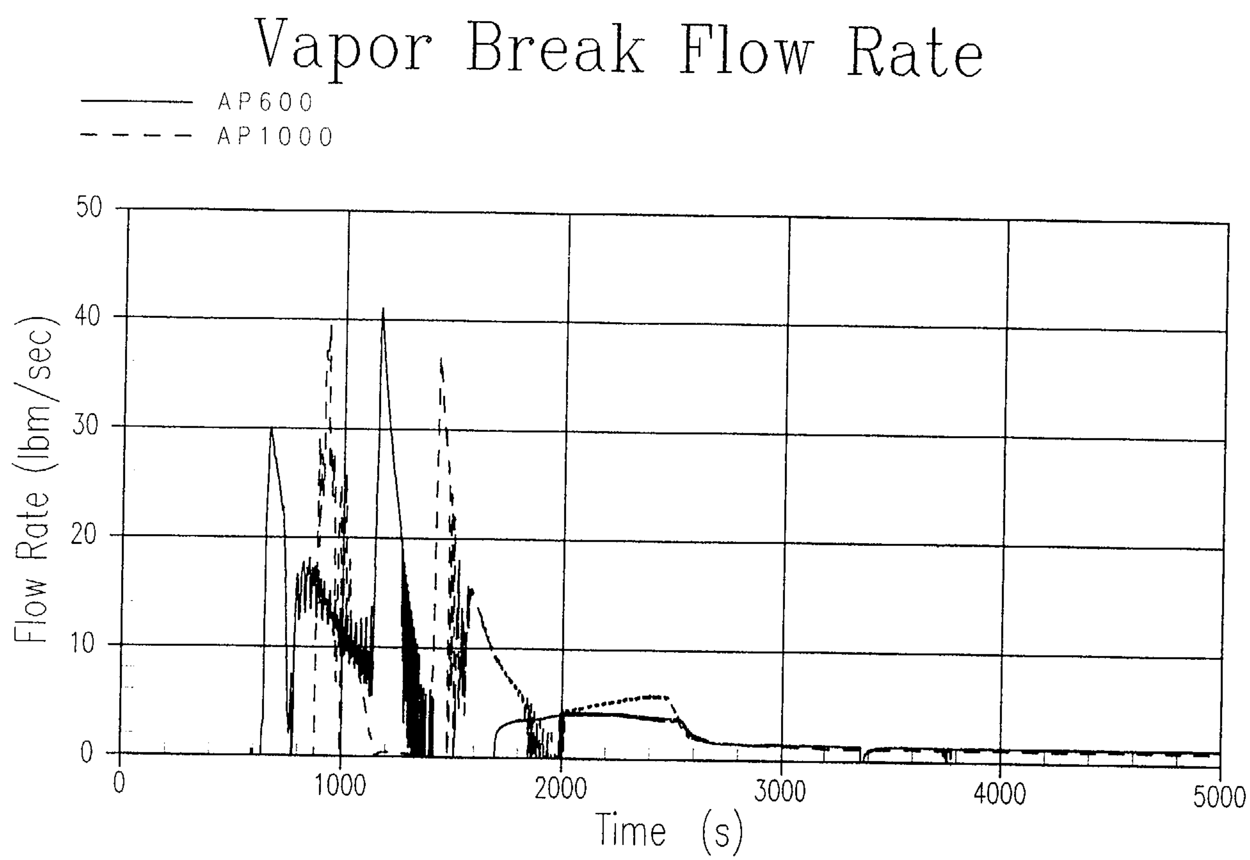
2-Inch Break Results (AP600 vs. AP1000)



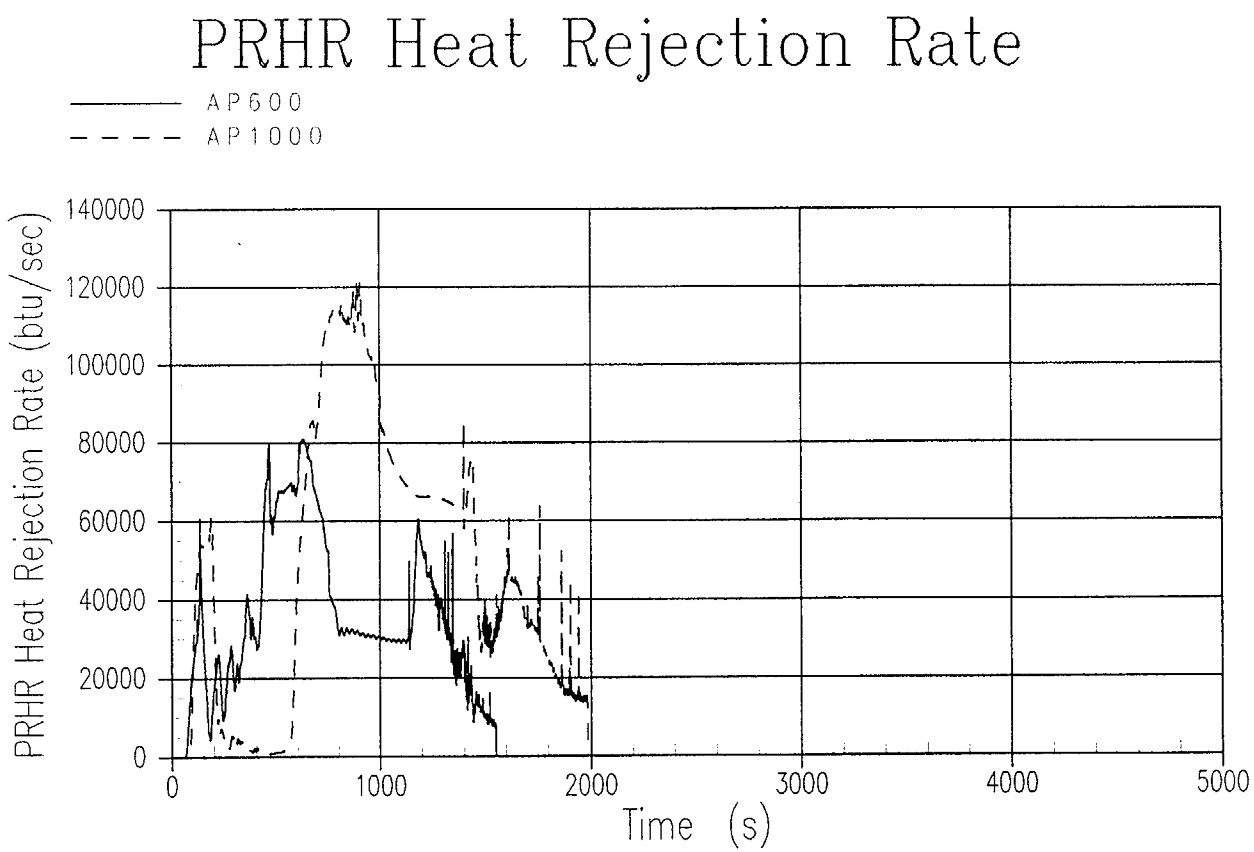
2-Inch Break Results (AP600 vs. AP1000)



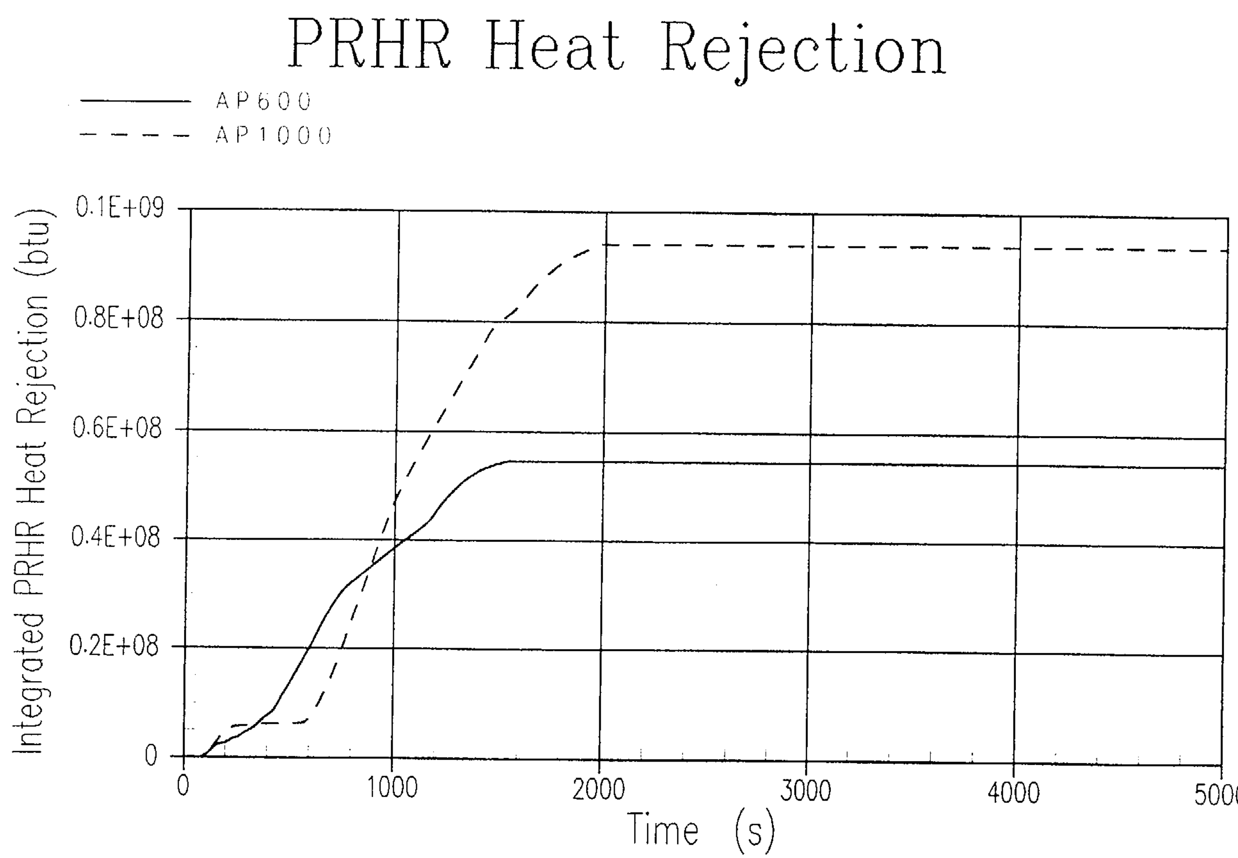
2-Inch Break Results (AP600 vs. AP1000)



2-Inch Break Results (AP600 vs. AP1000)



2-Inch Break Results (AP600 vs. AP1000)



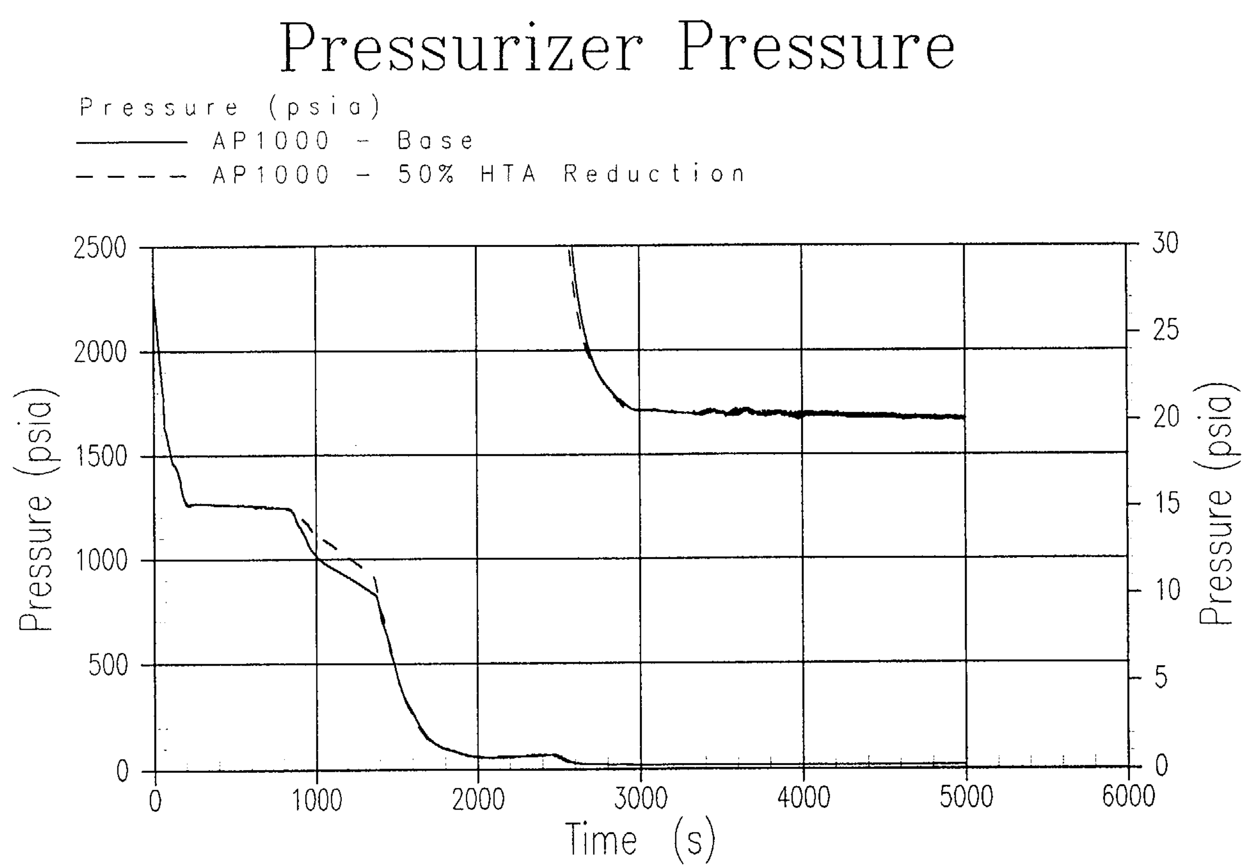
2-Inch Break Results (AP600 vs. AP1000)

- Conclusions reached from Scoping analysis effort are unchanged
  - –No core uncovery observed
  - –No new phenomena observed

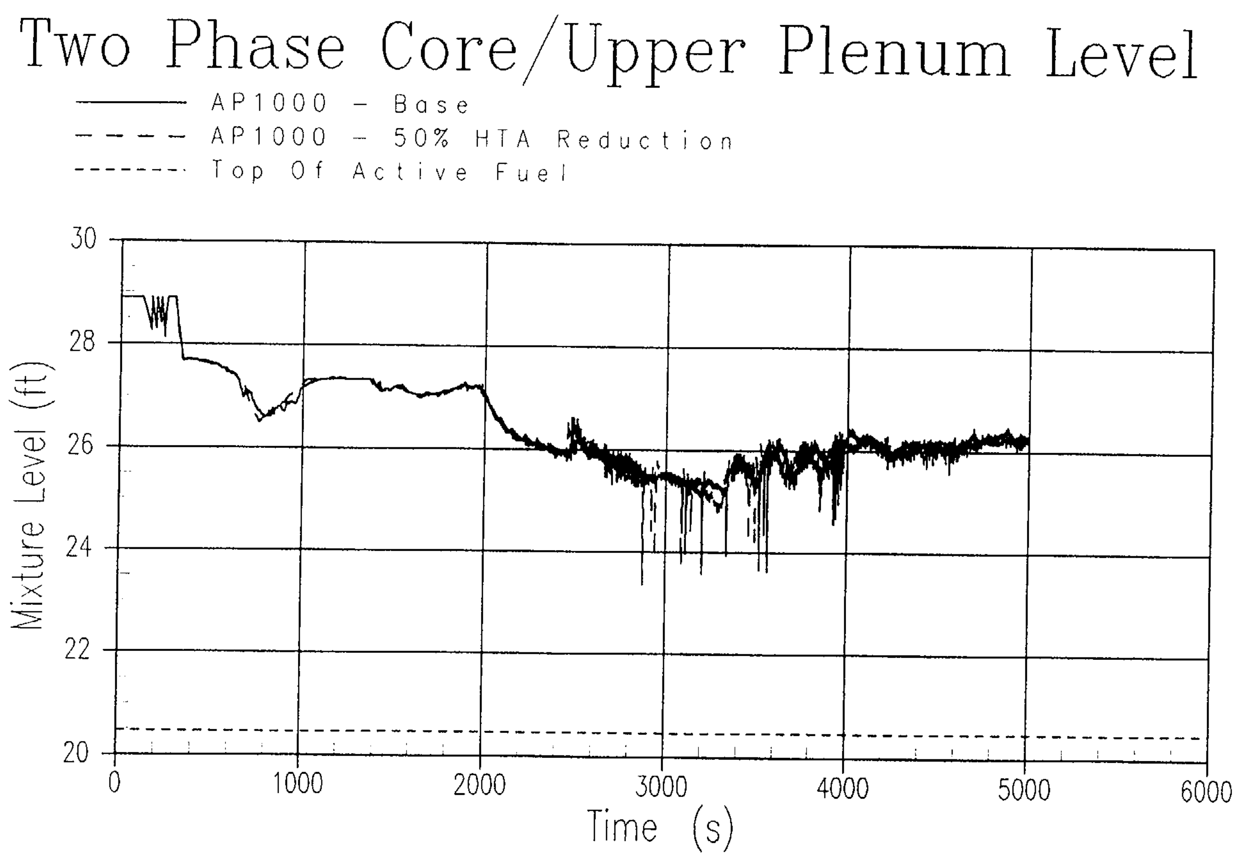
2-Inch Break Results (PRHR HT Reduction)

- Heat Transfer reduced by 50% at transient start time
  - Negligible impact observed on transient results
  - PRHR heat transfer distributed further along exchanger
- Appropriate Heat Transfer area reduction will be justified and implemented in SAR calculations

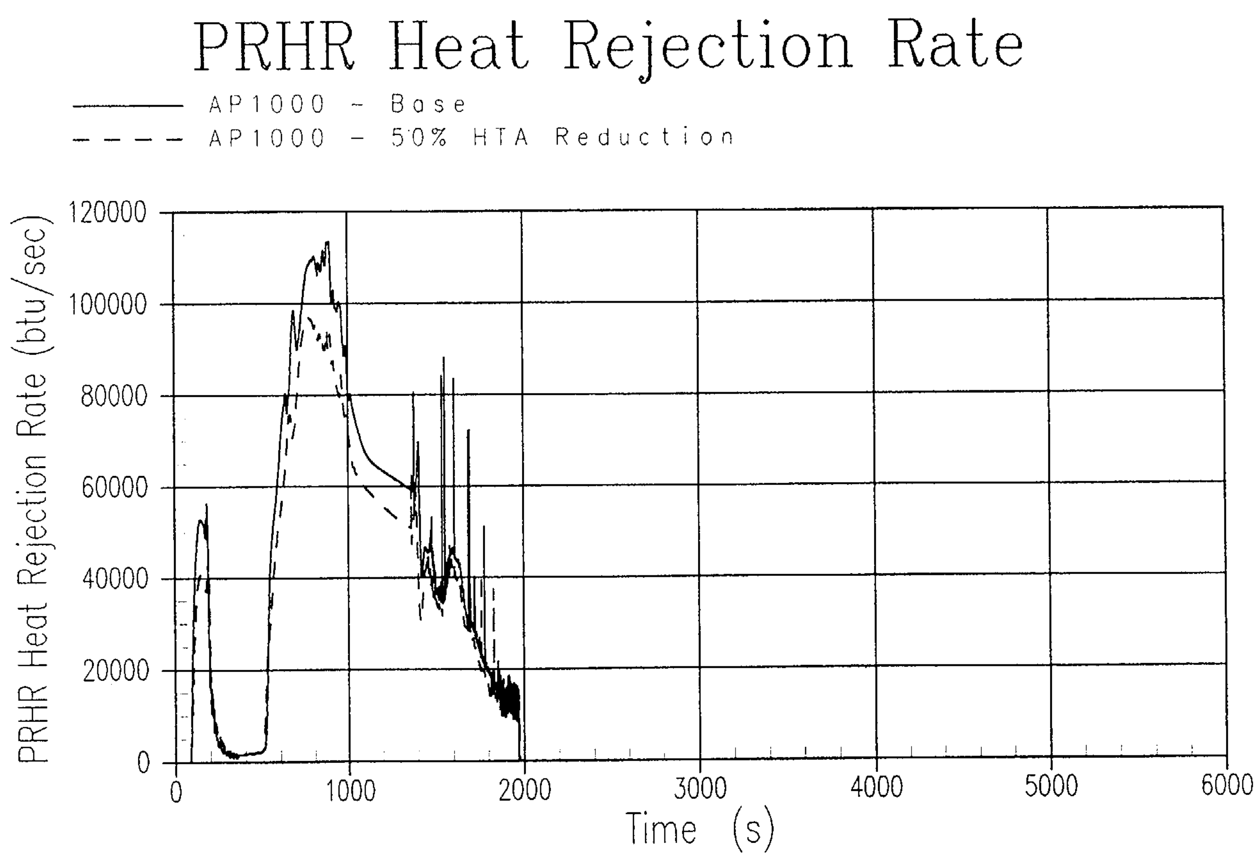
2-Inch Break Results (PRHR HT Reduction)



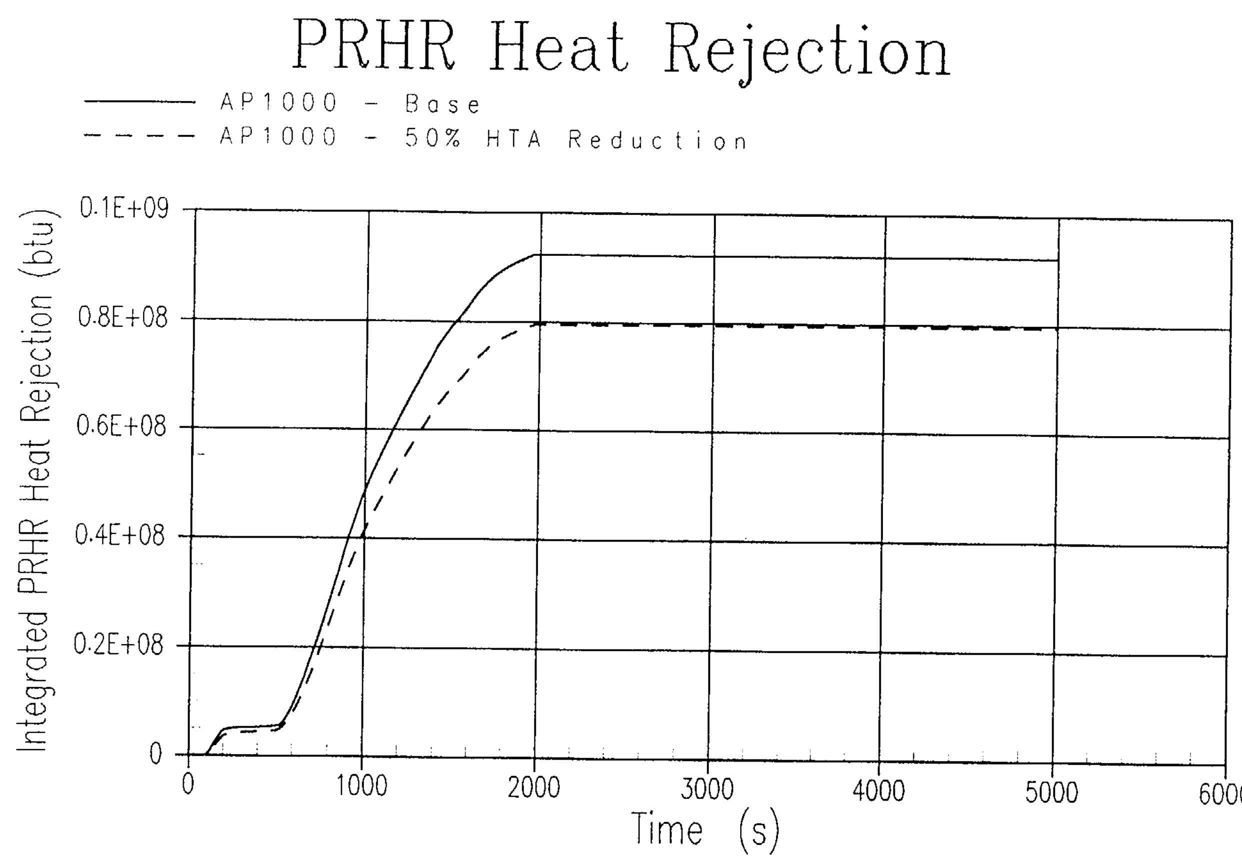
2-Inch Break Results (PRHR HT Reduction)



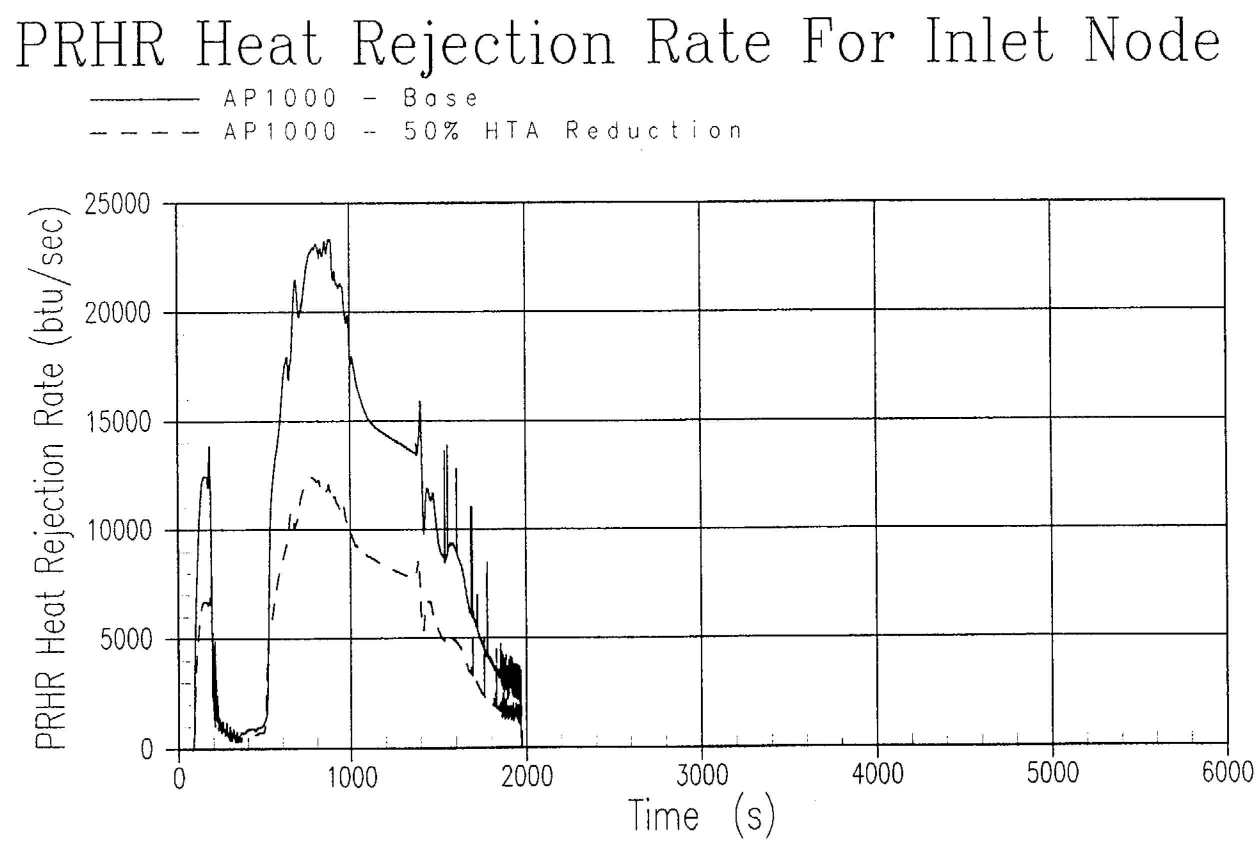
2-Inch Break Results (PRHR HT Reduction)



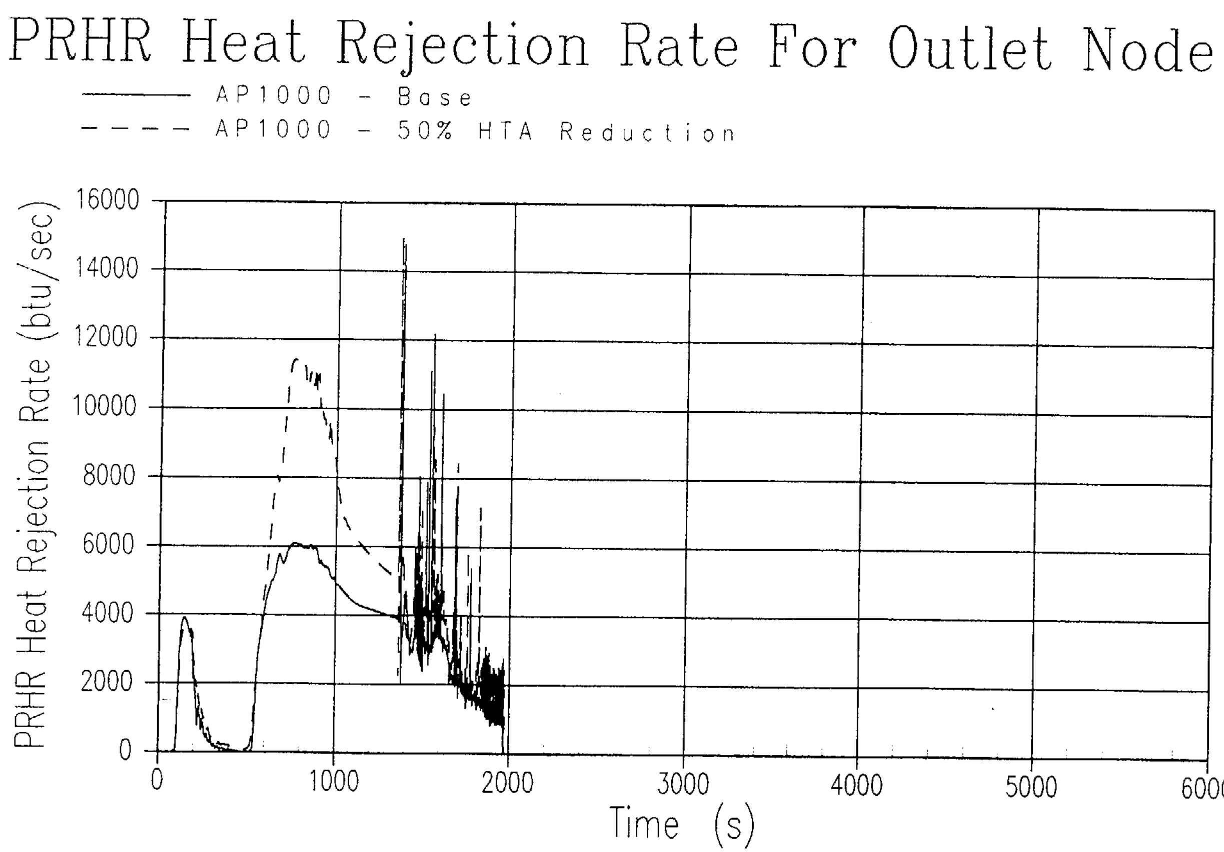
2-Inch Break Results (PRHR HT Reduction)



2-Inch Break Results (PRHR HT Reduction)



2-Inch Break Results (PRHR HT Reduction)



AP1000 SBLOCA Conclusions

- Entrainment
  - Westinghouse will benchmark WCOBRA/TRAC to adjust NOTRUMP model
- PRHR Heat Transfer
  - Westinghouse will justify and implement PRHR Heat Transfer area reduction as required
- Core Heat Transfer
  - In the event of core uncovery, Westinghouse will provide documentation of the NOTRUMP core heat transfer package and SBLOCTA code

AP1000 Issued Raised by ACRS

AP1000 Issues Raised by ACRS

Background

- ACRS wrote two letters related to AP1000 prior to any formal presentations
  - –Many issues related to phase 3 (Design Certification)
- W made presentations to T/H Subcommittee and Full ACRS in March & April 2001
  - –Most issues addressed in our Phase 2 review
  - –Some issues not explicitly addressed

AP1000 Issues Raised by ACRS

- Scope of additional analyses needed for the SSAR
  - –W will provide a similar scope as was provided for AP1000
    - –May use AP600 insights where applicable
      - –Mostly a phase 3 issue
    - –Additional W/COBRA-TRAC provided to supplement NOTRUMP analysis

- Applicability of NOTRUMP
  - –Explicitly addressed in our submittals & RAI responses

AP1000 Issues Raised by ACRS

- Scalability of Existing T/H Test Facilities
  - –Explicitly addressed in Phase 2
    - –PIRT & Scaling Report
    - –Response to RAI:
      - –Supplemental OSU / SPES Scaling
      - –ROSA Scaling

AP1000 Issues Raised by ACRS

- Staff Should Obtain and Exercise Codes
  - For codes approved codes for AP600:
    - Staff reviewed AP1000 Code Applicability Report and AP1000 Code Manuals
  - Staff performed independent analyses
  - For new codes required, W will make the code available to the staff as part of Design Certification Review

- Flow Regimes in ADS-4 / Hot Leg Vent Paths
  - Not explicitly addressed in the review - See Presentation Material

AP1000 Issues Raised by ACRS

- Treatment of entrainment
  - –ADS-4 / Hot leg

- Homogeneous treatment of 2-phase flow
  - –Scaling low pressure phases of SBLOCA
  - –Not explicitly addressed
  - –See Presentation Material

AP1000 Issues Raised by ACRS

- Mixing in containment
  - W presented 2-D CFD analysis results to demonstrate air-mixing unaffected by additional height of AP1000 containmemt
  - Dr. Wallis requested 3-D CFD analysis
  - See Presentation Material