The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

IAEA International Atomic Energy Agency

SMR/1848-T09

Course on Natural Circulation Phenomena and Modelling in Water-Cooled Nuclear Reactors

25 - 29 June 2007

T09 - AP600 and AP1000 Passive Safety System Design & Testing in APEX

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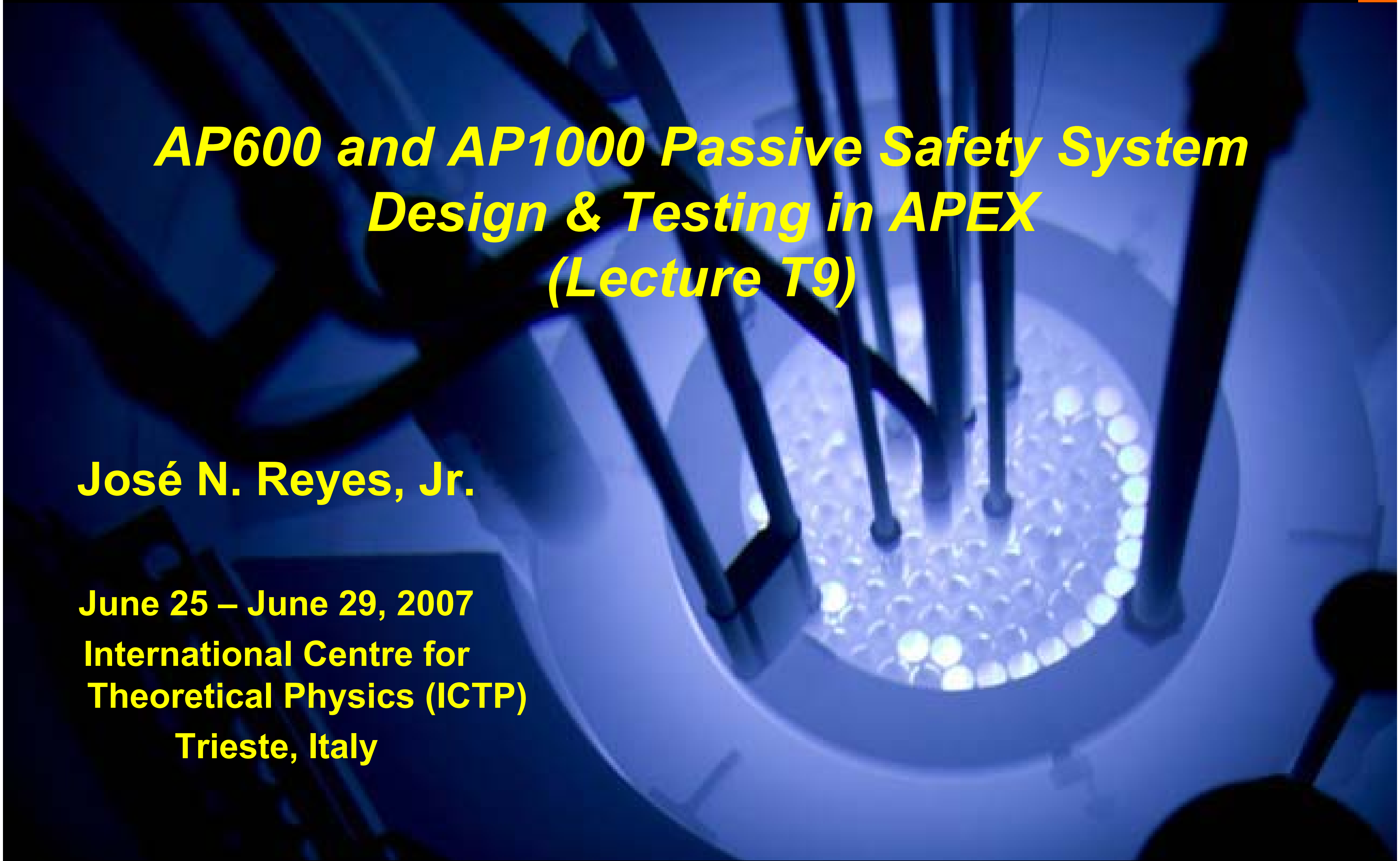


AP600 and AP1000 Passive Safety System Design & Testing in APEX (Lecture T9)

José N. Reyes, Jr.

June 25 – June 29, 2007

International Centre for Theoretical Physics (ICTP)

Trieste, Italy

Course Roadmap

Opening Session

- INTRODUCTIONS
- ADMINISTRATION
- COURSE ROADMAP

Introduction

- GLOBAL NUCLEAR POWER
- ROLE OF N/C ADVANCED DESIGNS
- ADVANTAGES AND CHALLENGES

Local Transport Phenomena & Models

- LOCAL MASS, MOMENTUM AND ENERGY TRANSPORT PHENOMENA
- PREDICTIVE MODELS & CORRELATIONS

Integral System Phenomena & Models

- SYSTEMS MASS, MOMENTUM AND ENERGY TRANSPORT PHENOMENA
- N/C STABILITY AND NUMERICAL TECHNIQUES
- STABILITY ANALYSIS TOOLS
- PASSIVE SAFETY SYSTEM DESIGN

Natural Circulation Experiemnts

- INTEGRAL SYSTEMS TESTS
- SEPARATE EFFECTS TESTS
- TEST FACILITY SCALING METHODS

Reliability & Advanced Computational Methods

- PASSIVE SYSTEM RELIABILITY
- CFD FOR NATURAL CIRCULATION FLOWS

Lecture Objectives

- To describe the integral operation of the AP600/AP1000 passive safety systems.
- To understand the methods used to:
  - Calculate and scale injection flow rates for gravity drain tanks and pressurized tanks,
  - Estimate depressurization flow rates for an ADS system.

Outline

- The Evolution of Nuclear Power
  - Passive Safety
- The AP600/AP1000 Designs
- Passive Safety Injection System Design
  - Governing equations
  - CMTs and IRWST
  - Accumulators
- Primary System Depressurization (ADS)
- APEX Test Facility at OSU
  - Comparison of Test Facility Results
- Conclusions

The Advanced Passive 600 and 1000 MW(e) Plants in the Evolution of Nuclear Power [1,2]

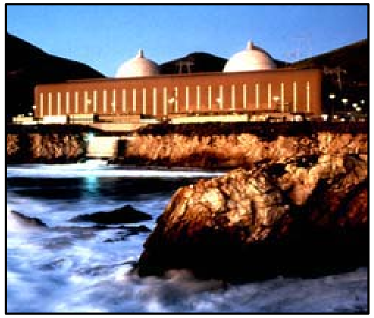
Generation I

Early Prototype Reactors

- Shippingport
- Dresden
- Fermi I
- Magnox

Generation II

Commercial Power Reactors



- LWR-PWR, BWR
- CANDU
- VVER/RBMK

Generation III

Advanced LWRs

- ABWR
- System 80+
- **AP600**
- EPR

Generation III+

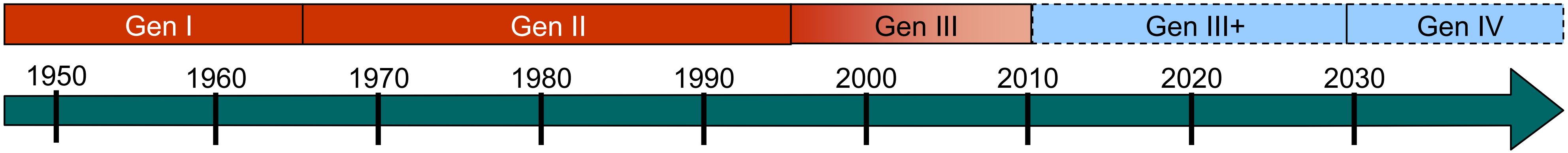
Near-Term Deployment

- **AP1000**
- PBMR
- SWR-1000
- ABWR-II

Evolutionary Designs Offering Improved Economics

Generation IV

- Highly Economical
- Enhanced Safety
- Minimal Waste
- Proliferation Resistant



1. *U.S. Department of Energy Gen-IV Roadmap Report*
2. *Only lists a few examples, others include APR-1400, WWER-1000, EPR*

Introduction to Passive Safety in Nuclear Power Plants

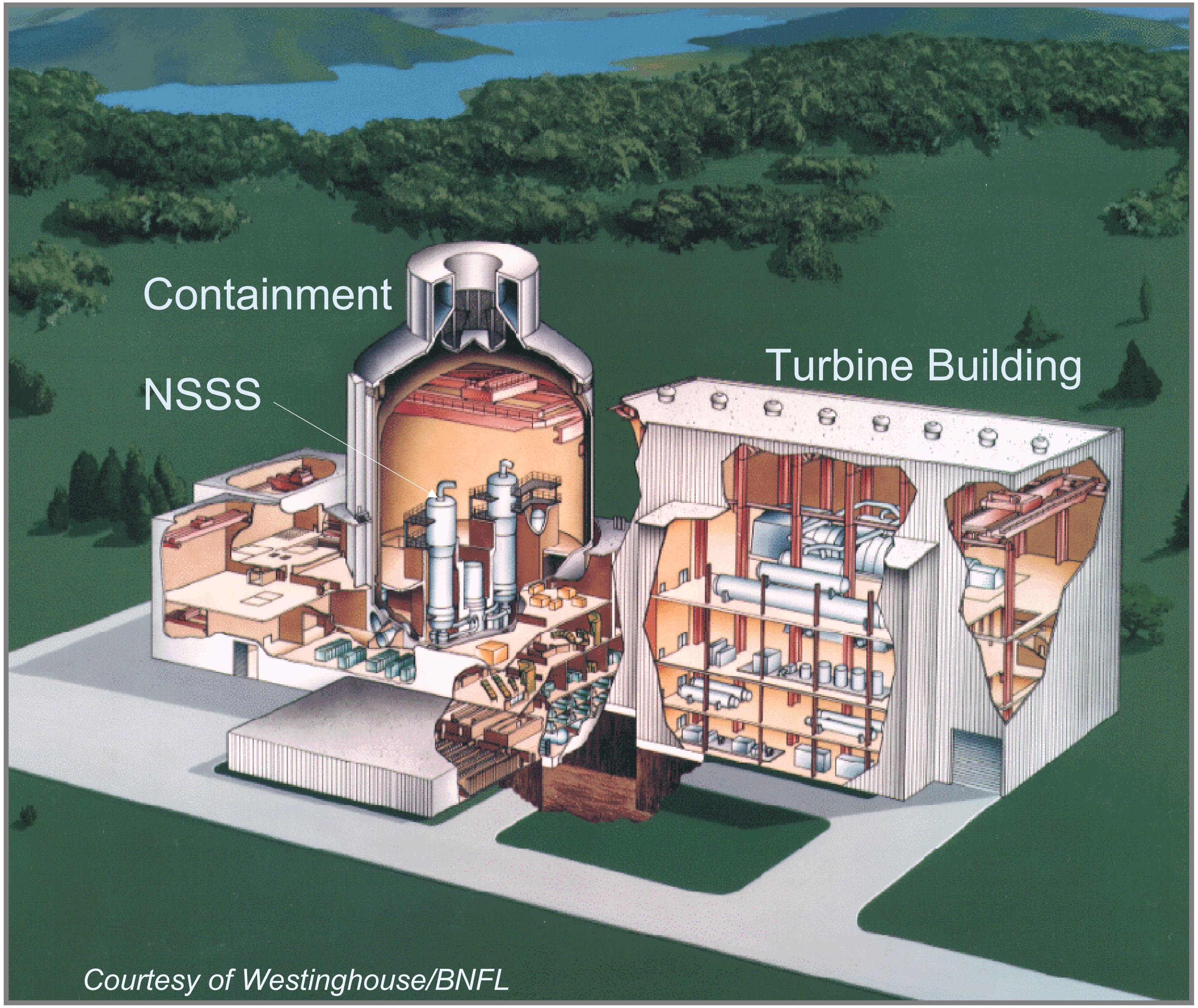
- What is Passive Safety?
  - A passive safety system* provides cooling to the nuclear core or containment using processes such as:
    - Natural convection heat transfer
    - Vapor condensation
    - Liquid evaporation
    - Pressure driven coolant injection, or
    - Gravity driven coolant injection.
  - It does not rely on external mechanical and/or electrical power, signals or forces such as electric pumps.
  - To obtain design certification in the U.S. as a passively safe nuclear plant, the designer must demonstrate that under worst case accident conditions the plant can be passively cooled without external power or operator actions for a *minimum of 3 days*.

**IAEA-TECDOC-626*

Goals of Using Passive Safety Systems

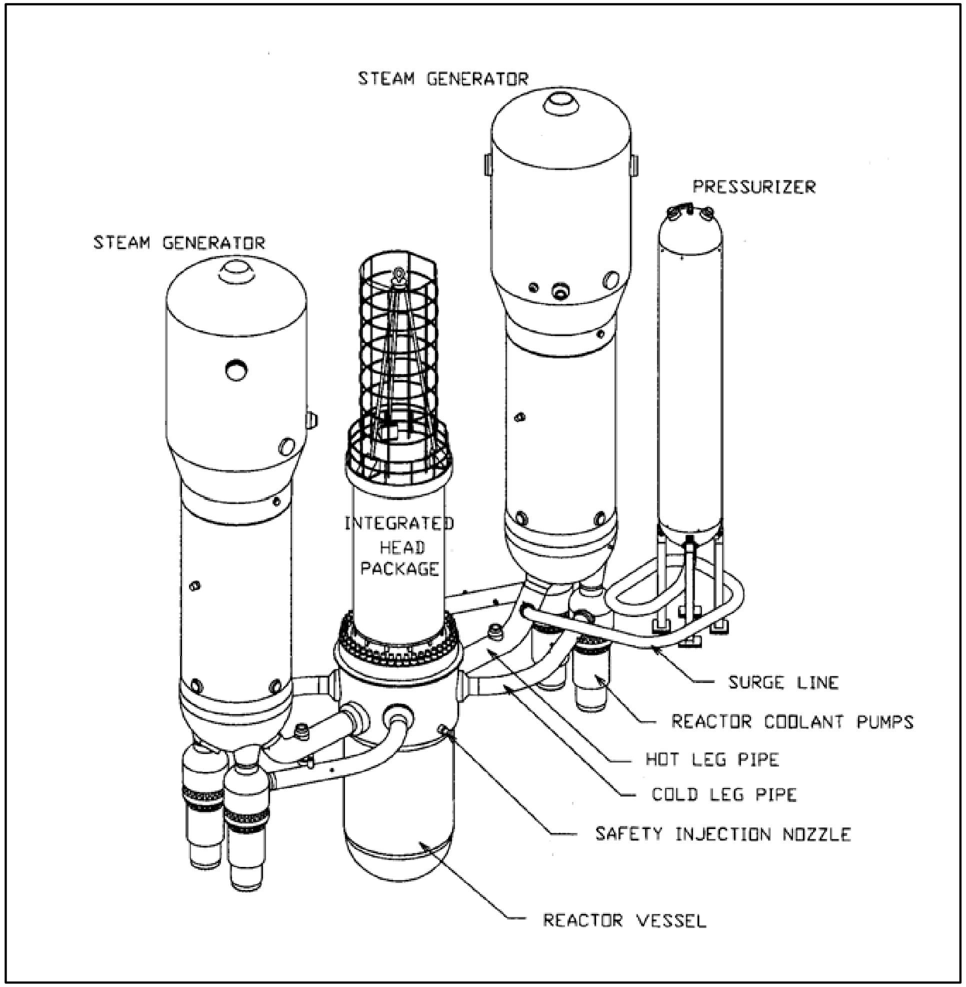
- To improve reliability and safety.
- To reduce construction and operating costs by eliminating or reducing safety grade pumps, power supplies, and associated piping, valves, and structures.
- The Westinghouse BNFL AP600 is the first, and currently the only, U.S. design to be certified as passively safe.
- The AP1000 incorporates the same passive safety system design at a higher power and is currently under Design Certification review.

Description of the AP600 and AP1000 Designs



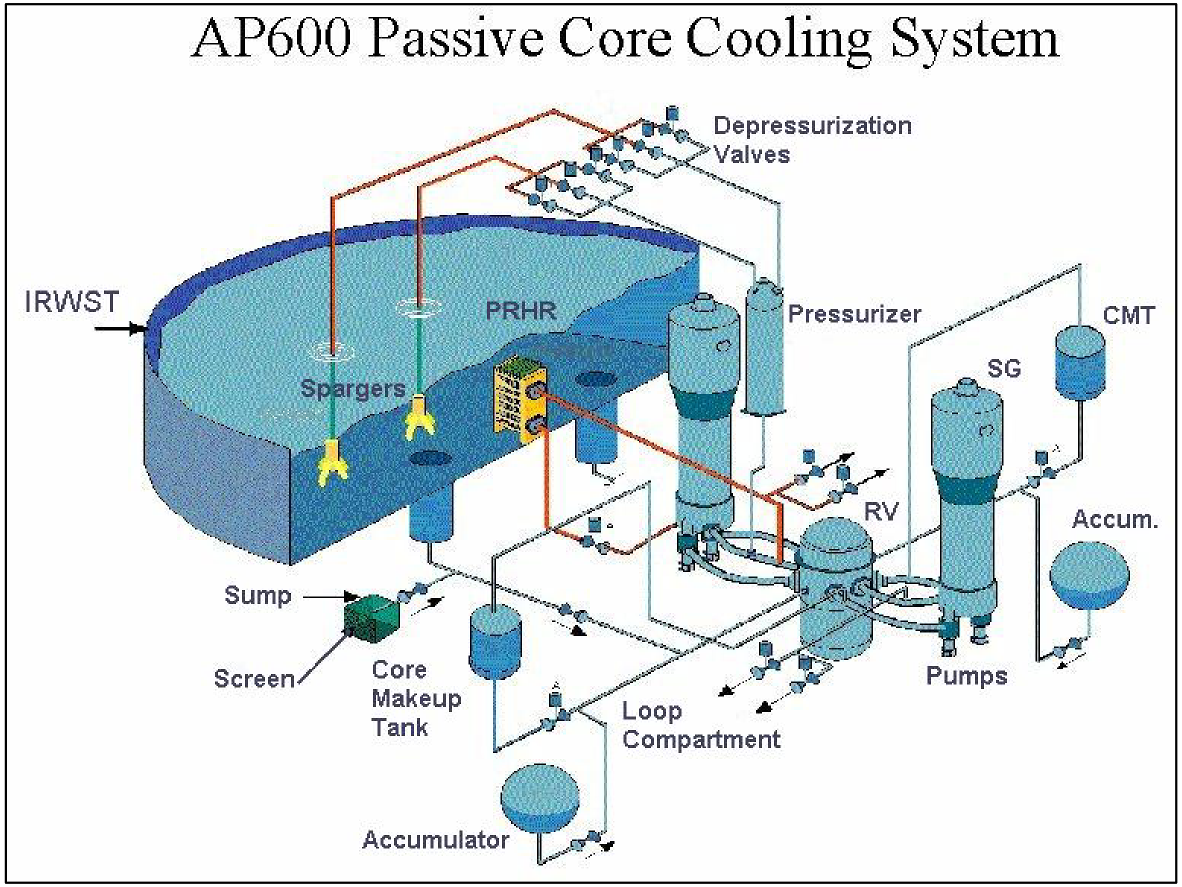
AP600/AP1000 NSSS

- Reactor Vessel
- 2x4 Loop Configuration
- 2 Steam Generators
- 4 Reactor Coolant Pumps
- Pressurizer

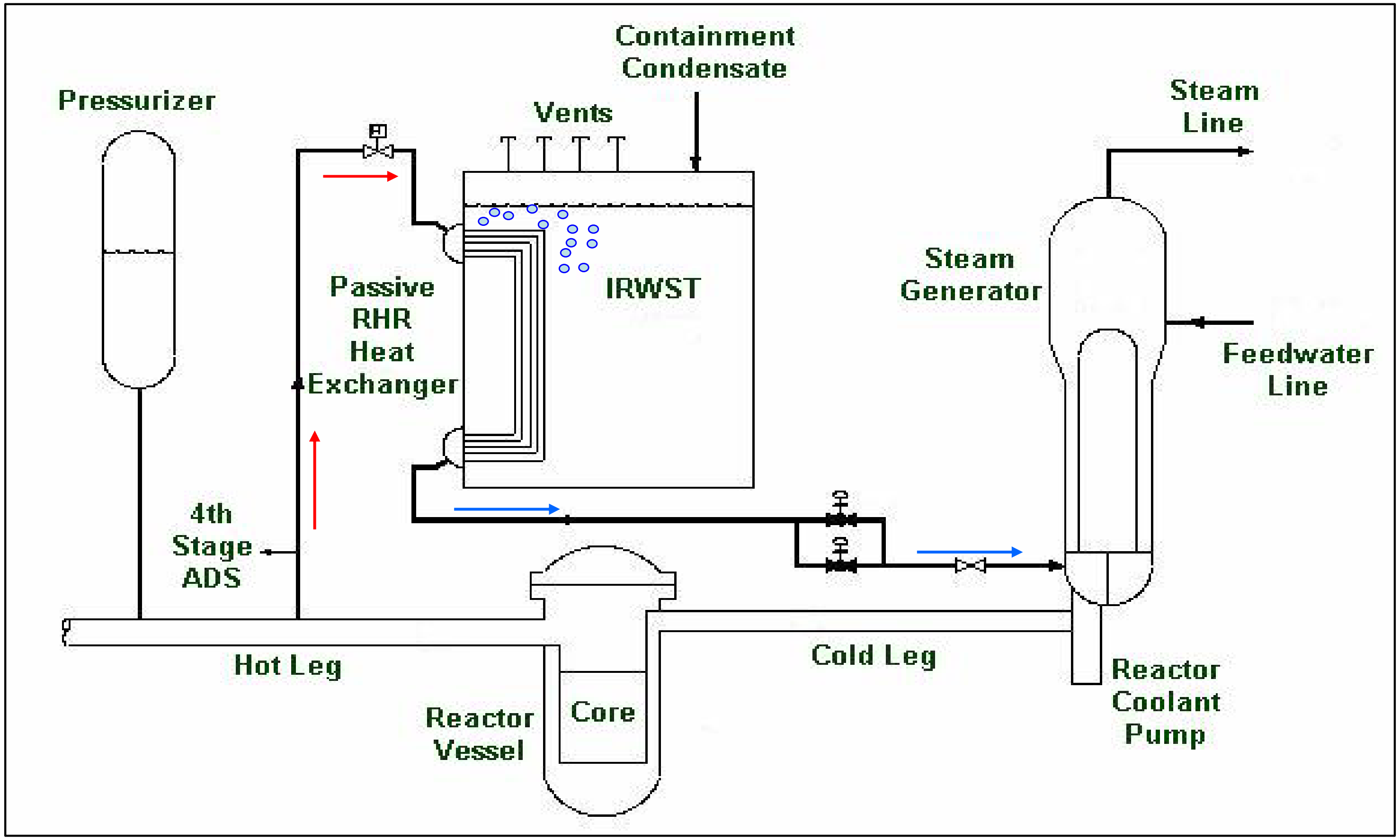


AP600/AP1000 Passive Safety Systems

- Passive Residual Heat Removal (PRHR) System
- Core Make-up Tanks (CMTs)
- Automatic Depressurization System (ADS)
- Accumulator Tanks
- In-containment Refueling Water Storage Tank, (IRWST)
- Lower Containment Sump

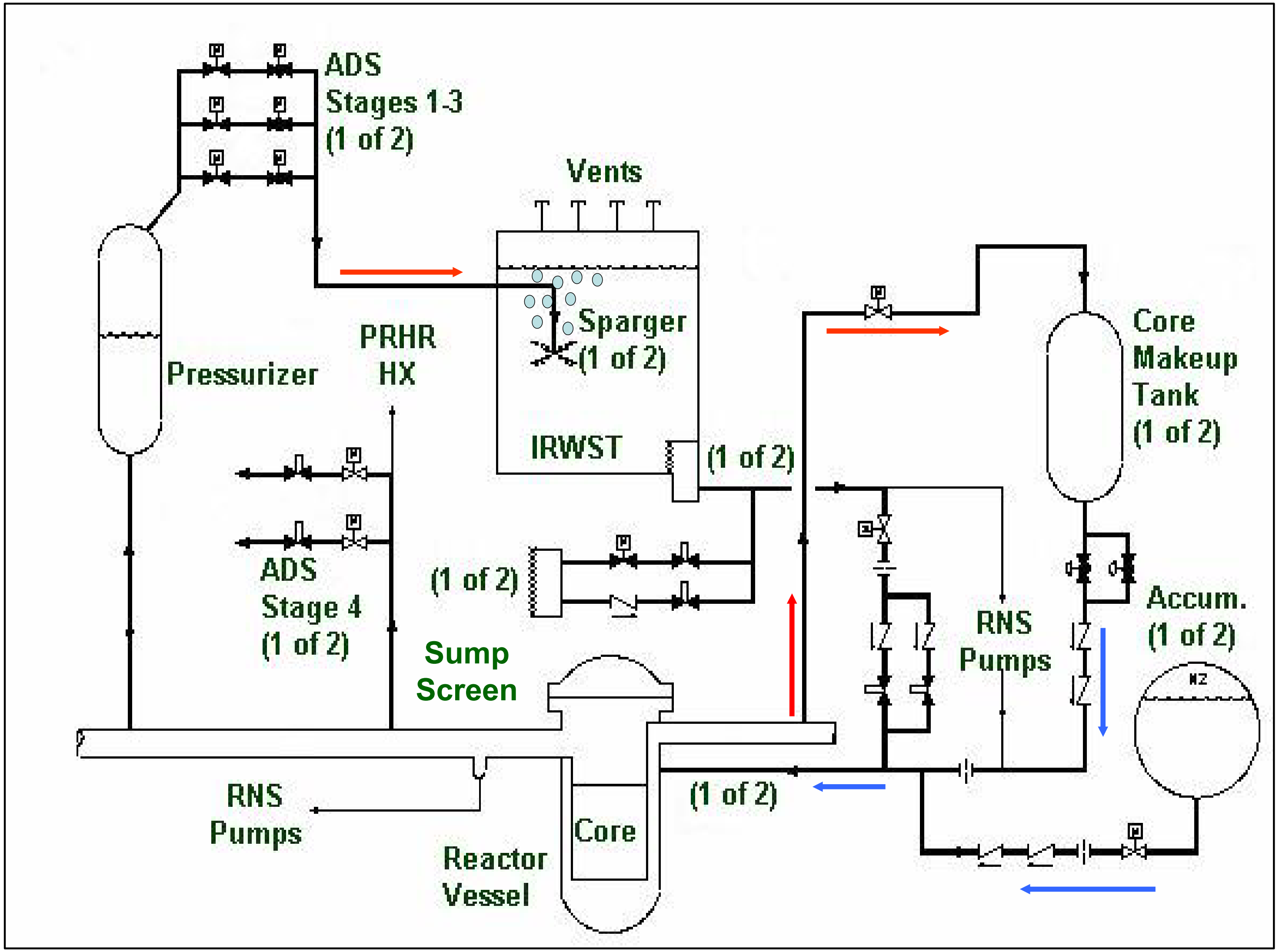


Passive Residual Heat Removal (PRHR) System

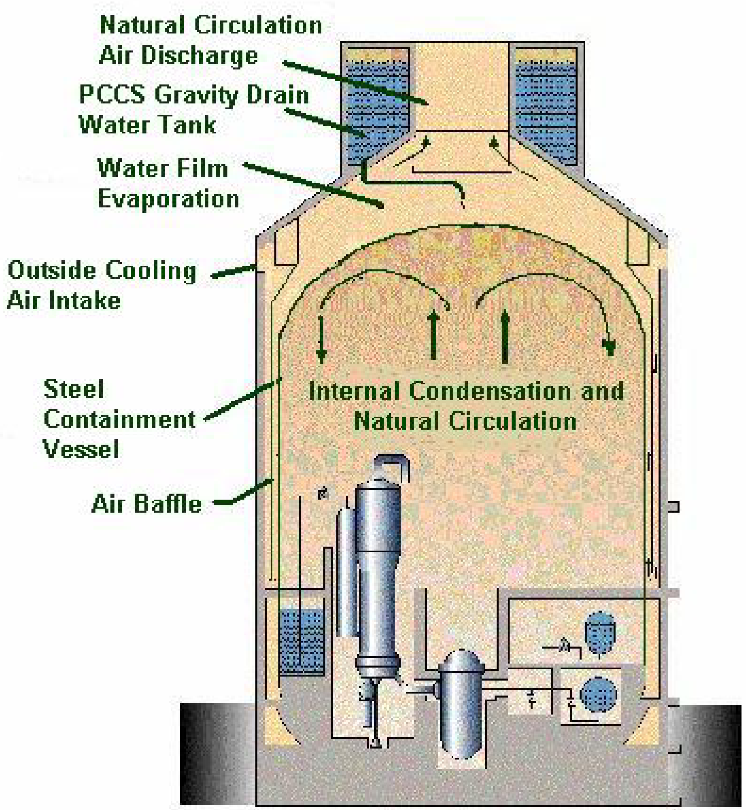


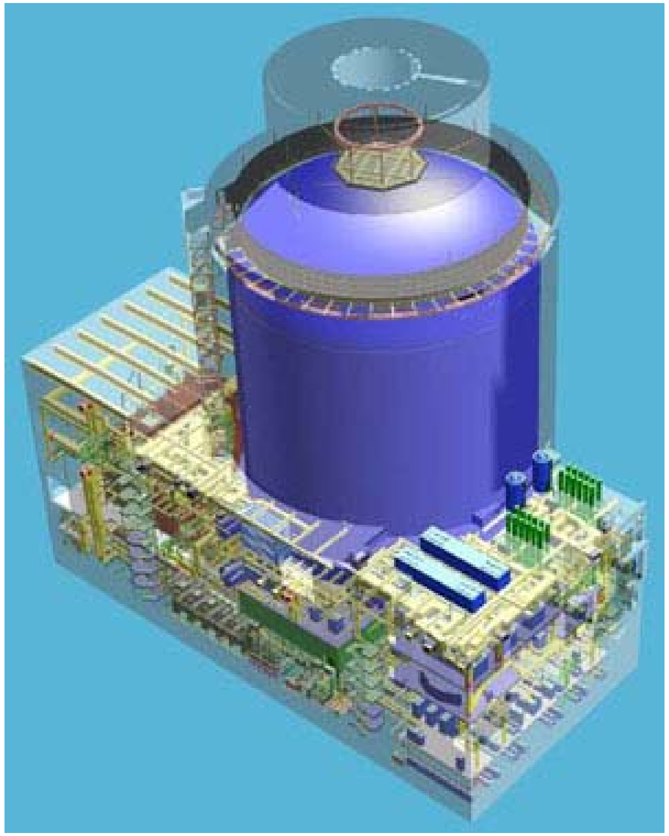
- Actuates on Low PZR Pressure or Level
- Station Blackout

Passive Safety Injection



AP600/AP1000 Containment Passive Cooling System





- A steel containment shell serves as an ultimate barrier to fission product release and removes decay heat by steam condensation and natural convection.
- The containment exterior is wetted to improve heat transfer during the early phase of an accident.
- Air cooling is sufficient for long term cooling.

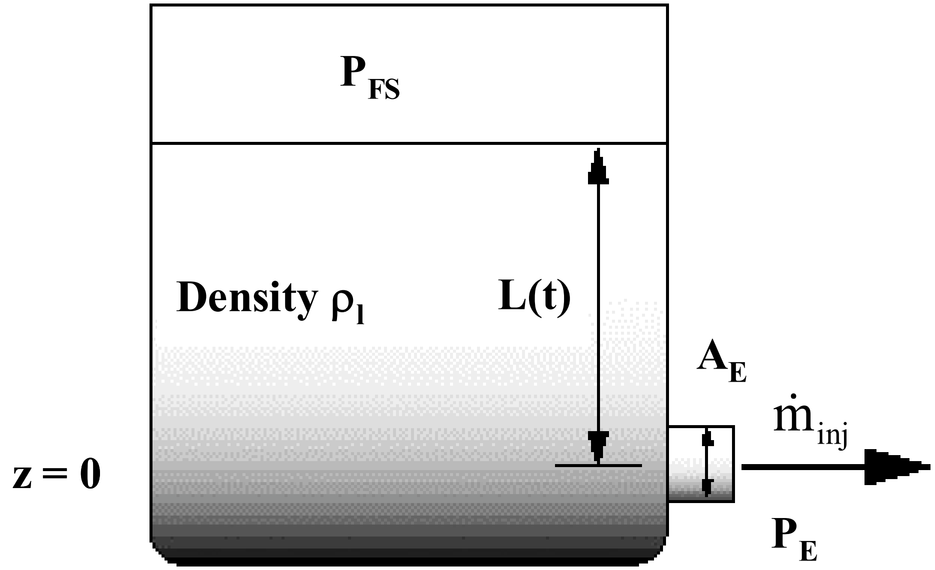
PASSIVE SAFETY INJECTION SYSTEM DESIGN

- Two Types of Passive Safety Injection Systems
  - The CMT and IRWST are filled with cold borated water and drain into the reactor vessel by gravity.
  - The Accumulators are also filled with cold borated water. However, they are pressurized with Nitrogen to provide high pressure fluid injection into the reactor vessel.
- Simple models can used to predict the tank draining and depressurization rates.
  - These models can also be used to design reduced scale experiments.

Passive Safety Injection System
General Governing Equations

Mass Conservation:

$$\rho_l A_{Tank} \frac{dL}{dt} = -\dot{m}_{inj}$$



Darcy Formula:

$$h_l = \frac{v_E^2}{2g}\left(\frac{fl}{d} + K\right)_E = \frac{v_E^2}{2g}\Pi_{FE}$$

Bernoulli Equation:

$$\frac{P_{FS}}{\rho_l g} + z_{FS} + \frac{v_{FS}^2}{2g} = \frac{P_E}{\rho_l g} + z_E + \frac{v_E^2}{2g} + h_l$$

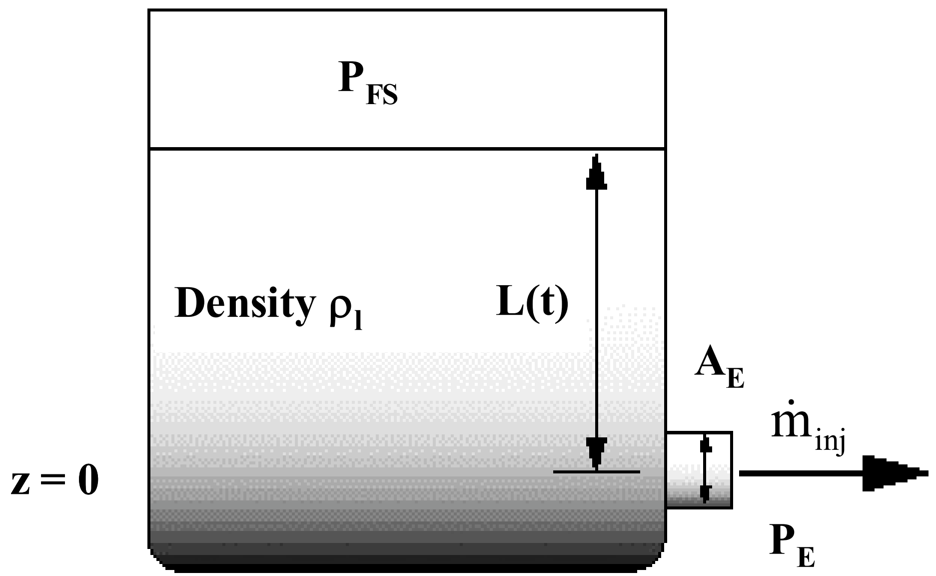
Passive Safety Injection System
General Governing Equations

Time Dependent Liquid Level:

$$\rho_l A_{Tank}\frac{dL}{dt} = -\dot{m}_o\left[\frac{\Delta P + \rho_l g L}{\Delta P_o + \rho_l g L_o}\right]^{1/2}$$

Initial Mass Flow Rate:

$$\dot{m}_o = A_E\left\{\frac{2\rho_l\left(\Delta P_o + \rho_l g L_o\right)}{1+\Pi_{FE}}\right\}^{1/2}$$



Gravity Draining Tanks (CMT and IRWST)

Governing Differential Equation:

$$\rho_l A_{Tank} \frac{dL}{dt} = -\rho_l A_E \left\{ \frac{2gL}{1+\Pi_{FE}} \right\}^{1/2}$$

Initial Conditions:

$$L_o = \frac{M_o}{\rho_l A_{Tank}}$$

$$\dot{m}_o = \rho_l A_E \left\{ \frac{2gL_o}{1+\Pi_{FE}} \right\}^{1/2}$$

Dimensionless Equation:

$$\frac{dL^+}{dt^+} = -\left(L^+\right)^{1/2}$$

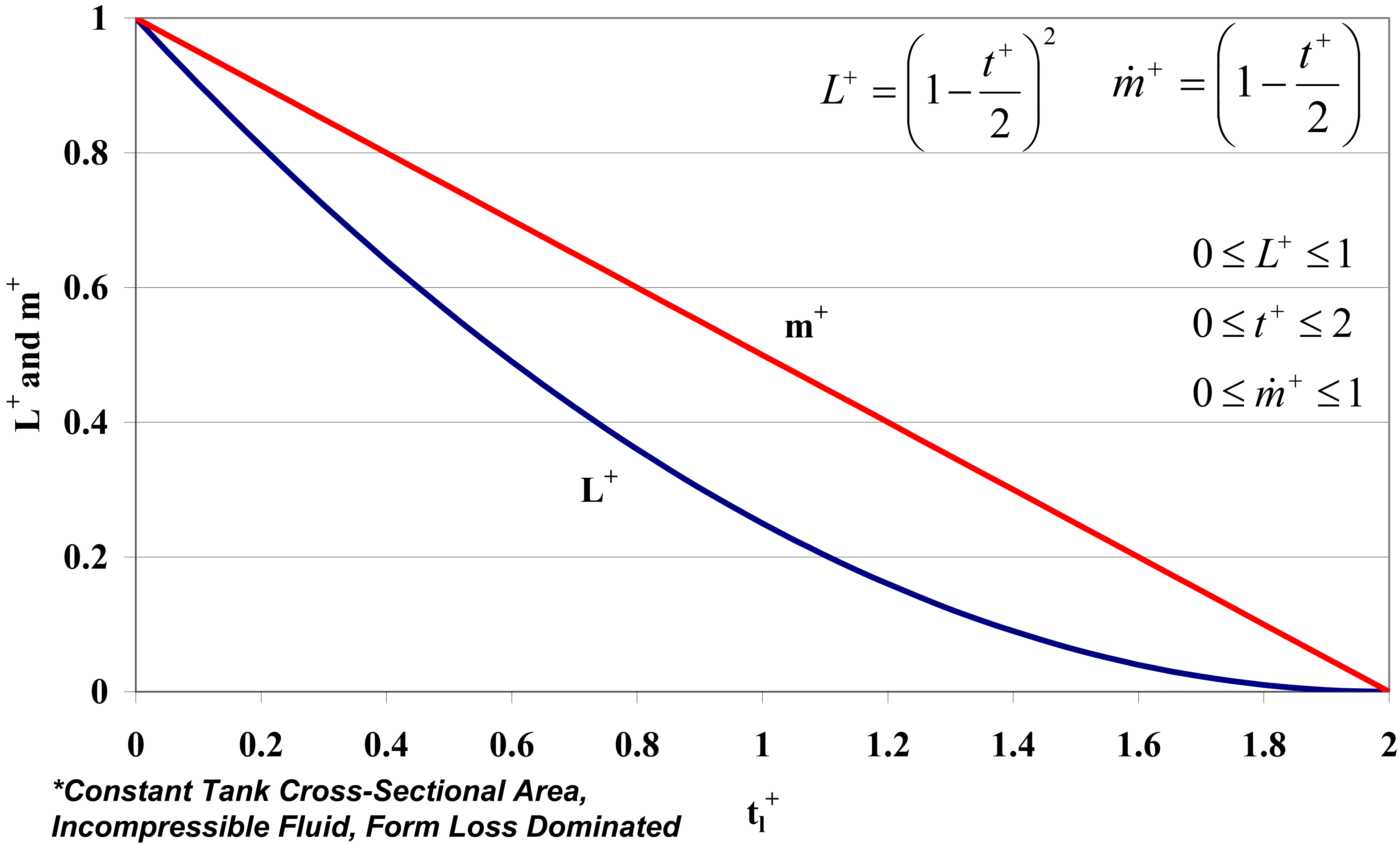
where:

$$L^+ = \frac{L}{L_o}$$

$$\dot{m}^+ = \frac{\dot{m}}{\dot{m}_o}$$

$$t^+ = \frac{t}{\tau} = \frac{t}{\left(M_o / \dot{m}_o\right)}$$

Dimensionless Curves for Gravity Drain Tanks*



Constant Tank Cross-Sectional Area, Incompressible Fluid, Form Loss Dominated at Exit.

Pressurized Injection Tanks (ACC)
Governing Equations

Liquid Mass Conservation:

$$\rho_l \frac{dV_l}{dt} = -\dot{m}_o \left(\frac{P - P_E}{P_o - P_E} \right)^{1/2}$$

Liquid Bernoulli Equation:

$$\frac{P}{\rho_l g} + z_{FS} + \frac{v_{FS}^2}{2g} = \frac{P_E}{\rho_l g} + z_E + \frac{v_E^2}{2g} + h_l$$

Darcy Equation:

$$h_l = \frac{v_E^2}{2g}\left(\frac{fl}{d} + K \right)_E = \frac{v_E^2}{2g}\Pi_{FE}$$

Component Volumes:

$$V_g = V_{Tank} - V_l$$

Isothermal Expansion (Gas):

$$P_o V_{go} = P V_g$$

Isentropic Expansion (Gas):

$$\frac{P}{P_o} = \left(\frac{V_{go}}{V_g} \right)^{1/\gamma}$$

Pressurized Injection Tanks (ACC)
Governing Equations

Dimensionless Terms:

$$P^+ = \frac{P}{P_o}$$

$$P_E^+ = \frac{P_E}{P_o}$$

$$\Delta P_E^+ = 1 - P_E^+$$

$$\Delta P^+ = P^+ - P_E^+$$

$$t_g^+ = \frac{t}{\tau_g} = \frac{t}{\left(\rho_l V_{go} / \dot{m}_o\right)}$$

Dimensionless Equation - Isothermal Expansion (Gas):

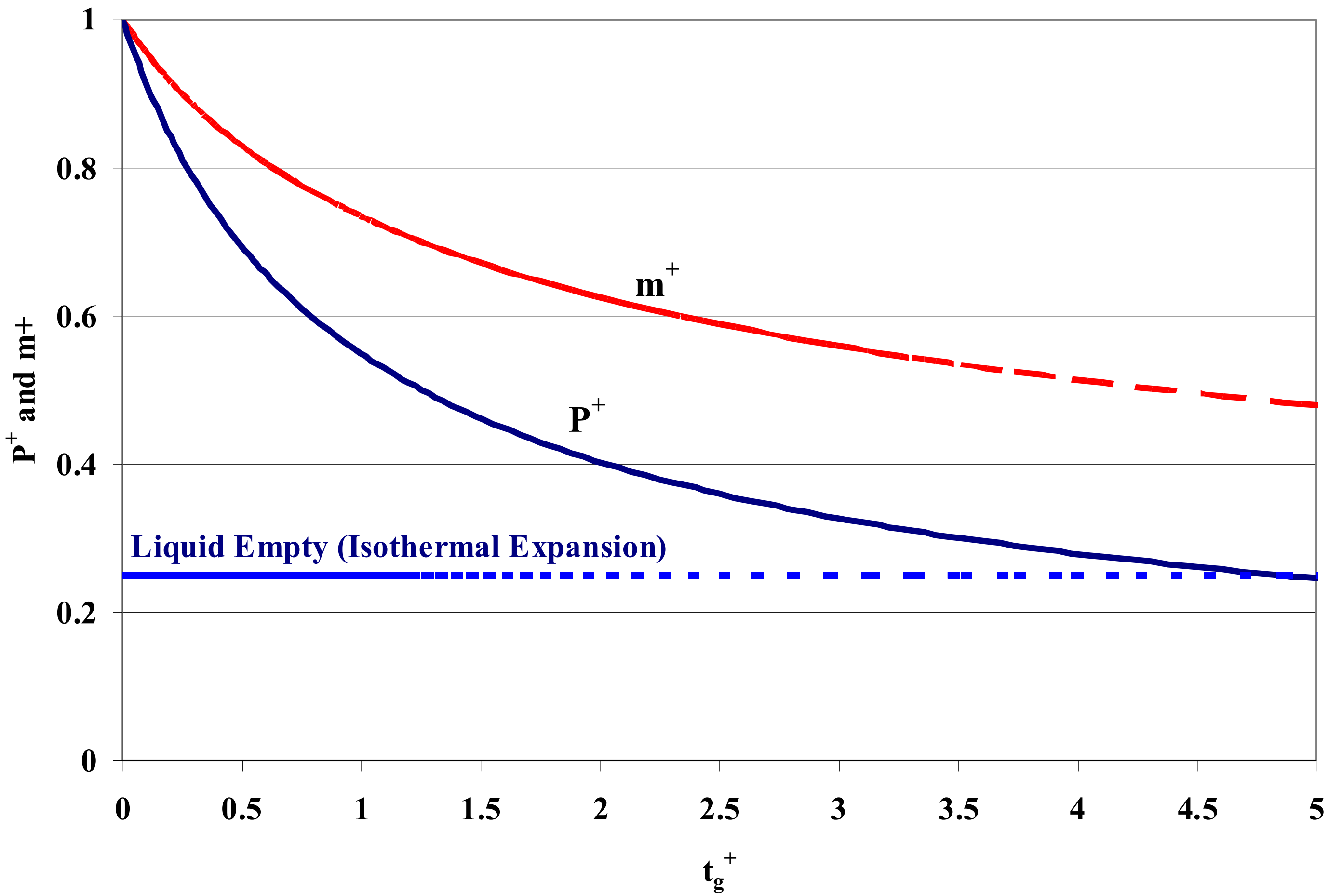
$$\frac{dP^+}{dt^+} = -\left(P^+\right)^2 \left[\frac{\Delta P^+}{\Delta P_E^+}\right]^{1/2}$$

Dimensionless Equation – Isentropic Expansion (Gas):

$$\frac{dP^+}{dt^+} = -\gamma\left(P^+\right)^{\frac{\gamma+1}{\gamma}} \left[\frac{\Delta P^+}{\Delta P_E^+}\right]^{1/2}$$

Pressurized Injection Tanks (ACC)

Analytical Solution (Isothermal Expansion)



Solution:

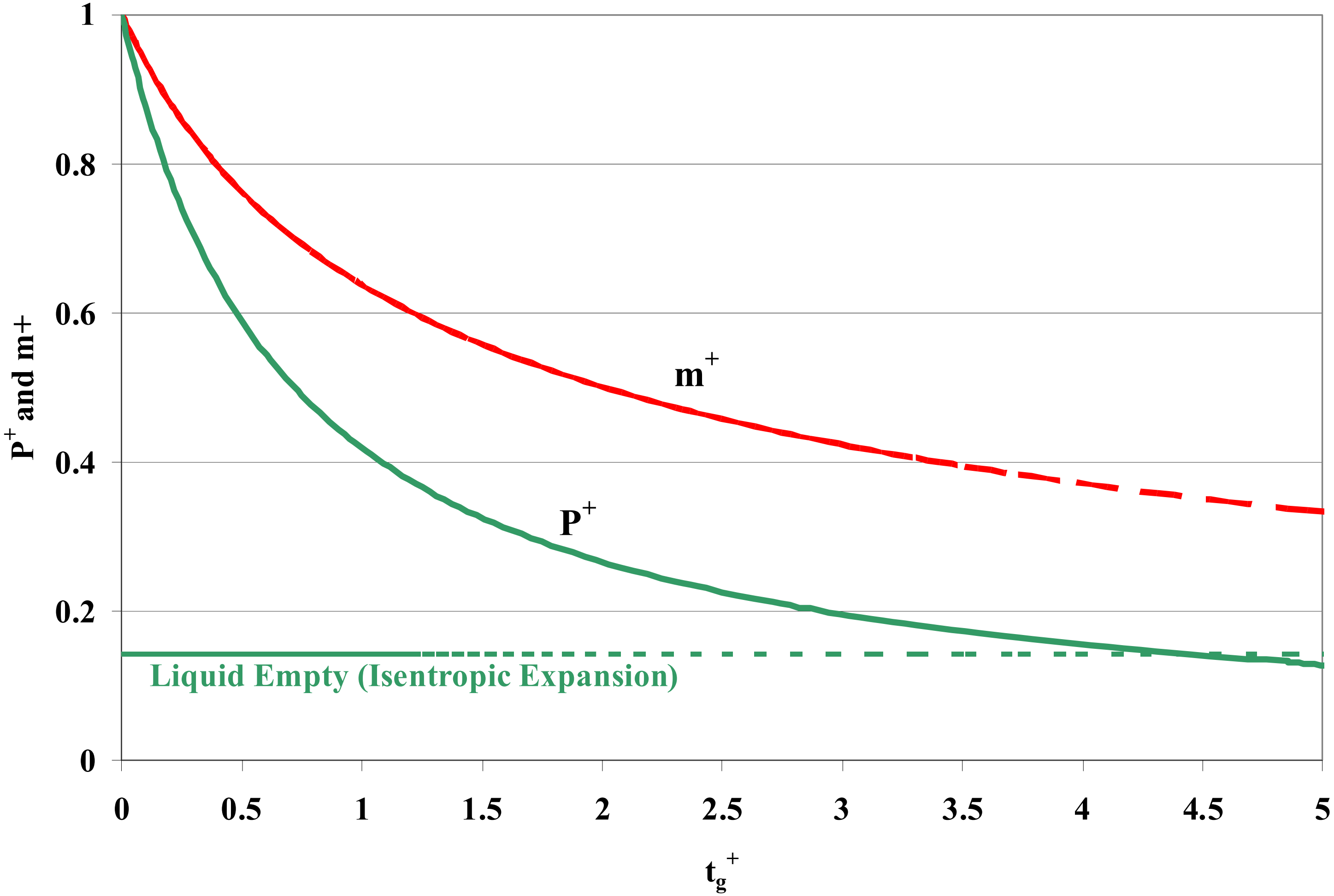
$$\frac{\left(\Delta P^+\right)^{1/2}}{P^+} + \frac{1}{\left(P_E^+\right)^{1/2}} \tan^{-1}\left(\frac{\Delta P^+}{P_E^+}\right)^{1/2} = \phi - \frac{P_E^+ t_g^+}{\left(\Delta P_E^+\right)^{1/2}}$$

where:

$$\phi = \left(\Delta P_E^+\right)^{1/2} + \frac{1}{\left(P_E^+\right)^{1/2}} \tan^{-1}\left(\frac{\Delta P_E^+}{P_E^+}\right)^{1/2}$$

Pressurized Injection Tanks (ACC)

Analytical Solution (Isentropic Expansion)



Approximate Solution:

$$P^+ \approx \frac{4P_E^+ \Delta P_E^+}{4\Delta P_E^+ - \left(2\Delta P_E^+ - \gamma P_E^+ t_g^+\right)^2}$$

Primary System Depressurization (ADS)
Governing Equations

Mass Balance:

$$\frac{dM}{dt} = \sum \dot{m}_{inj} - \sum \dot{m}_{ADS}$$

Depressurization Rate Equation:

$$M\left(\frac{\partial e}{\partial P}\right)_v \frac{dP}{dt} = \left(\sum \dot{m}_{inj}\right)\left[h_{inj} - e + v\left(\frac{\partial e}{\partial v}\right)_p\right]$$

$$- \left(\sum \dot{m}_{ADS}\right)\left[h_{ADS} - e + v\left(\frac{\partial e}{\partial v}\right)_p\right] + \dot{q}_{SG} + \dot{q}_{core} + \dot{q}_{loss}$$

Primary System Depressurization (ADS)
Dimensionless Balance Equations

Mass Balance:

$$\tau_{RCS}\frac{dM^{+}}{dt}=\Pi_{m}\ \Sigma\dot{m}_{inj}^{+}\ -\ \Sigma\dot{m}_{ADS}^{+}$$

Depressurization Rate Equation:

$$M^{+}\left(\frac{\partial e}{\partial P}\right)_{v}^{+}\tau_{RCS}\frac{dP^{+}}{dt}=\ \frac{\Pi_{h}}{\Pi_{\varepsilon}}\Sigma\dot{m}_{inj}^{+}\left[h_{inj}\ -\ e\ +\ v\left(\frac{\partial e}{\partial v}\right)_{p}\right]^{+}$$

$$-\ \frac{\Sigma\dot{m}_{ADS}^{+}}{\Pi_{\varepsilon}}\left[h_{ASDS}\ -\ e\ +\ v\left(\frac{\partial e}{\partial v}\right)_{p}\right]^{+}++\ \frac{\Pi_{\Gamma}}{\Pi_{\varepsilon}}q_{net}^{+}$$

Primary System Depressurization (ADS) *Dimensionless Terms*

Characteristic Time:

$$\tau_{rcs} = \frac{M_o}{\sum \dot{m}_{ADS,o}}$$

Mass Balance Number:

$$\Pi_m = \frac{\sum \dot{m}_{inj,o}}{\sum \dot{m}_{ADS,o}}$$

Enthalpy Balance Number:

$$\Pi_h = \frac{\sum \dot{m}_{inj,o} \cdot \left[h_{inj} - e + v\left(\frac{\partial e}{\partial v}\right)_p \right]_o}{\sum \dot{m}_{ADS,o} \cdot \left[h_{Brk} - e + v\left(\frac{\partial e}{\partial v}\right)_p \right]_o}$$

Heat Source Number:

$$\Pi_\Gamma = \frac{\dot{q}_{net,o}}{\sum \dot{m}_{ADS} \cdot \left[h_{brk} - e + v\left(\frac{\partial e}{\partial v}\right)_p \right]_o}$$

Fluid Mixture Dilation Number:

$$\Pi_\varepsilon = \varepsilon_o = \frac{P_o \left(\frac{\partial e}{\partial P}\right)_{v,o}}{\left[h_{ADS} - e + v\left(\frac{\partial e}{\partial v}\right)_p \right]_o}$$

Primary System Depressurization (ADS)
Similarity Criteria – Fluid Property Similitude

Characteristic Time Ratio:

$$(\tau_{RCS})_R = \left(\frac{\mathrm{M_o}}{\dot{m}_{ADS,o}}\right)_R = \left(\frac{V_o}{A_{ADS,o}}\right)_R = 1$$

ADS Flow Area Criterion:

$$(A_{ADS})_R = (V_o)_R$$

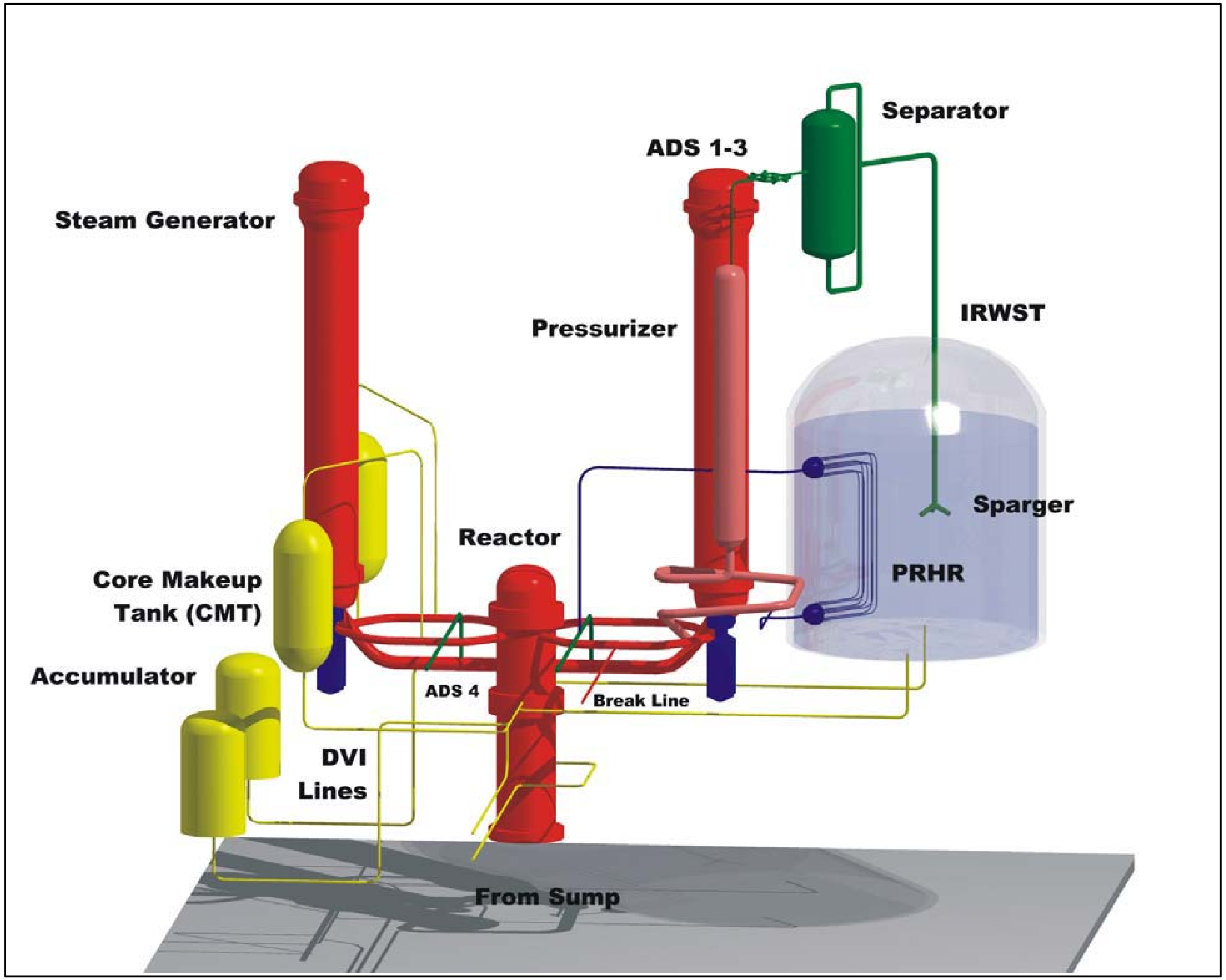
Injection Flow Area Criterion:

$$(\dot{m}_{inj,o})_R = (A_{ADS}) = (V_o)_R$$

Power Criterion:

$$(\dot{q}_{net,o})_R = (A_{ADS})_R = (V_o)_R$$

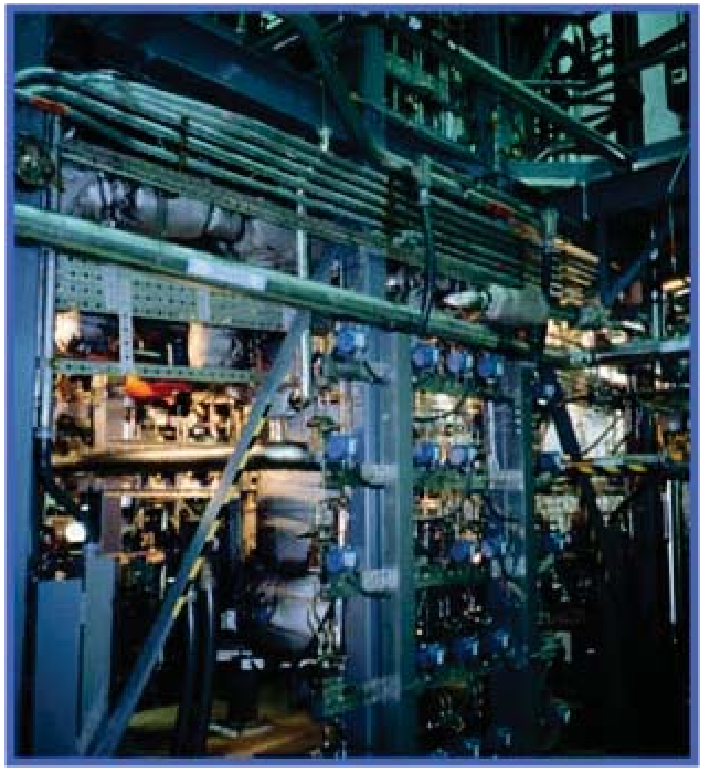
APEX Test Facility at Oregon State University

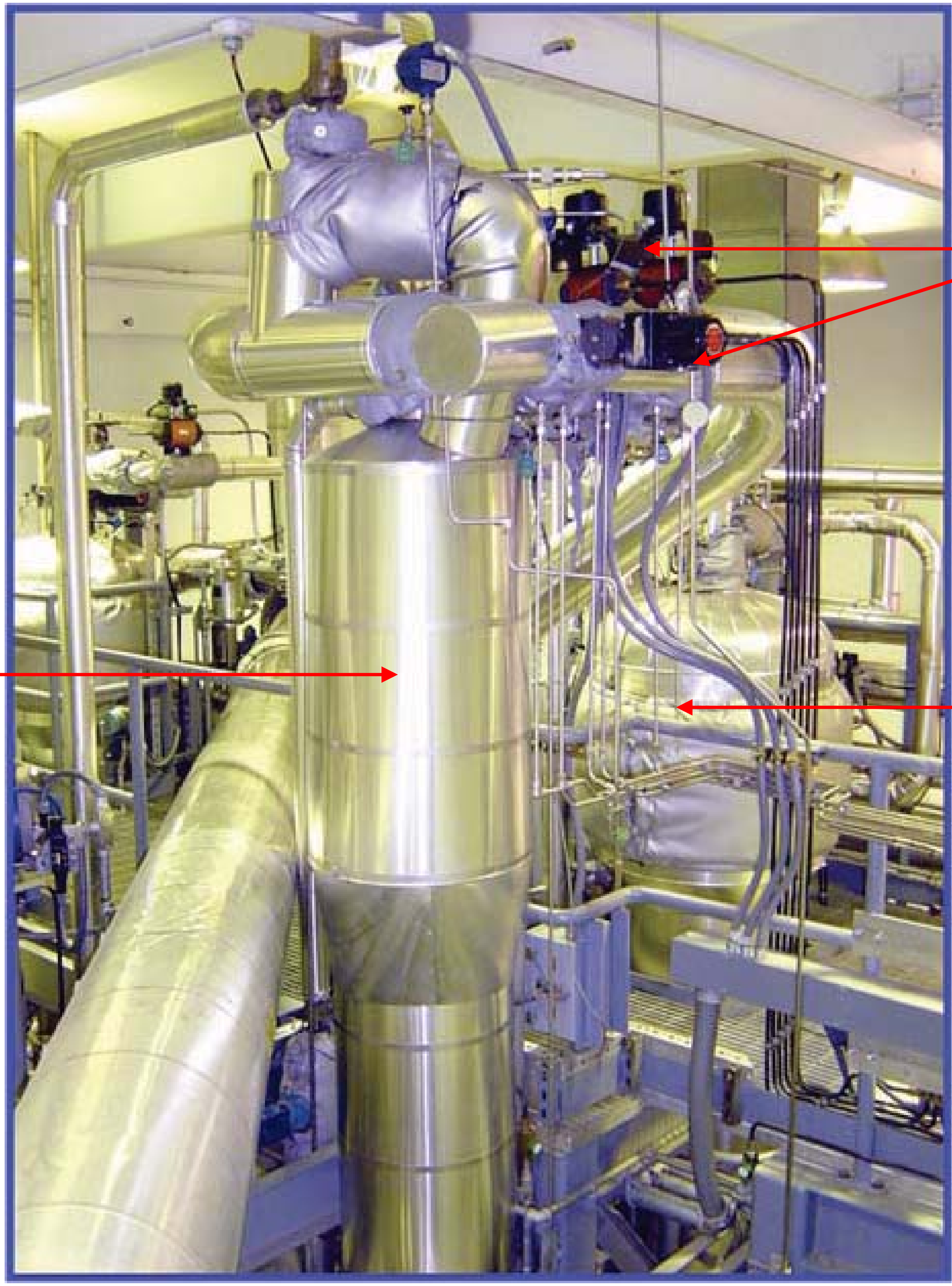


APEX Facility Description

- Complete 2x4 Loop Primary System:
  - 1:4 Length Scale, 1:2 Time Scale, 1:192 Volume Scale, Stainless Steel Construction.
  - 2 Hot Legs, 4 Cold Legs, 2 Steam Generators, Pressurizer, Reactor Vessel with an Electrically Heated Rod Bundle and Upper Plenum Internals.
- Passive Safety Systems:
  - 2 Core Makeup Tanks (CMTs) , 2 Accumulators, a Passive Residual Heat Removal (PRHR) Heat Exchanger, IRWST, and a 4-Stage ADS System.
- Operating Conditions:
  - Core Power ~ 1 MW, Steam Generator Shell Side Pressure (20 Bar), Pressurizer Pressure (25.5 Bar)
- Testing Capabilities:
  - Hot & Cold Leg SBLOCAs, MSLB, Inadvertent ADS, Double-Ended DVI Line Break, Station Blackout and Long Term Recirculation.

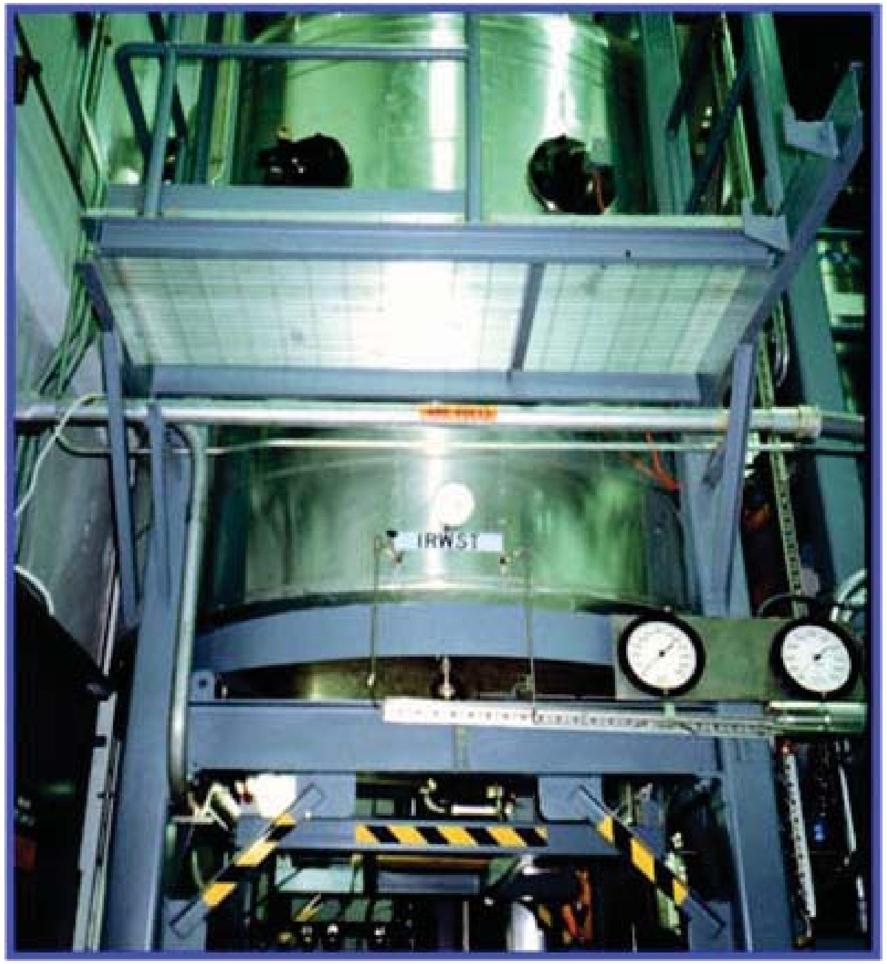
APEX Facility Description




ADS 1-3
Valves
Pressurizer
Steam
Generator

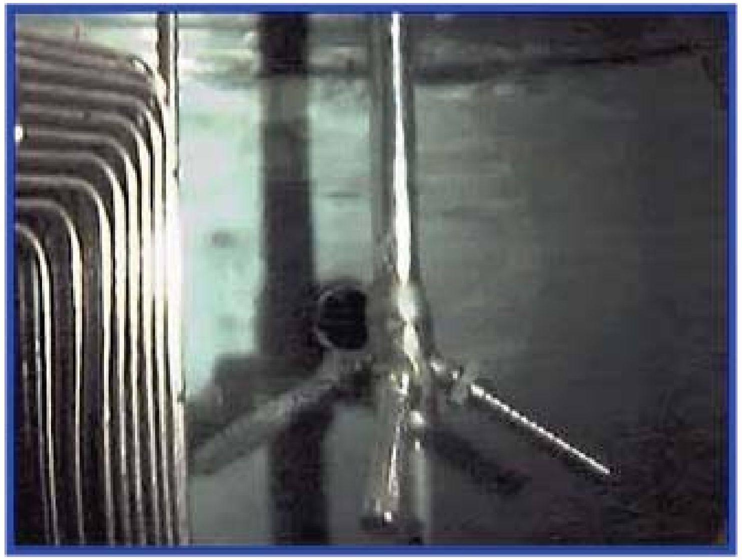
Accumulator (1 of 2)

Core Makeup Tank
(1 of 2)



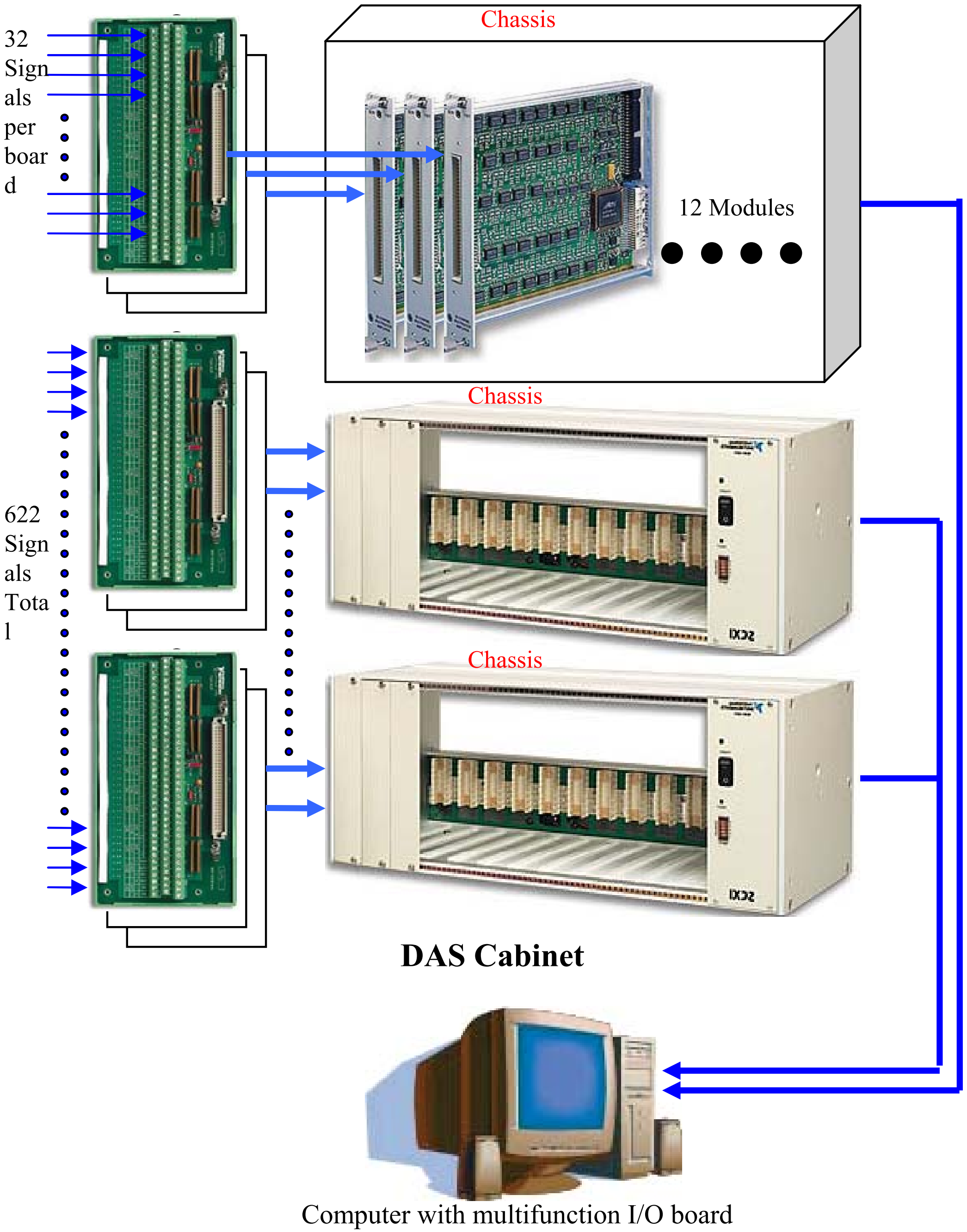
IRWST

PRHR Heat Exchanger



ADS Sparger

Data Acquisition System

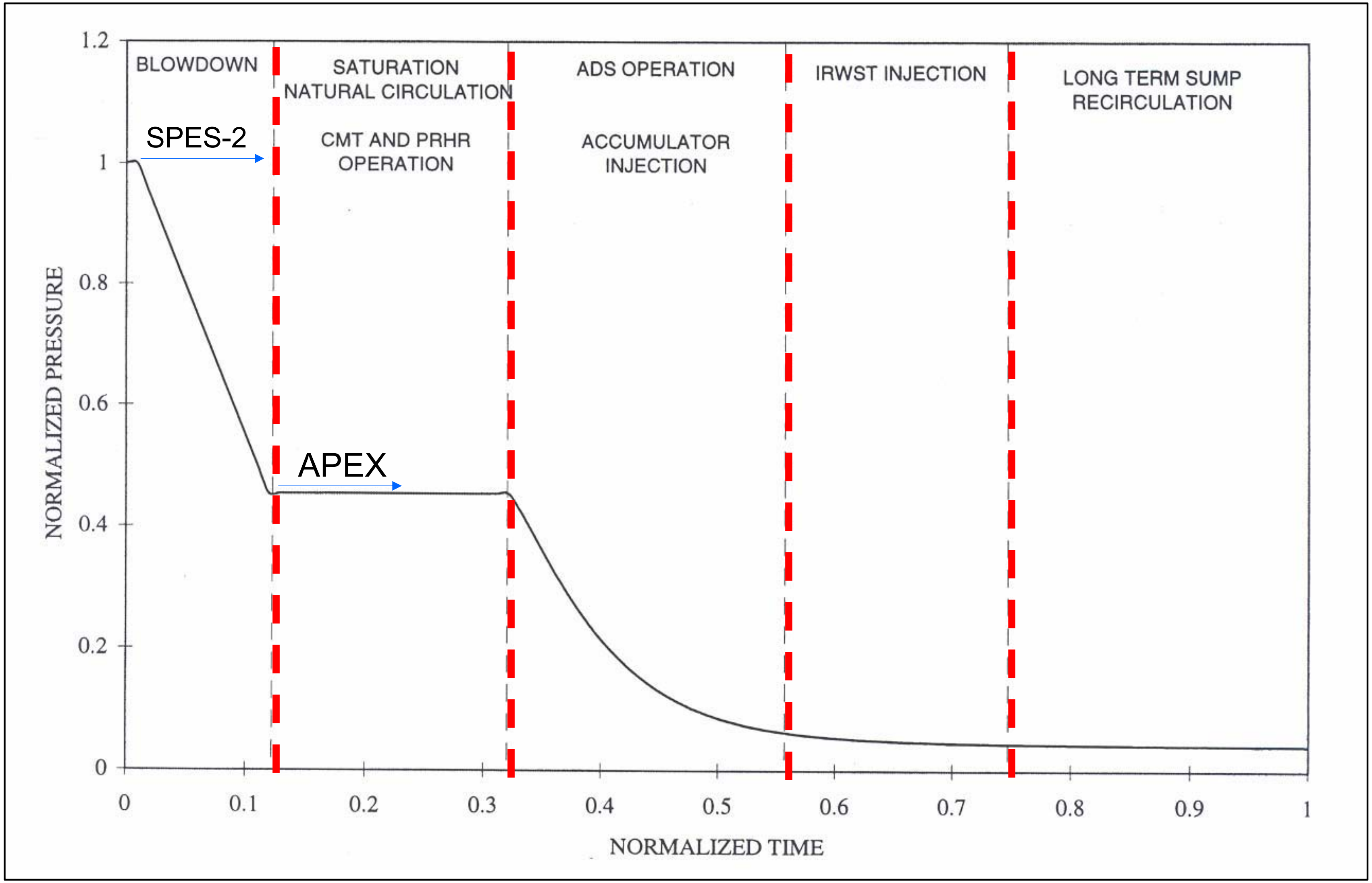


Comparison of Test Facility Results

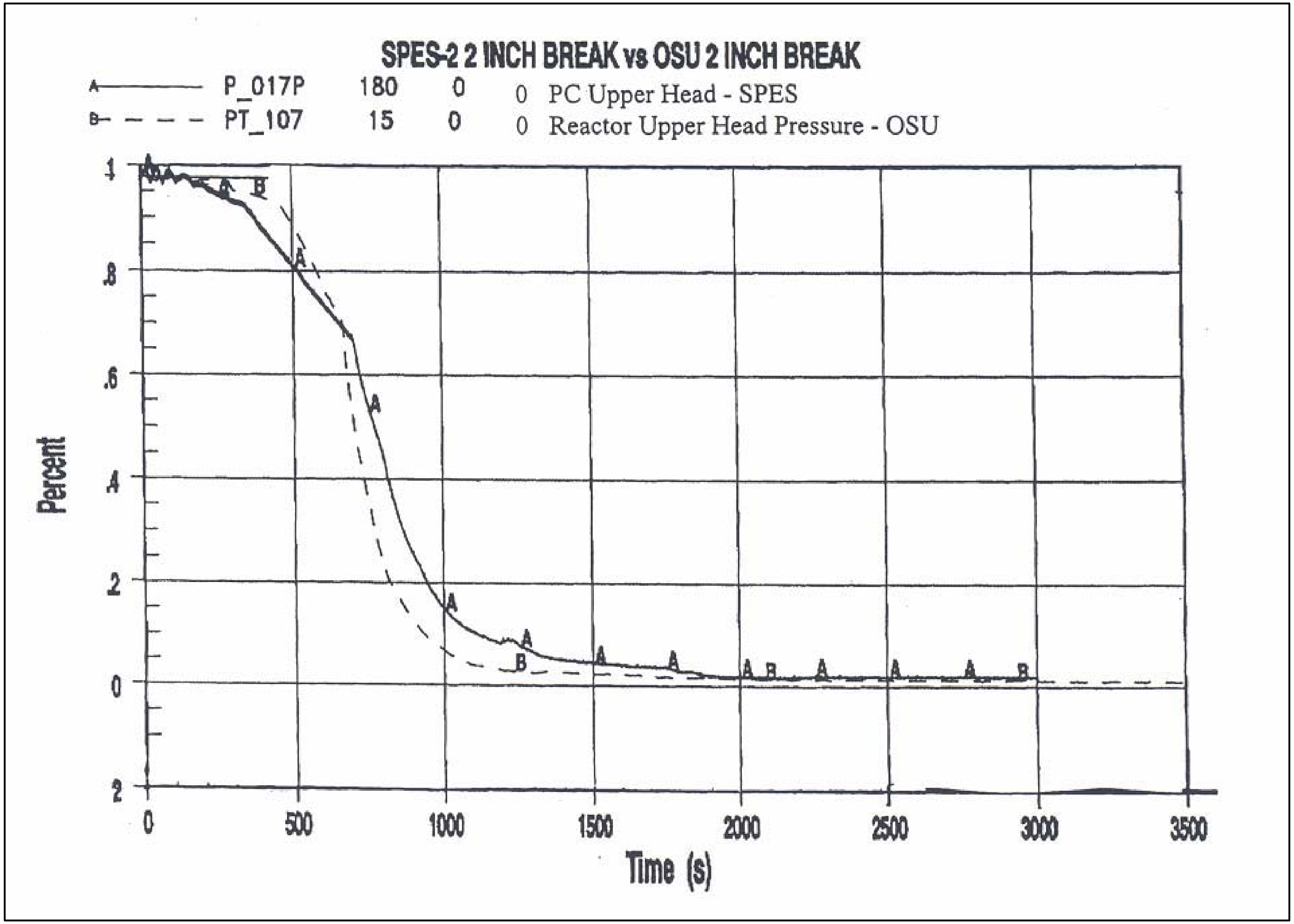
- Can reduced scale facilities duplicate full scale plants?
- Scaling Assessment. A comparison of the Full Height-Full Pressure SPES-2 and the ¼-Height Reduced Pressure OSU APEX Two-Inch LOCA

Scaling Ratios	APEX	SPES-2
Lengths	1:4	1:1
Relative elevations	1:4	1:1
Flow Areas	1:48	1:395
Volumes	1:192	1:395
Decay Power	1:96	1:395
Fluid Velocity	1:2	1:1
Fluid Transient Time	1:2	1:1
Mass Flow Rate	1:96	1:395

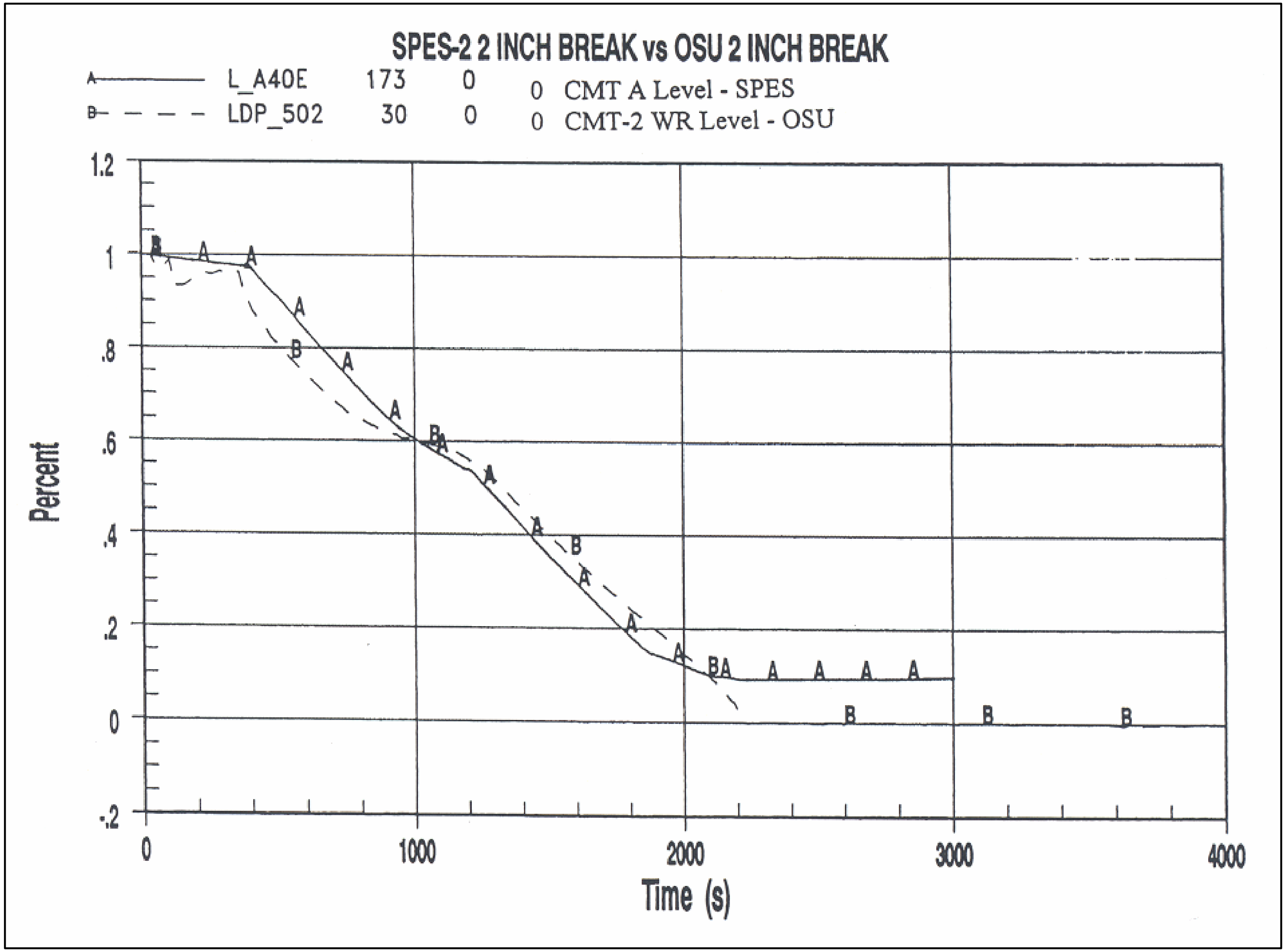
AP600/AP1000 SBLOCA Scenario



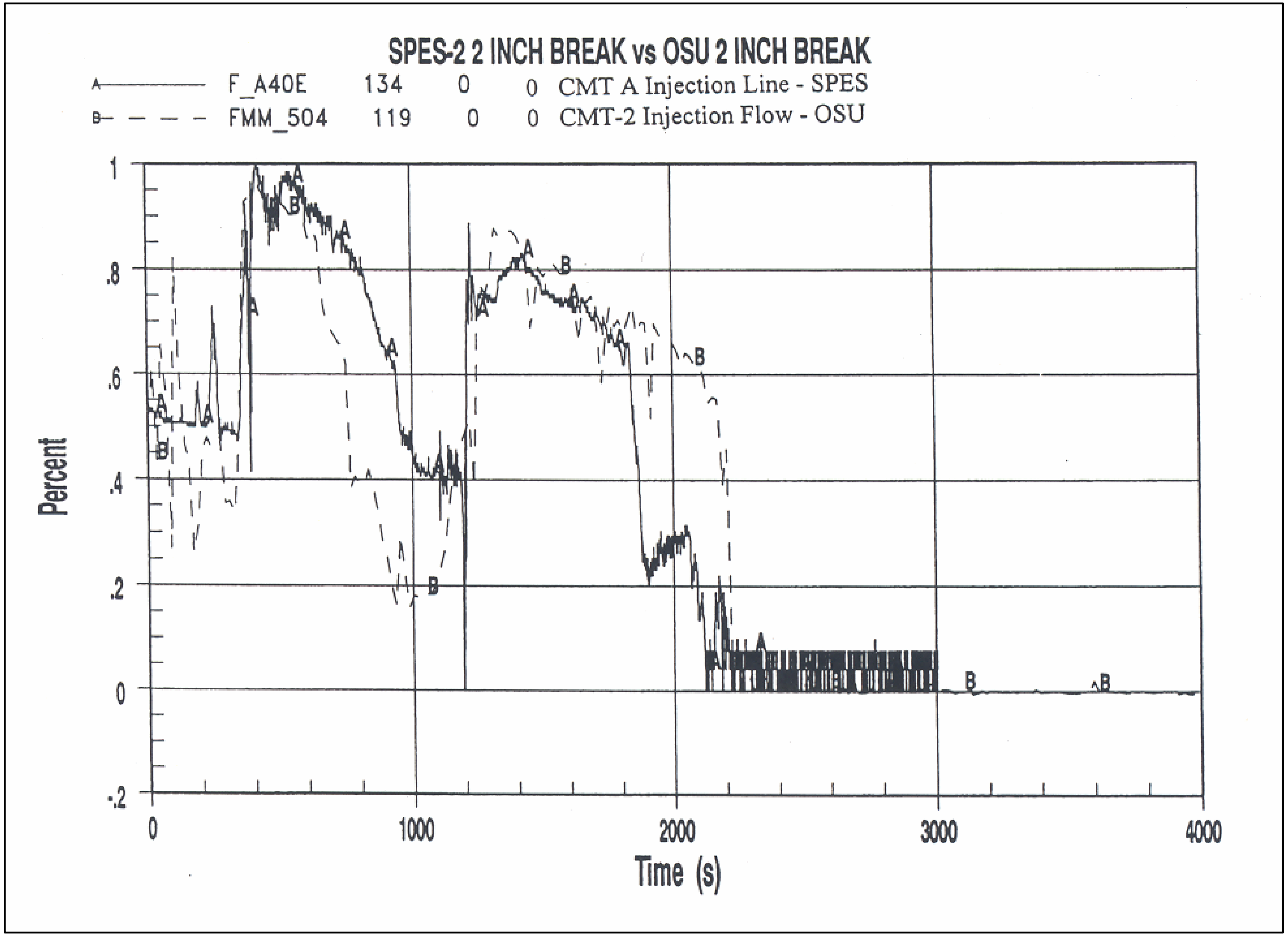
Comparison of Reactor Head Pressures (AP600 Testing)



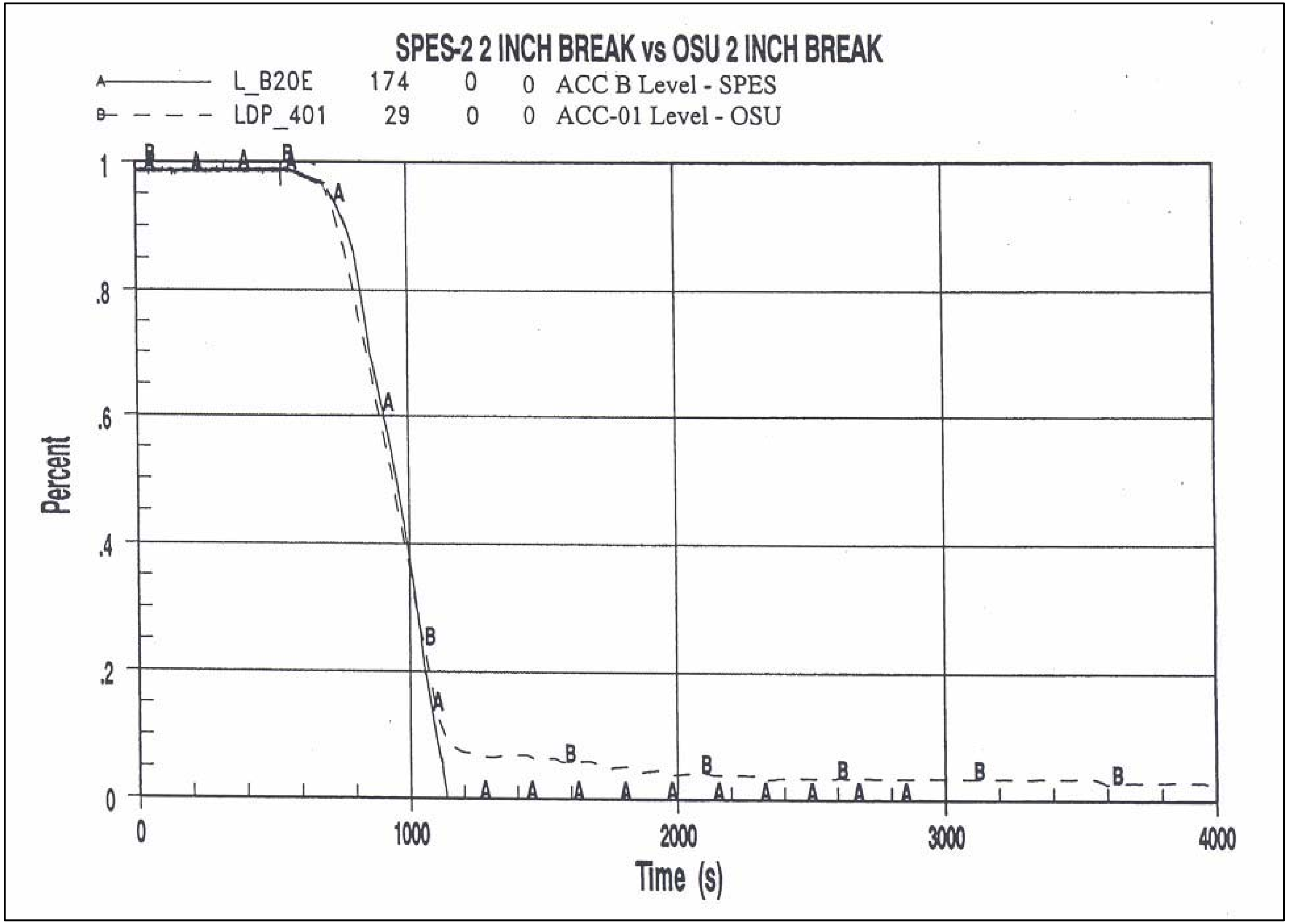
Comparison of Core Makeup Tank Liquid Levels (AP600 Testing)



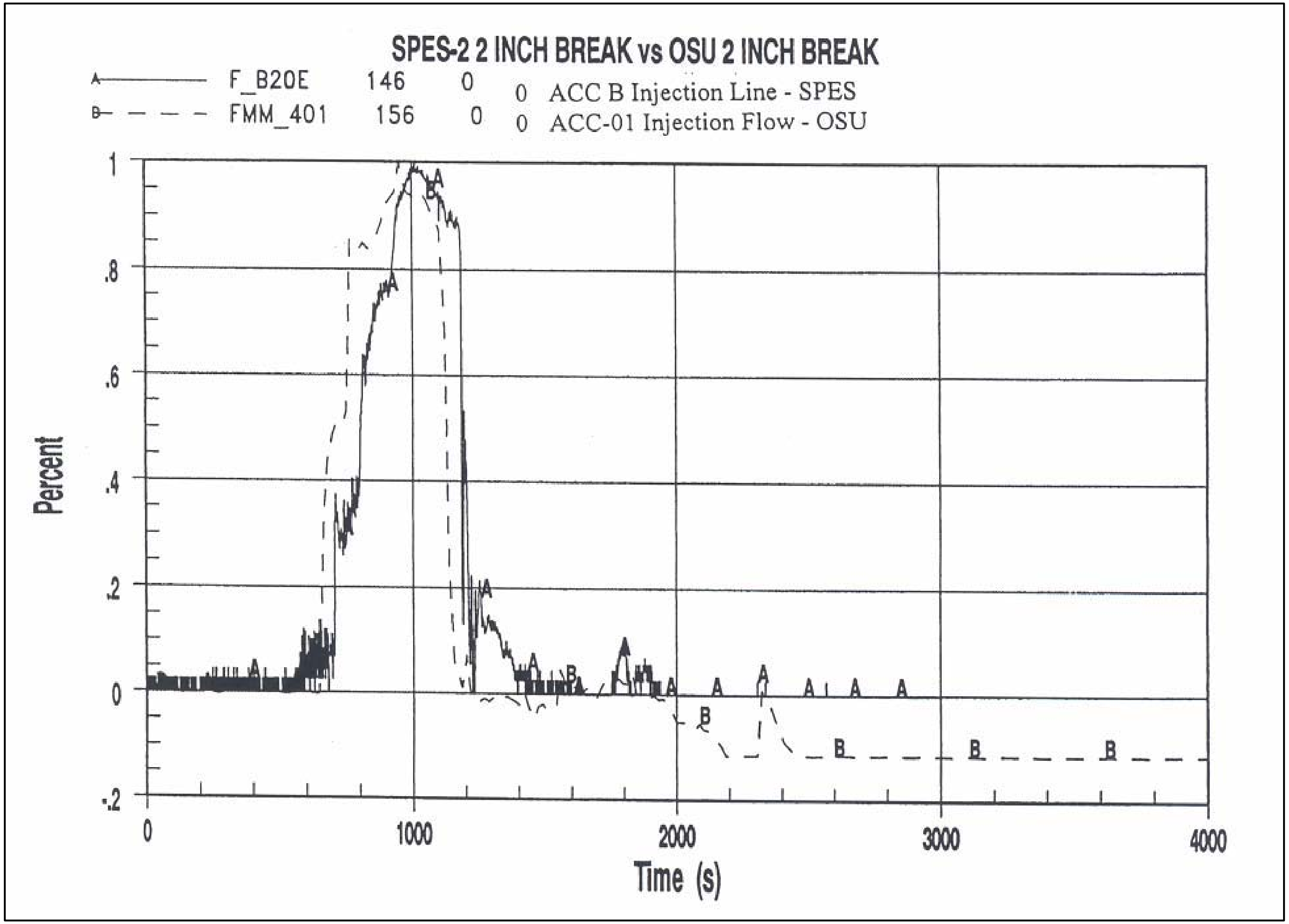
Comparison of Core Makeup Tank Injection Flow Rates (AP600 Testing)



Comparison of Accumulator Tank Liquid Levels (AP600 Testing)



Comparison of Accumulator Tank Flow Rates (AP600 Testing)



Conclusions

- The AP600 and AP1000 plants are the first passively safe plants to be certified in the US.
- The integral operation of the AP600 and AP1000 passive safety systems have been described.
- Methods used to calculate and scale injection flow rates for gravity drain tanks and pressurized tanks,and to estimate depressurization flow rates for an ADS system have been presented.
- Scaled Integral System Tests have provided valuable insights into AP600/AP1000 operation and safety, and have been used successfully in the certification process.
- 10-12 AP1000 nuclear plants are being considered for construction in the US.