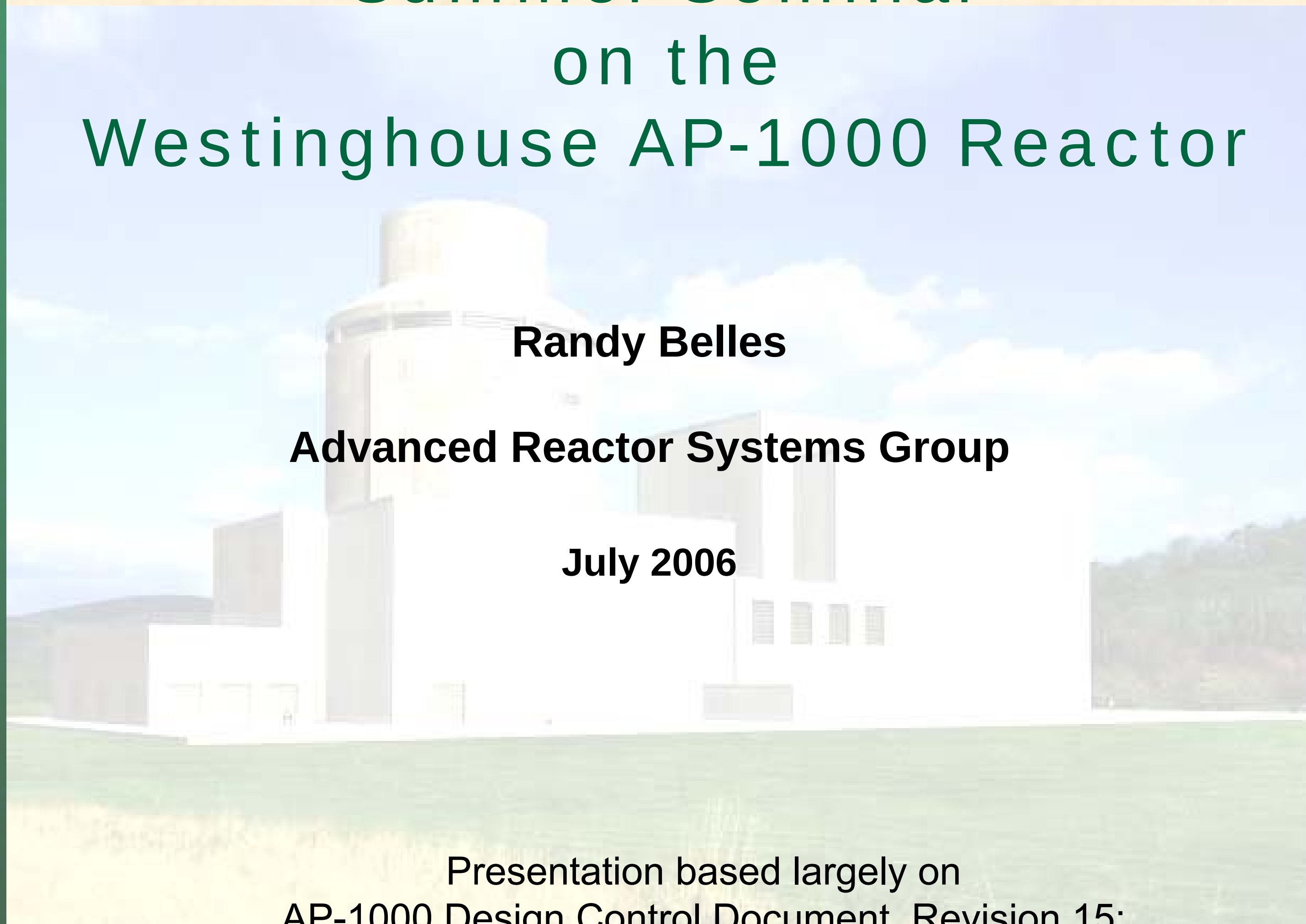
Summer Seminar on the Westinghouse AP-1000 Reactor



Randy Belles

Advanced Reactor Systems Group

July 2006

Presentation based largely on
AP-1000 Design Control Document, Revision 15;
Status of Advanced Light Water Reactor Designs, 2004, IAEA TECDOC-1391;
and various industry presentations on the AP-1000.

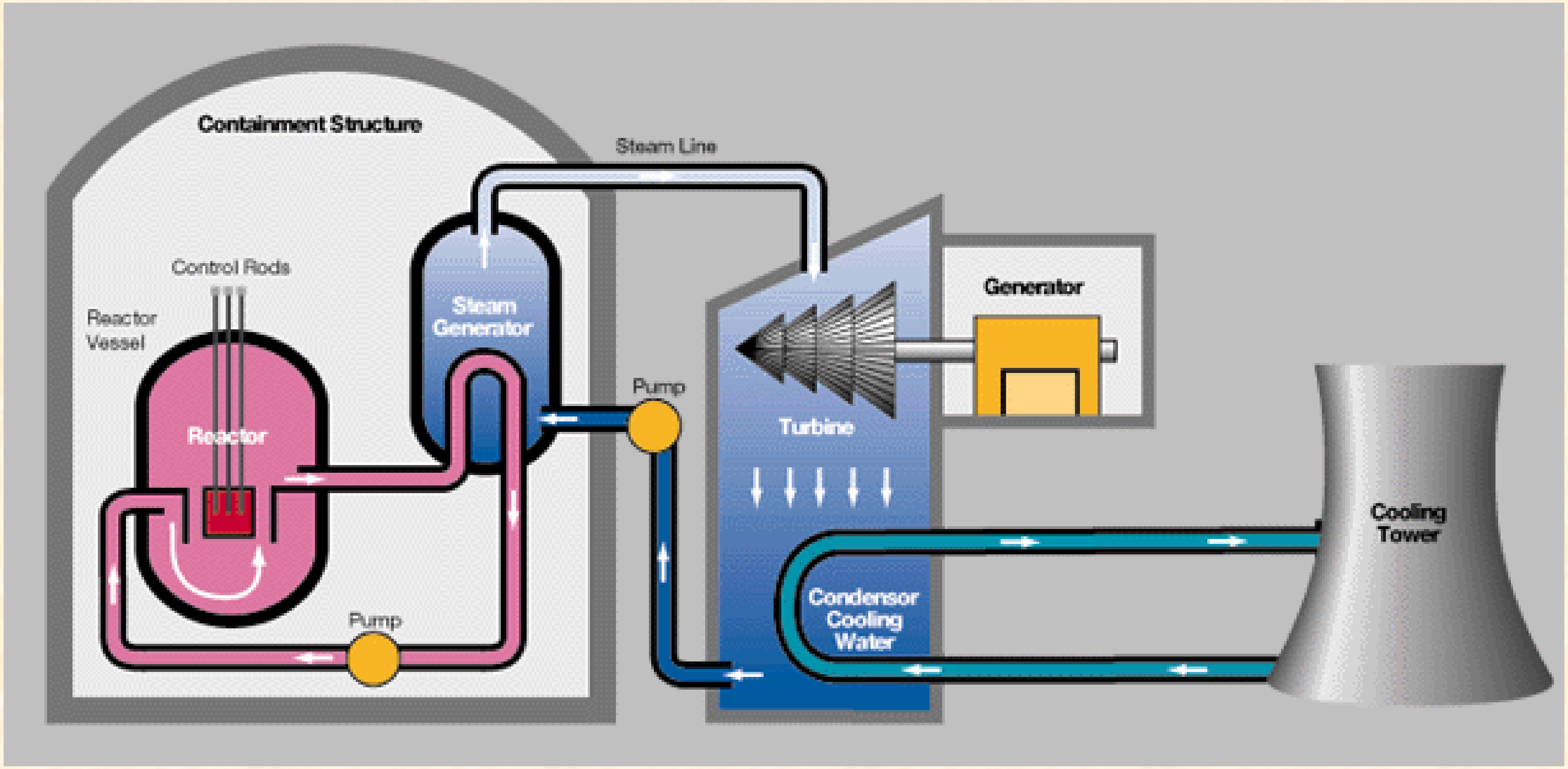
Course Content Disclaimer

Information contained herein is derived exclusively from publicly available documents. The content of this introductory course does not necessarily represent what may be submitted to the Nuclear Regulatory Commission in the form of a license application for a new reactor. ORNL neither endorses this design nor has performed any design reviews to validate design improvements, design margins, or accident probabilities. The intent in compiling this information at this time is for the express purpose of constructing an internal, introductory course for our own staff.

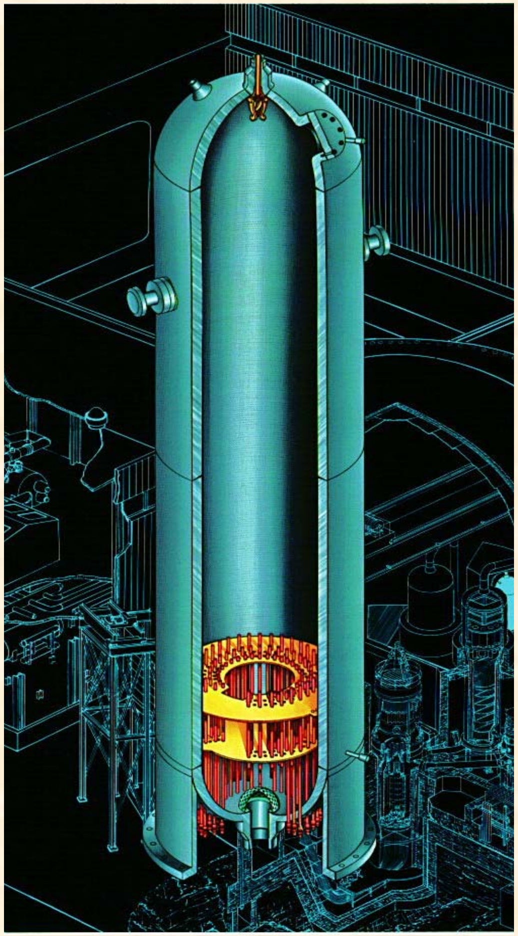
AP-1000 Summer Seminar Outline

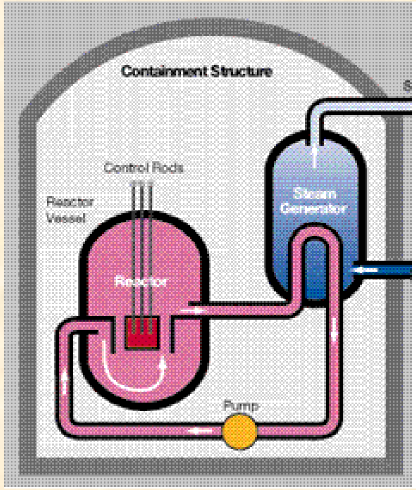
- **PWR Primer** **(10 minutes)** **(02)**
- **Design Status** **(5 minutes)** **(02)**
- **Plant Overview and Key Design Features** **(20 minutes)** **(21)**
- **Key Systems** **(20 minutes)** **(20)**
- **Accident Analysis** **(5 minutes)** **(03)**
- **Questions & Wrap-up**

A Quick Discussion of the Basic Operation of a PWR…



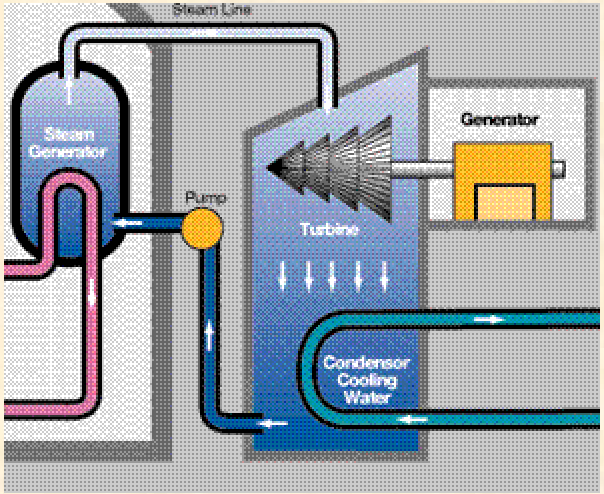
Pressurizer Operation and Typical PWR Safety Systems





- Safety Injection (SI) – High pressure water injection
- Residual Heat Removal (RHR) – Low pressure injection, emergency sump recirculation, and decay heat removal
- Containment Spray – containment pressure control
- Charging system & cooling system

- Diverse feedwater pump for emergency feedwater (EFW)
- Service water cooling to transfer heat to the ultimate heat sink
- Emergency diesel generators to provide backup power to safety components



Pressurizer – Controls RCS pressure
Plant transient insurge→ steam bubble compressed → pressure ↑→ spray activated → pressure ↓
Plant transient outsurge→ steam bubble expands → pressure ↓ → heaters activated → pressure ↑

AP-1000 Design Certification Status

Final Design Approved in September 2004

(AP-600 Final Design Approved in Sep 1998)

Design Certification Issued January 27, 2006

10 CFR 52 Appendix D

(AP-600 Design Certification Issued in Dec 1999)

10 CFR 52 Appendix C

January 20, 2006 (Nuclear Energy Institute Release)

The Nuclear Regulatory Commission (NRC) approved the final design certification for the Westinghouse Electric Co. AP1000 advanced design reactor. The rule certifying the reactor, which will remain valid for 15 years, will be published in the Federal Register in mid-to-late January and become effective 30 days later.

Utilities Considering an AP-1000 COL Application

Utility	Site	Expected Application Date	Number of Reactors
Duke Power	Undetermined	Late 2007 – Early 2008	2
NuStart TVA	Bellefonte	4th Quarter 2007	2
Progress Energy	Harris	Late 2007 – Early 2008	2
Progress Energy	Florida (?)	Late 2007 – Early 2008	2
Southern Nuclear	Vogtle	March 2008	2
SCE&G	Summer	3rd Quarter 2007	2
Duke Power /Southern	Cherokee Co. South Carolina	Late 2007 – Early 2008	2

Nucleonics Week, Feb 16, 2006 & Nuclear News Flash, March 26, 2006

AP-1000 Summer Seminar Outline

- **PWR Primer** **(10 minutes)**
- **Design Status** **(5 minutes)**
- **Plant Overview and Key Design Features** **(20 Minutes)**
  - **Design and Operating Parameters**
    - **Primary**
    - **Secondary**
    - **Containment**
  - **Fuel Element Design**
  - **Reliability Goals**
  - **Power Capability Objectives**
  - **Site Schematic**
  - **Footprint Comparison to the AP-600**
  - **Component Reduction**
  - **Cost and Construction**
- **Key Systems** **(20 minutes)**
- **Accident Analysis** **(5 minutes)**
- **Questions & Wrap-up**

AP-1000 PWR Designed by Westinghouse
Currently owned by BNFL – Sale pending to Toshiba

The technology focus of the Nuclear Power 2010 program is on Generation III+ advanced light water reactor designs, which offer advancements in safety and economics over the Generation III designs. – DOE 2007 Budget Request

Design Objective:

The primary objective of the AP1000 design is to meet applicable safety requirements and goals defined for advanced light water pressurized water reactors with passive safety features. Since the AP600 has already received a Design Certification, it is also a design objective for AP1000 to be as similar as possible to the AP600.

Passive Safety Features Insure Reactor Safety Without Using Active Components

- **Passive Core Cooling**
  - **Passive Residual Heat Removal (RHR)**
  - **Passive Safety Injection (SI)**
- **Passive Containment Cooling**
  - **Emergency Ultimate Heat Sink is the Atmosphere**
- **Extensive battery-backed dc power systems**
- **Control Room Habitability**

However, Non-Safety Active Systems Remain as the Preferred Response Mechanism to a Casualty

AP-1000 Primary Parameters Compare Favorably to Existing Gen III PWRs

Component	Waterford 3	AP-600	AP-1000
NSSS Power	3410 MWt	1940 MWt	3415 MWt
Net Electrical Output	1075 MWe	600 MWe	1090 MWe
Operating Pressure	2250 psia	2250 psia	2250 psia
T_{HOT}	603ºF	600ºF	610ºF
T_{COLD}	561ºF	533ºF	535ºF
Forced Flow Rate	400,000 gpm	190,000 gpm	300,000 gpm
Nominal DNBR	2.20	3.48	2.80
Fuel Assemblies	217	145	157
Control Rods	83	45	53
Gray Rods	8 (part length)	16	16
Pressurizer Volume	1500 ft^3	1600 ft^3	2100 ft^3
Volume/MWt	.440	.825	.618

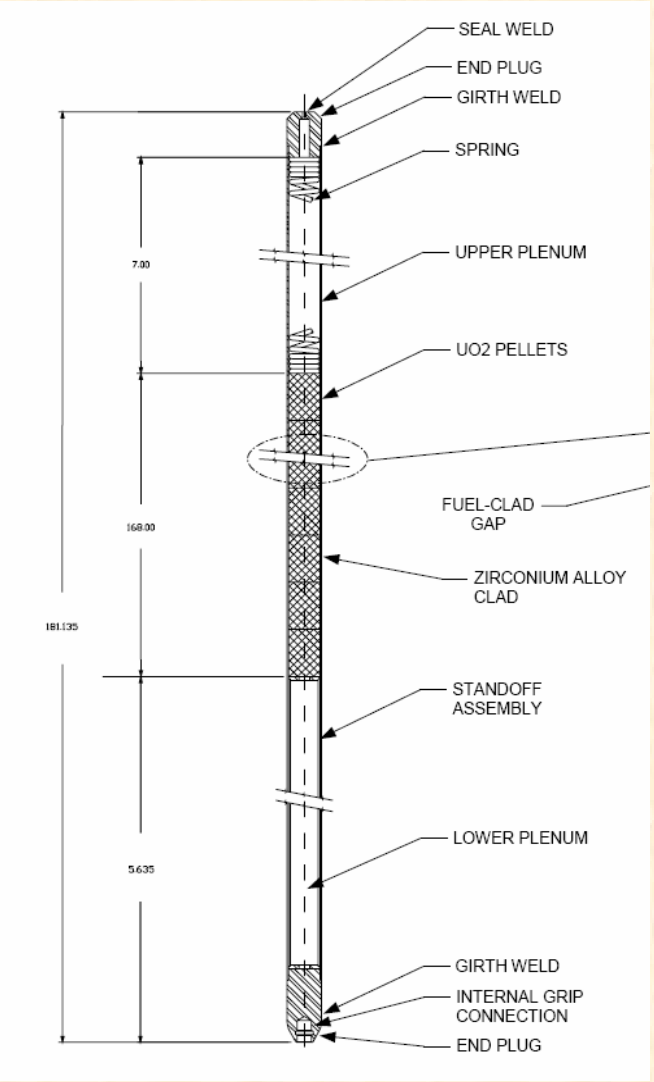
AP-1000 Secondary Parameters Are Typical

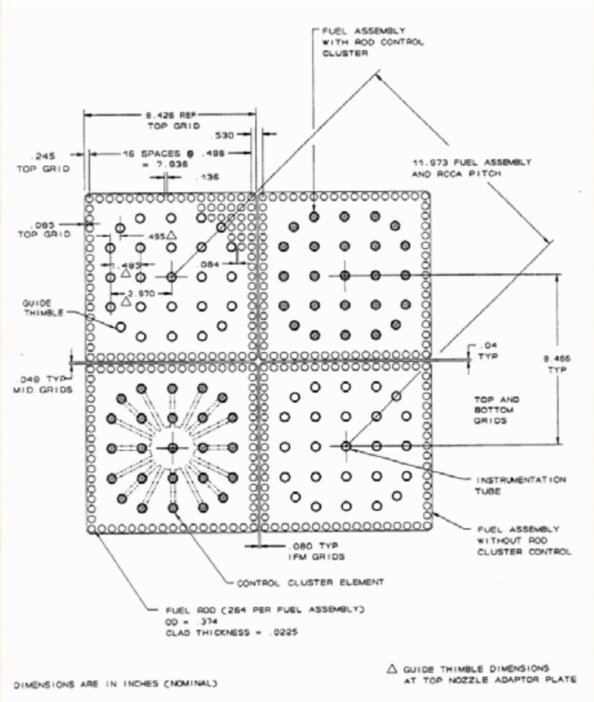
Steam Generator Outlet Steam Pressure - Design	**1200 psia**
Nominal Full Load	**838 psia**
Nominal Hot Standby	**1106 psia**
Steam Generator Outlet Steam Temperature - Design	**600ºF**
Nominal Full Load	**523ºF**
Nominal Hot Standby	**557ºF**
Maximum Steam Generator Outlet Steam Moisture (%)	**0.25**
Steam Generator Inlet Feedwater Temperature	**440ºF**
Flow Rate per Steam Generator (lb/hr)	**7.49×10^6**

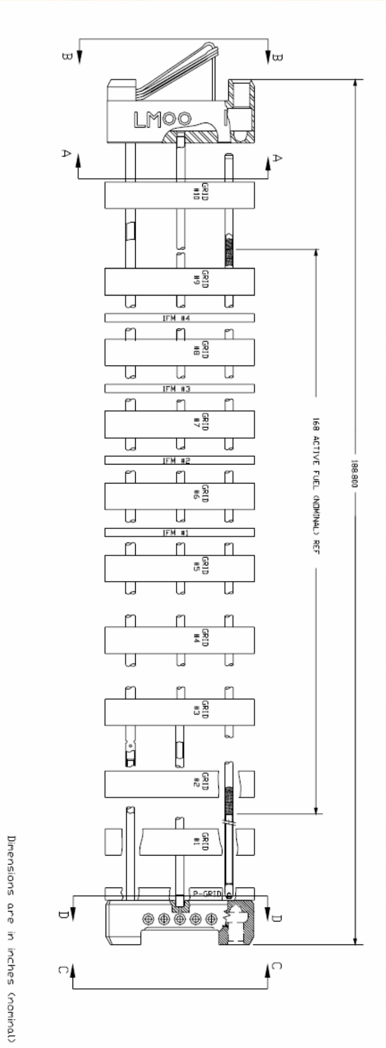
AP-1000 Containment Is Unique

Containment Pressure - Design	59.0 psig
Net Free Volume (ft3)	2.06E+06
Double-ended Hot Leg Guillotine - Max Pressure	50.0 psig
Max Temperature	416.5ºF
Double-ended Cold Leg Guillotine - Max Pressure	57.8 psig
Max Temperature	284.9ºF
Steamline DER, 101% Power, MSIV Failure - Pressure	53.7 psig
Max Temperature	375.3ºF
Assumptions: Outside Temperature 115ºF dry bulb/ 80ºF wet bulb Initial Containment Temperature 120ºF 1 of 3 cooling flow paths to containment is failed	

17x17 Fuel Assemblies Typical for PWR

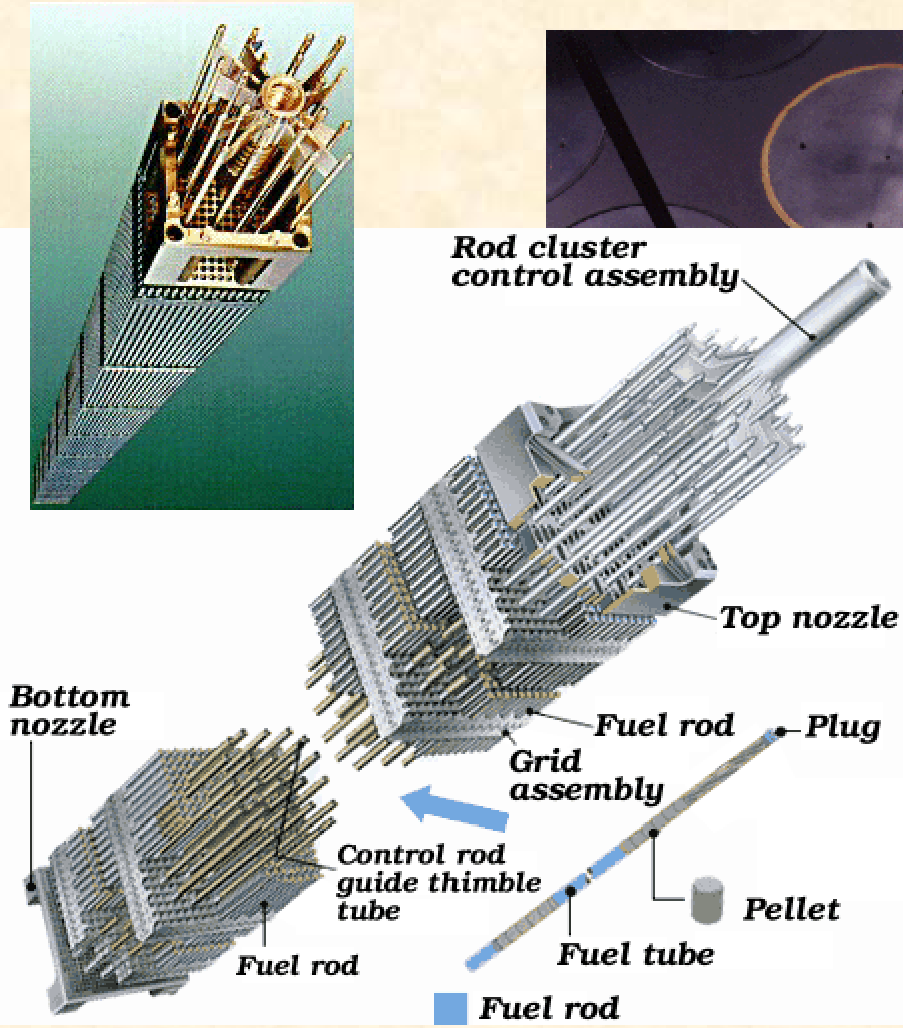


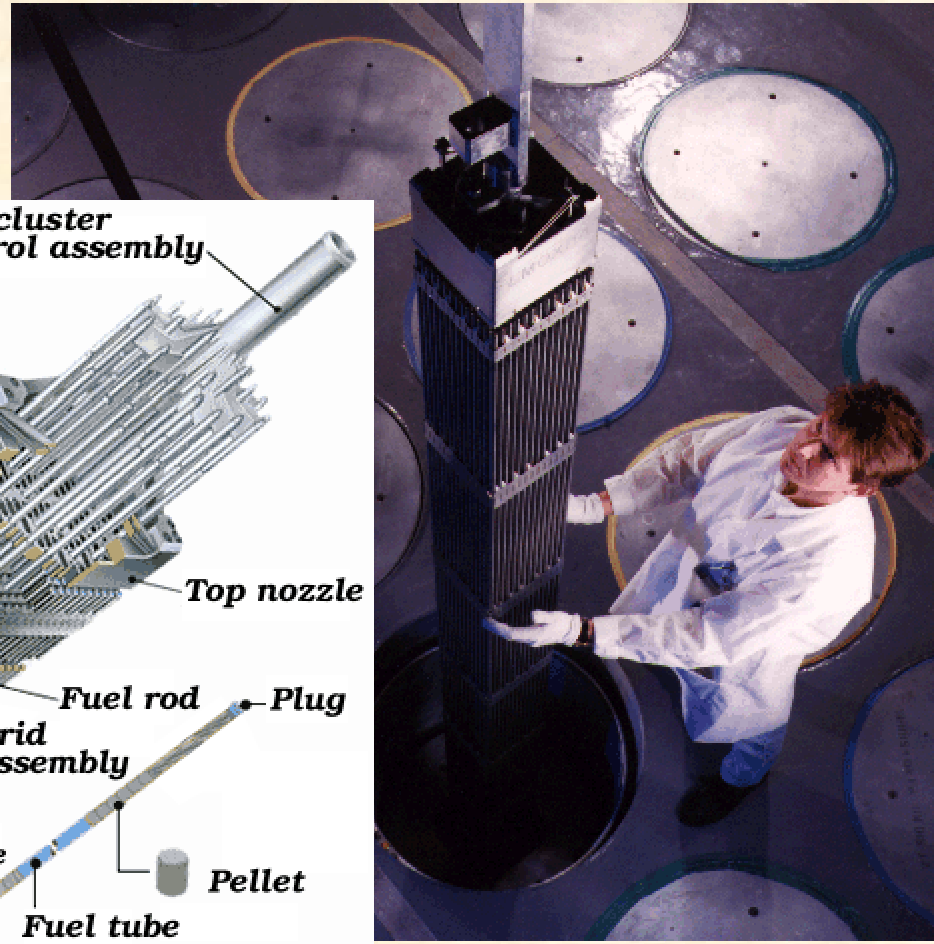




- Same core as used in existing operating plants (~120 worldwide)
  - 17x17 fuel assembly
  - Zirlo cladding, UO2 fuel
  - AP-600 has 145 assemblies, 12’ active core length, 4.1 kw/ft
  - AP-1000 has 157 assemblies, 14’ active core length, 5.7 kw/ft

Typical PWR Fuel Assemblies





AP-1000 Reliability Objectives

- **Capacity factor greater than 90 percent**
  - **Fewer Components**
  - **Less maintenance**
  - **Fewer Technical Specifications**
  - **Shorter Planned Outages**
- **60 year lifetime without the planned replacement of the reactor vessel**
- **Major components are based on proven design**
- **18-month fuel cycle consistent with current PWRs**

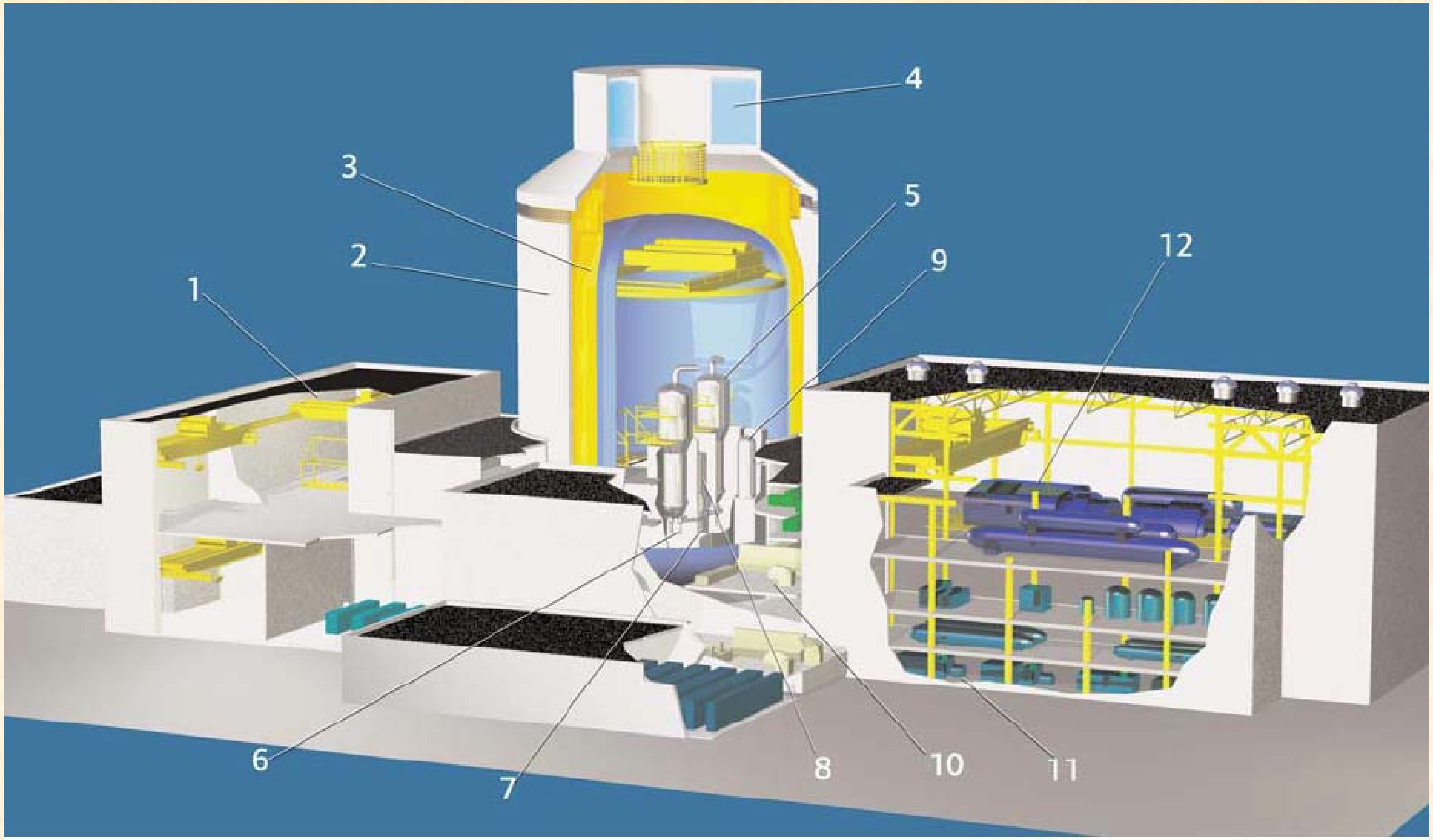
Source: AP-1000 DCD, Tier 2 Material, 1.2.1.1.2

Power Capability Objectives

- Net electrical power to the grid is at least 1000 MWe with a nuclear steam supply system power rating of about 3415 MWt (including reactor coolant pump heat).
- Attain rated performance with up to 10 percent of the steam generator tubes plugged without exceeding max hot leg temperature of 610°F.
- Accept a 100 percent load rejection from full power to house loads without reactor trip or operation of the pressurizer or steam generator safety valves. The design provides for a turbine capable of continued stable operation at house loads.
- Permit a design basis daily load follow cycle for at least 90 percent of the fuel cycle length. The daily load follow cycle is defined as operation at 100 percent power, followed by a 2-hour linear ramp to 50 percent power, operation at 50 percent power and a 2-hour linear ramp back to 100 percent power. The duration of time at 50 percent power can vary between 2 and 10 hours.

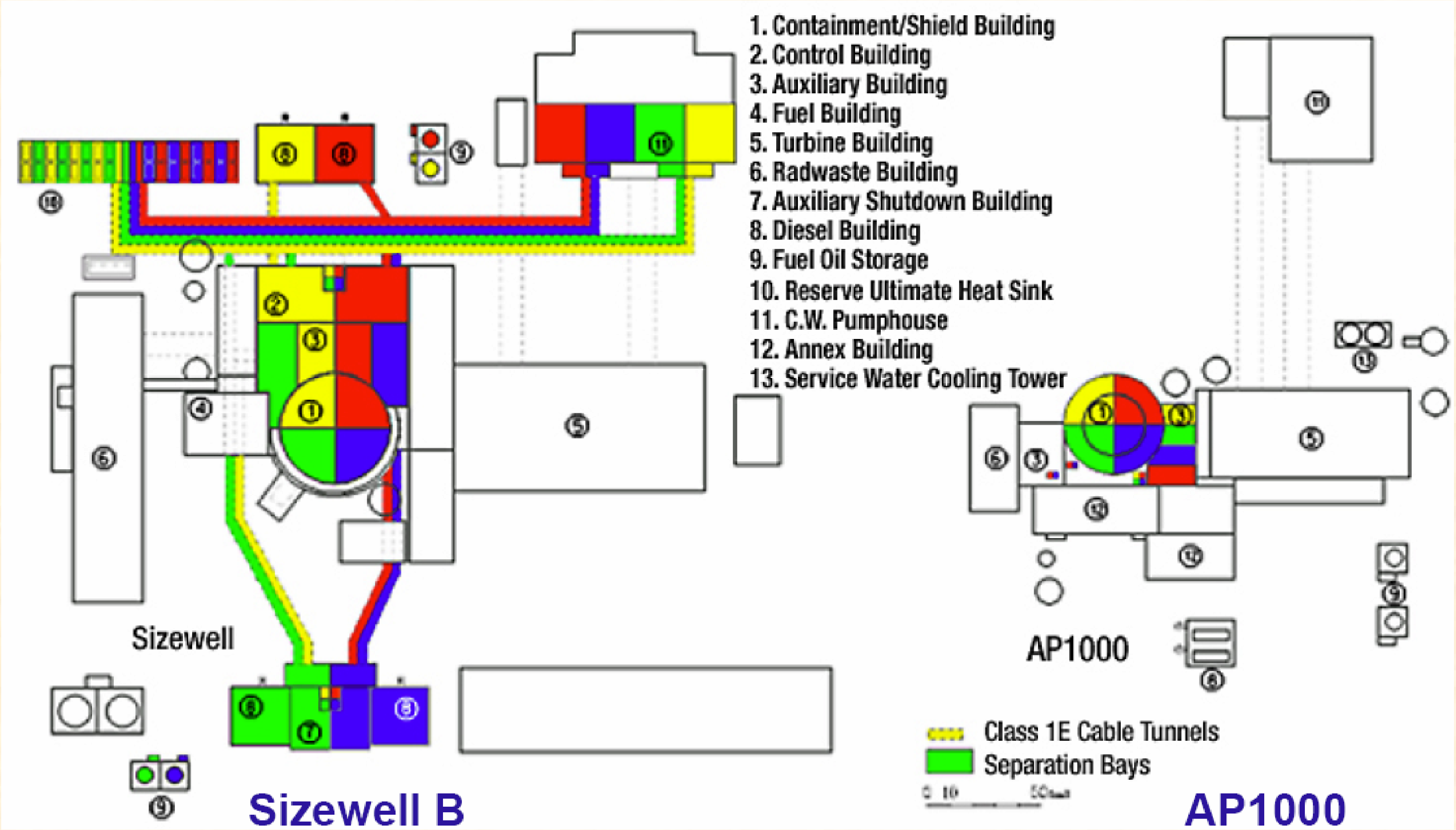
Source: AP-1000 DCD, Tier 2 Material, 1.2.1.1.1

AP-1000 Basic Plant Layout



1. Fuel-handling Area
2. Concrete Shield Building
3. Steel Containment
4. Passive Containment Cooling Water Tank
5. Steam Generators (2)
6. Reactor Coolant Pumps (4)
7. Reactor Vessel
8. Integrated Head Package
9. Pressurizer
10. Main Control Room
11. Feedwater Pumps
12. Turbine Generator

AP-1000 Site Comparison



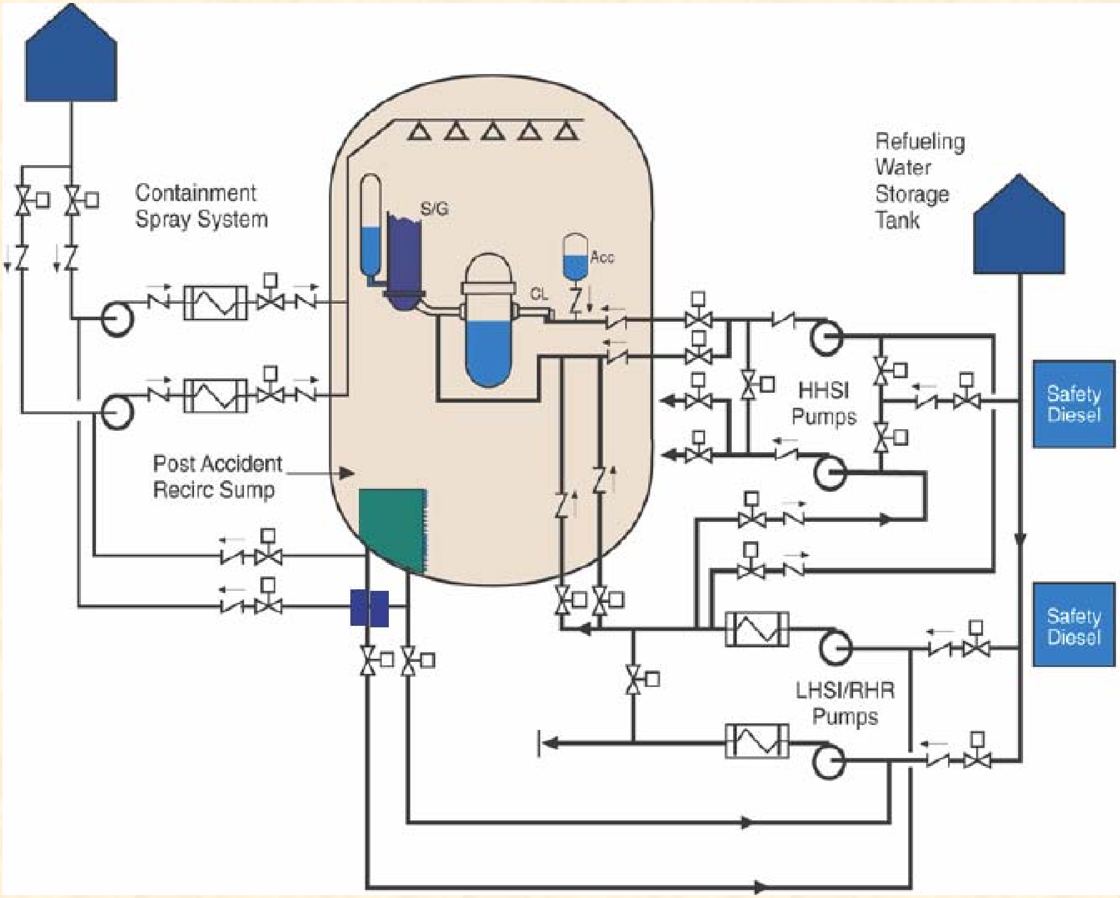
Major AP-1000 Safety Advancements

- **Long Term Plant Safety Assured without Active Components**
  - **Use "passive" process only, no active pumps, diesels, ….**
    - **One time alignment of valves**
    - **No support systems required after actuation (72 hours)**
    - **No Reliance on AC Power**
    - **No Operator Action Required to Assure Safety**
- **Containment is Not Breached for Postulated Design Basis Events**
- **In Severe Accidents, Reactor Vessel Cooling Keeps Core in Vessel**
- **Large Margin to Safety Limits**
- **Defense in Depth - Active (Non-Safety) Systems Provide ADDITIONAL first line of defense**

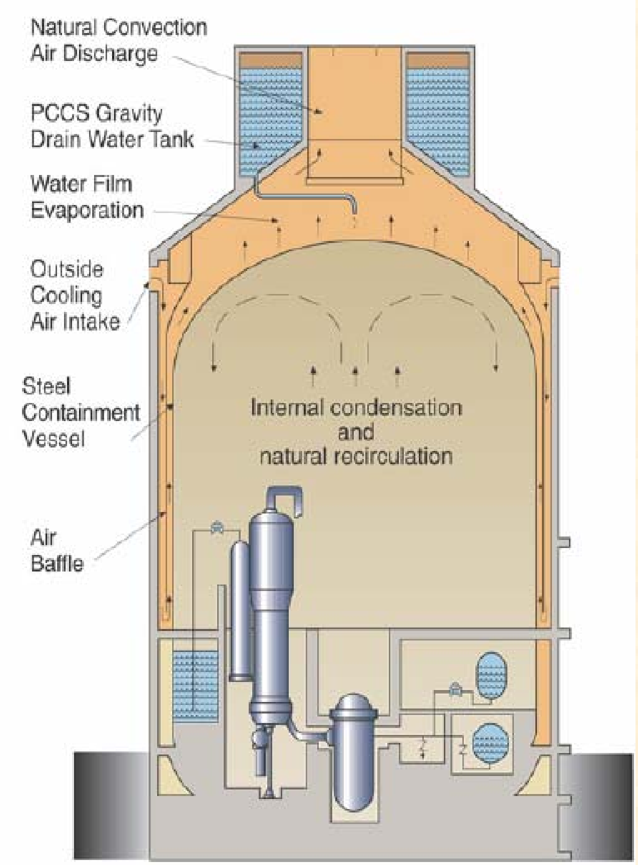
Resulting Safety Systems Eliminated or Replaced by Nonsafety Systems

- **Safety Injection (SI)**
  - **No active components after valves reposition**
- **Residual Heat Removal (RHR)**
  - **No active components after valves reposition for passive response**
  - **Active nonsafety system uses 2-1000 gpm pumps**
  - **Current plants use 2-4000 gpm safety-related pumps**
- **Containment Spray**
  - **Two non-safety spray rings exist to provide the capability to remove airborne particulates or elemental iodine**
  - **Manual valve alignment to fire protection system required**
- **Emergency Diesel Generators**
  - **Starting and loading requirements reduced because AP-1000 EDGs are a nonsafety system**
- **Larger Pressurizer**
  - **Power Operated Relief Valves (PORVs) eliminated**
  - **Pressurizer Relief Tank eliminated**
- **Canned Reactor Coolant Pumps**
  - **RCP seal leakage eliminated**
  - **Charging pumps become a nonsafety system**

Simplified Emergency Systems

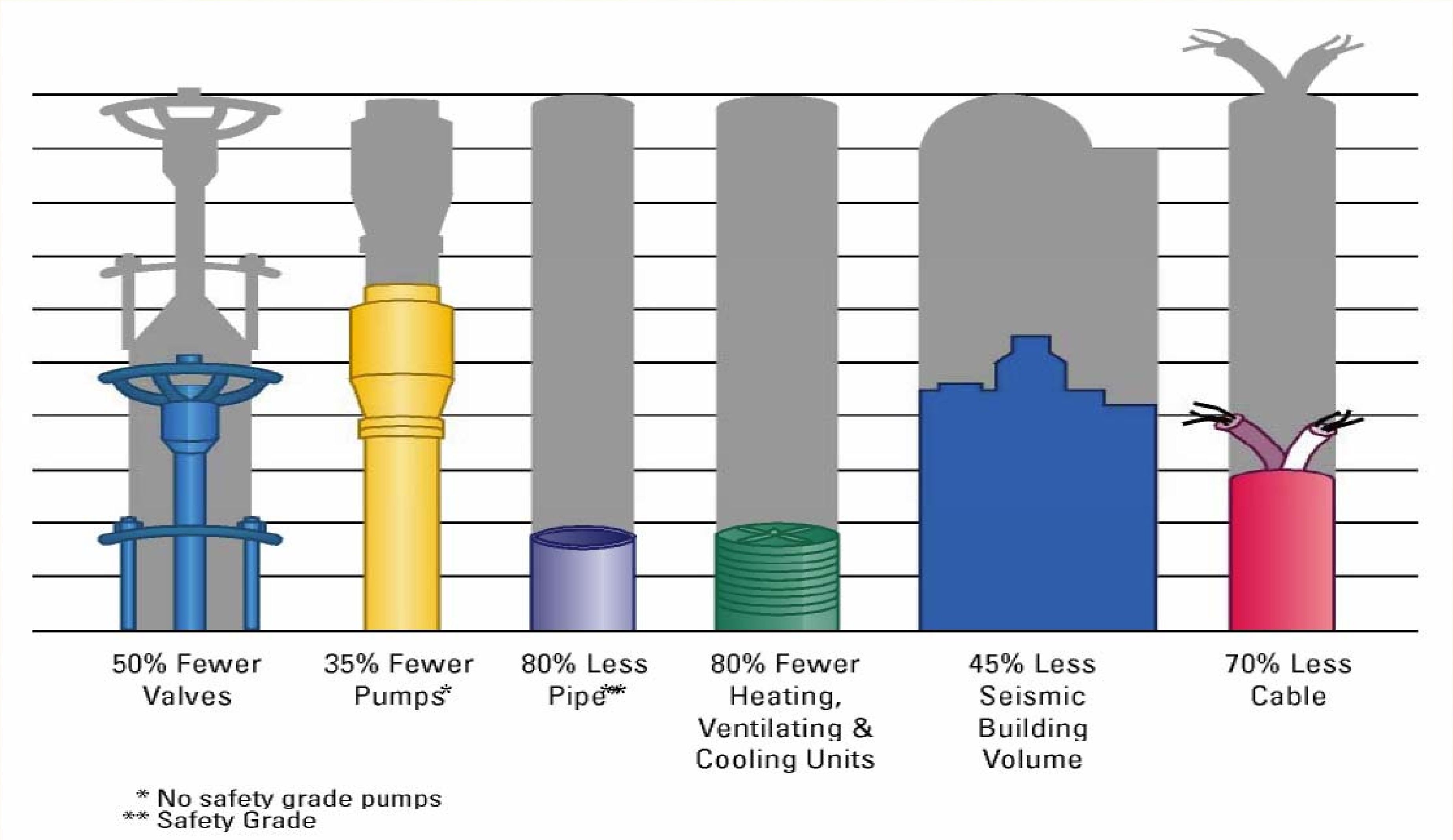


Current PWR

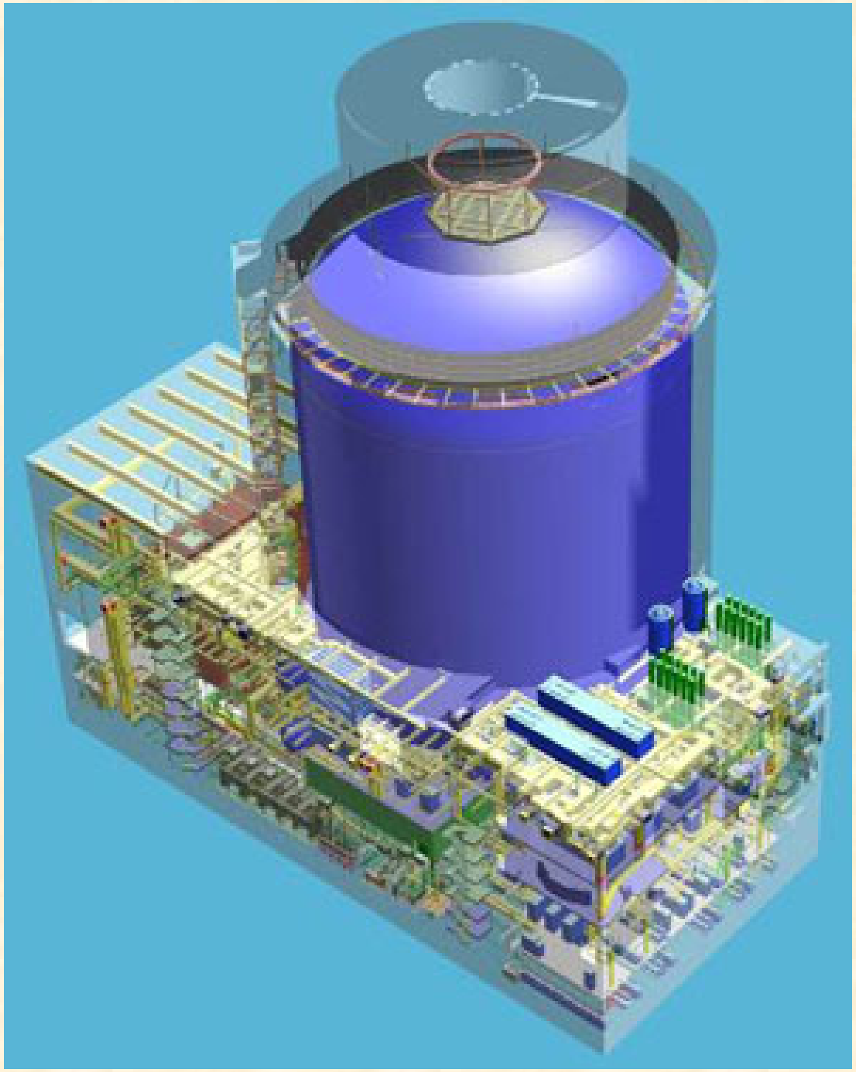


AP-1000

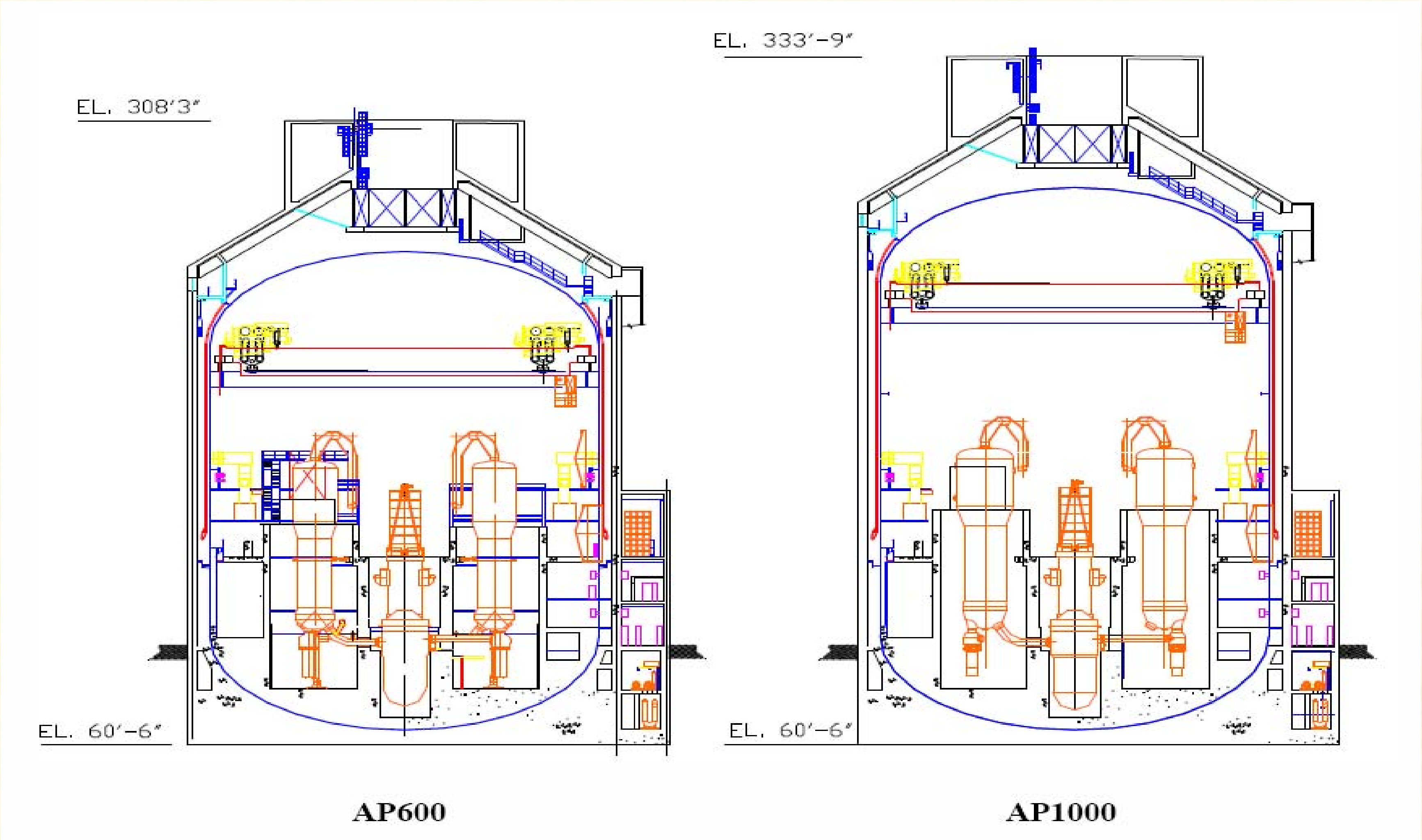
Resulting Component Reduction…



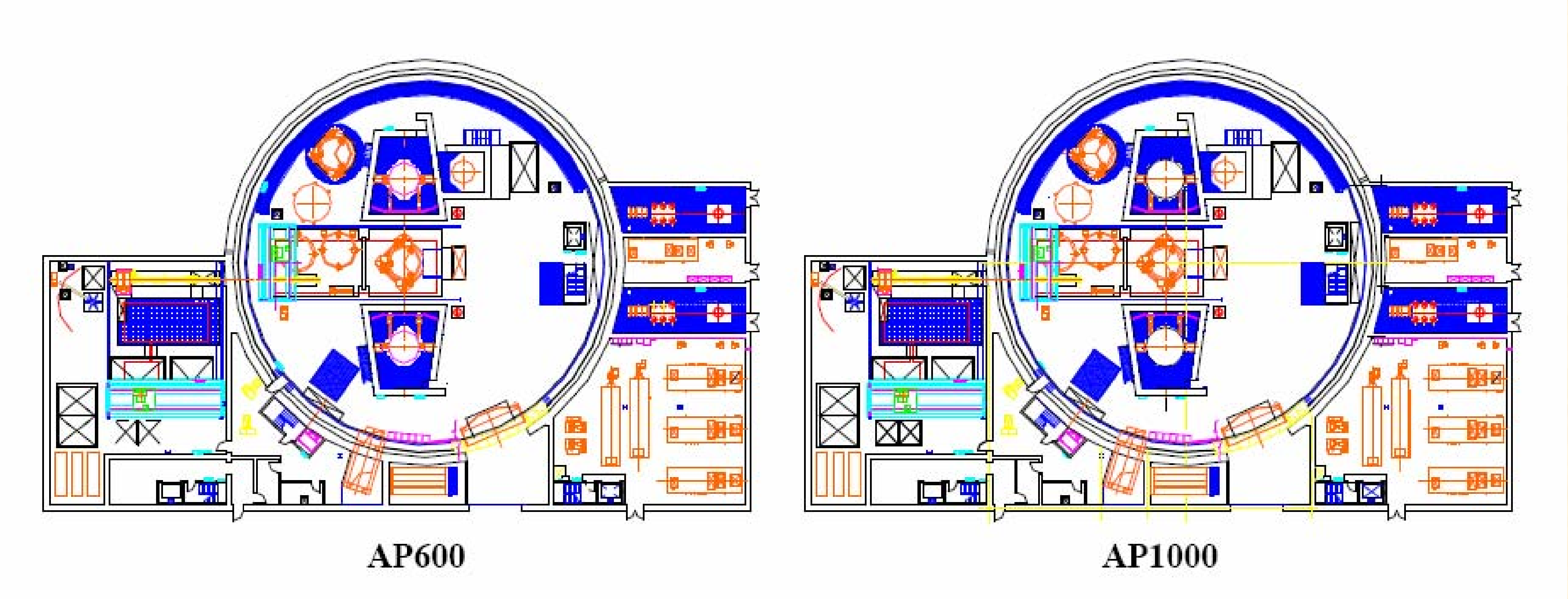
3-D Views of Containment



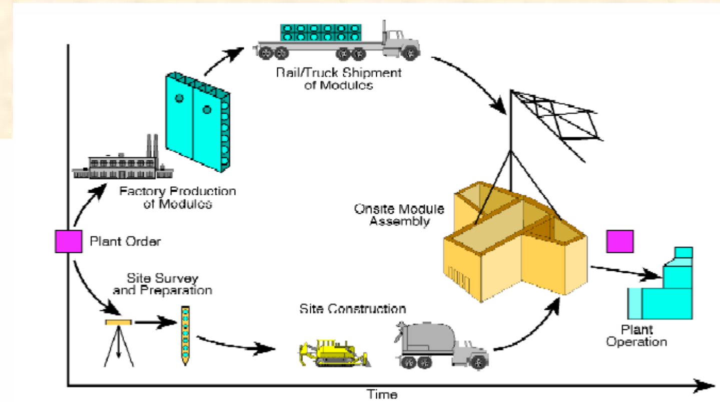
AP-1000 Axial Containment Volume Slightly Larger Than AP-600

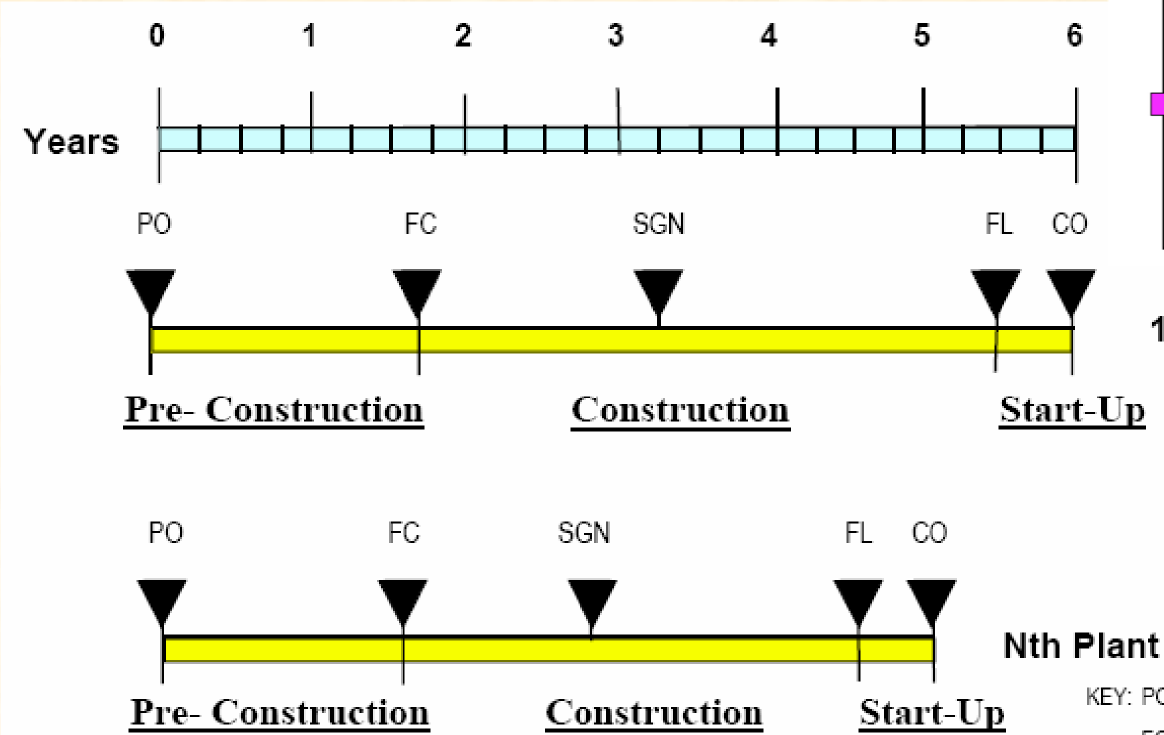


AP-1000 Radial Containment Footprint Is the Same as the AP-600



Modular Design Improves Schedule





KEY: PO = Place Order (Release Procurements, Start Site Work)

FC = First Basemat Concrete

SGN = Steam Generator Installation

FL = Fuel Load

CO = Commercial Operation

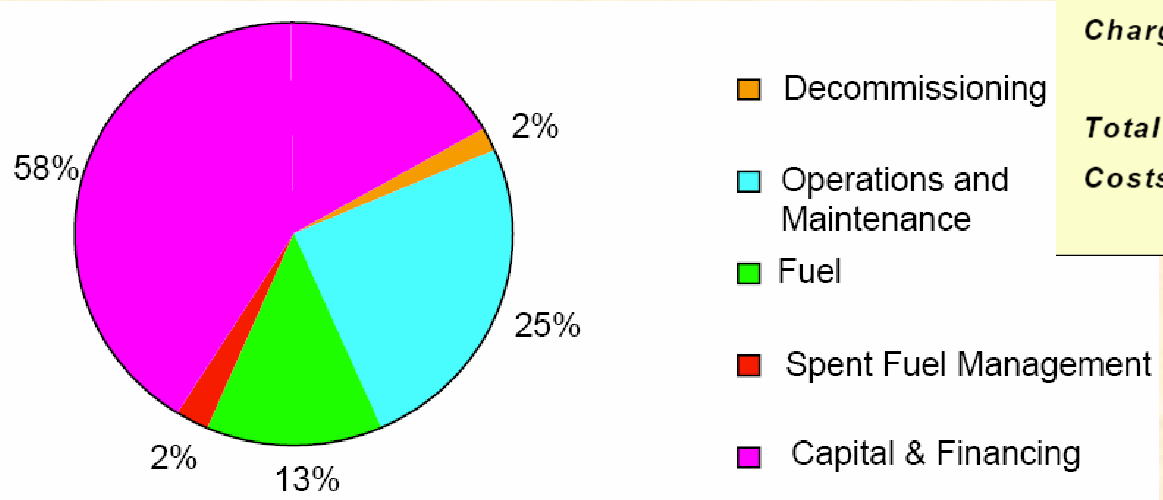
Source: Richard Mayson, BNFL Technical Director for Reactor Systems, 2003

AP-1000 Cost Analysis

- **Construction and Operating Costs**
  - **20-30% reduction in capital cost**
  - **1/3 lower staffing (particularly maintenance)**
- **Projected electricity costs**
  - **4.1 – 4.6 cents/KWh for AP-600**
  - **3.0 – 3.5 cents/KWh for AP-1000**

Aspect	AP1000
Overnight Capital Cost ($/kWe)	1000 - 1200
Capital Cost Recovery Charge (¢/kWh)	2.1 – 2.5
Fuel & O&M Charge (¢/kWh)	1.0
Decommissioning Charge (¢/kWh)	0.1
Total Generation Costs (¢/kWh)	3.2 – 3.6

Source: Dr. Regis Matzie, BNFL Chief Technology Officer, 2003

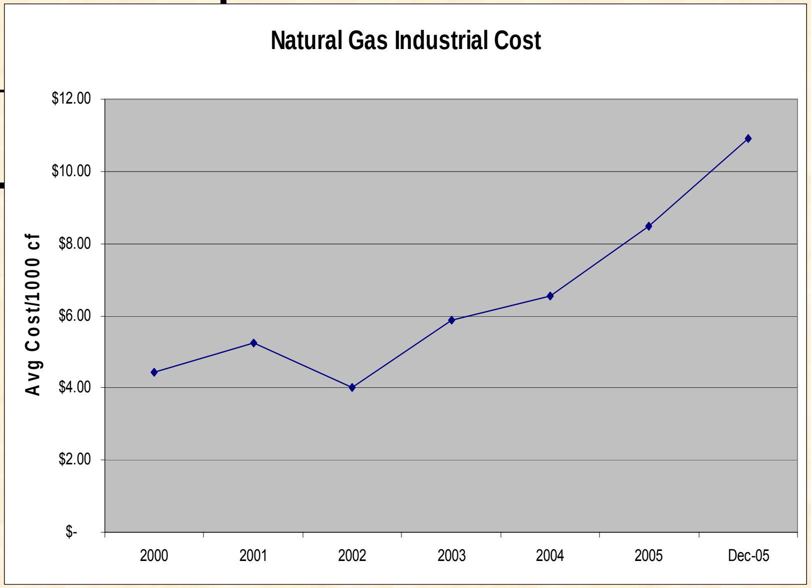


Source: Richard Mayson, BNFL Technical Director for Reactor Systems, 2003

O&M Cost of Alternative Fuels

Source	Fuel and O&M Charge Cents/kWh
Typical Nuclear Plant	1.83
Coal-Fired Plant	2.07
Oil-Fired Plant	3.18
Natural Gas Plant	3.52
AP-1000 Projection	1.0 (3.6 total)

Source: IAEA-TECDOC-1290, May 2002



Source: DOE Energy Information Administration / Natural Gas Monthly February 2006

AP-1000 Summer Seminar Outline

- **PWR Primer** **(10 minutes)**
- **Design Status** **(5 minutes)**
- **Plant Overview and Key Design Features** **(20 minutes)**

Key Systems **(20 minutes)**

- **Primary System**
- **Engineered Safeguards**
- **Primary Support Systems**
- **I&C**

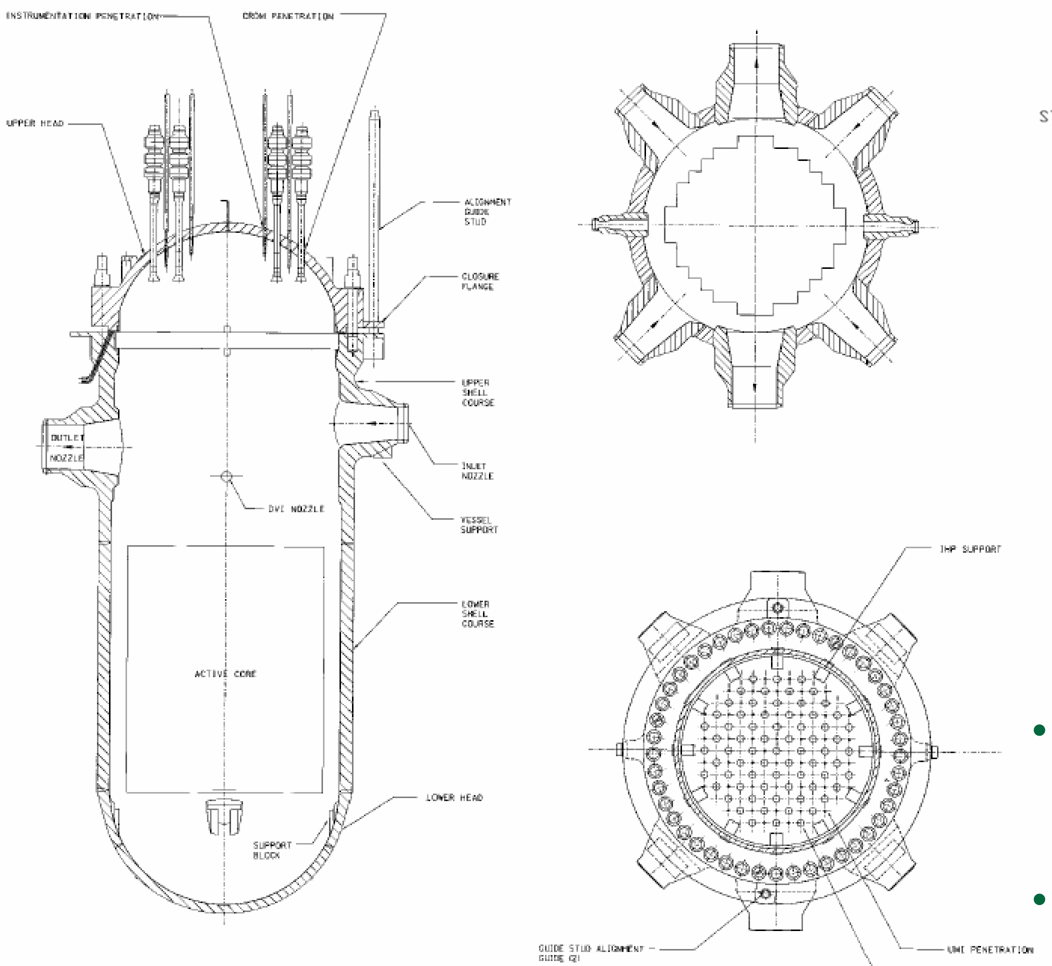
- **Accident Analysis** **(5 minutes)**
- **Questions & Wrap-up**

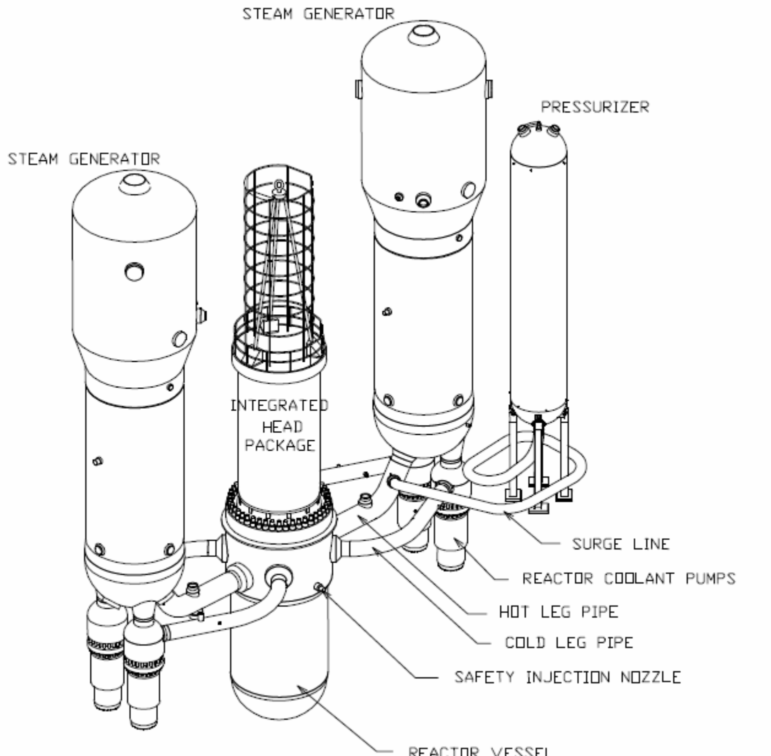
Primary System

- Reactor Vessel
- Reactor Piping
- Reactor Coolant Pumps
- Pressurizer

Principle Source: AP-1000 DCD, Tier 2 Material, Chapter 5

Reactor Vessel Schematic Shows the Results of the Reactor Design Objectives

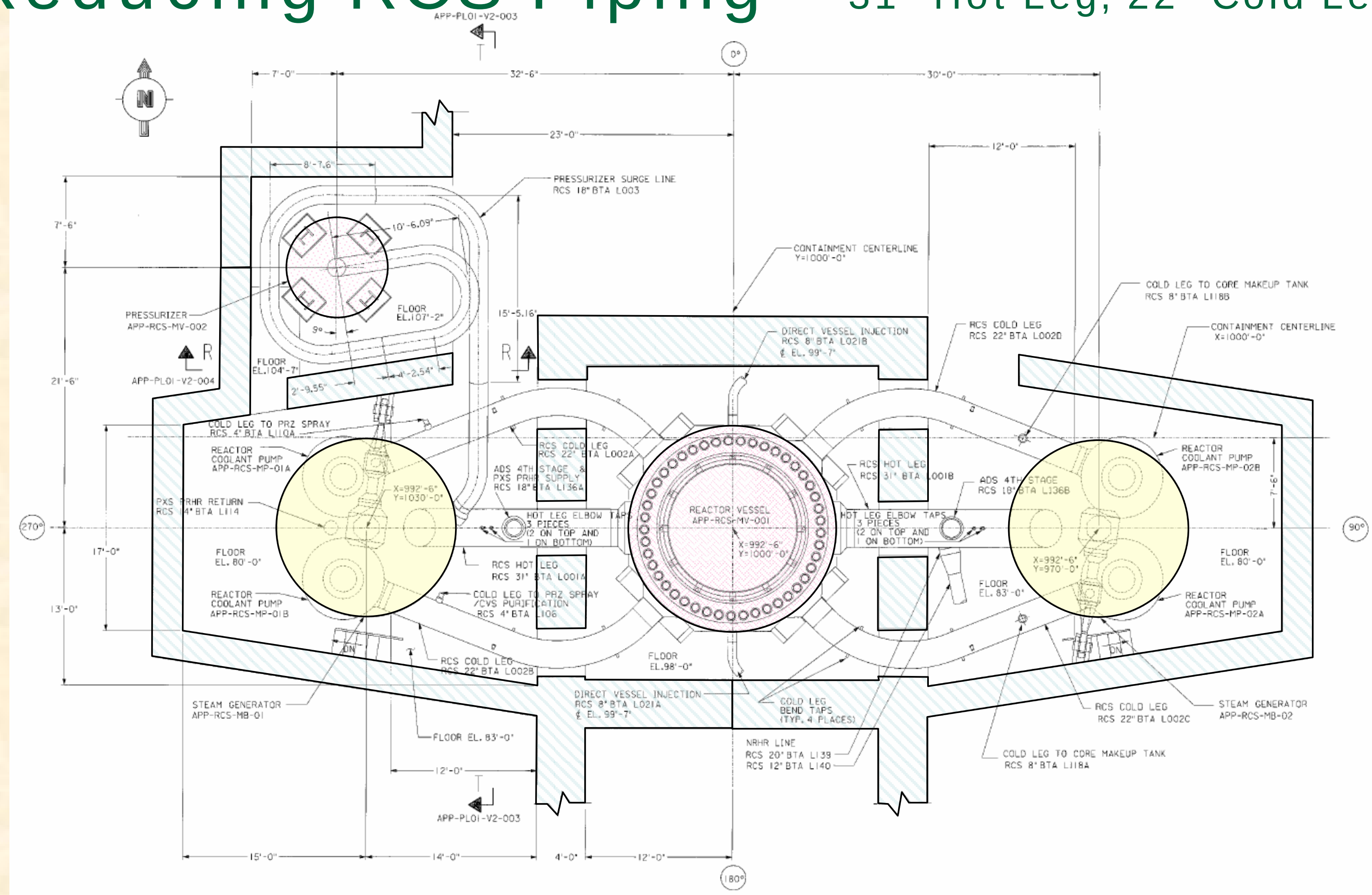




Source: AP-1000 DCD, Tier 2 Material, 1.2.1.2.1

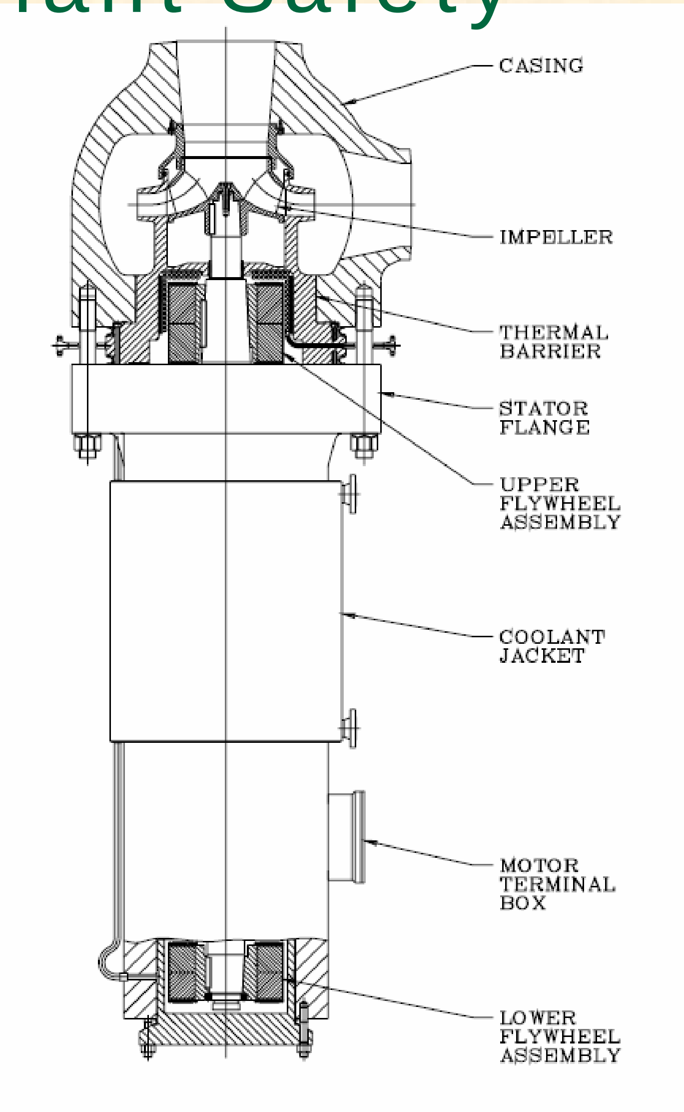
- **There are no reactor vessel penetrations below the top of the core.**
  - **Bottom mounted incore instrumentation is not used.**
- **The core is designed for a negative moderator temperature coefficient over the entire fuel cycle at any power level with the reactor coolant at the normal operating temperature.**

Component Placement Key to Reducing RCS Piping – 31” Hot Leg, 22” Cold Leg



Reactor Coolant Pump Placement and Design Enhances Plant Safety

- **Variable Speed Pumps**
  - **Run in slow speed when plant is cold to minimize power requirements**
  - **Used to adjust heat up rate during plant heatup**
  - **Run at constant speed when reactor trip breakers are closed**
  - **Proven design**
  - **Good Coast down**
    - **30% flow at 10 sec**
  - **No seal leakage – SBLOCA path eliminated**
  - **Height: 21 ft 11.5 inches**
  - **Weight: 184,500 lbs**



Engineered Safeguards

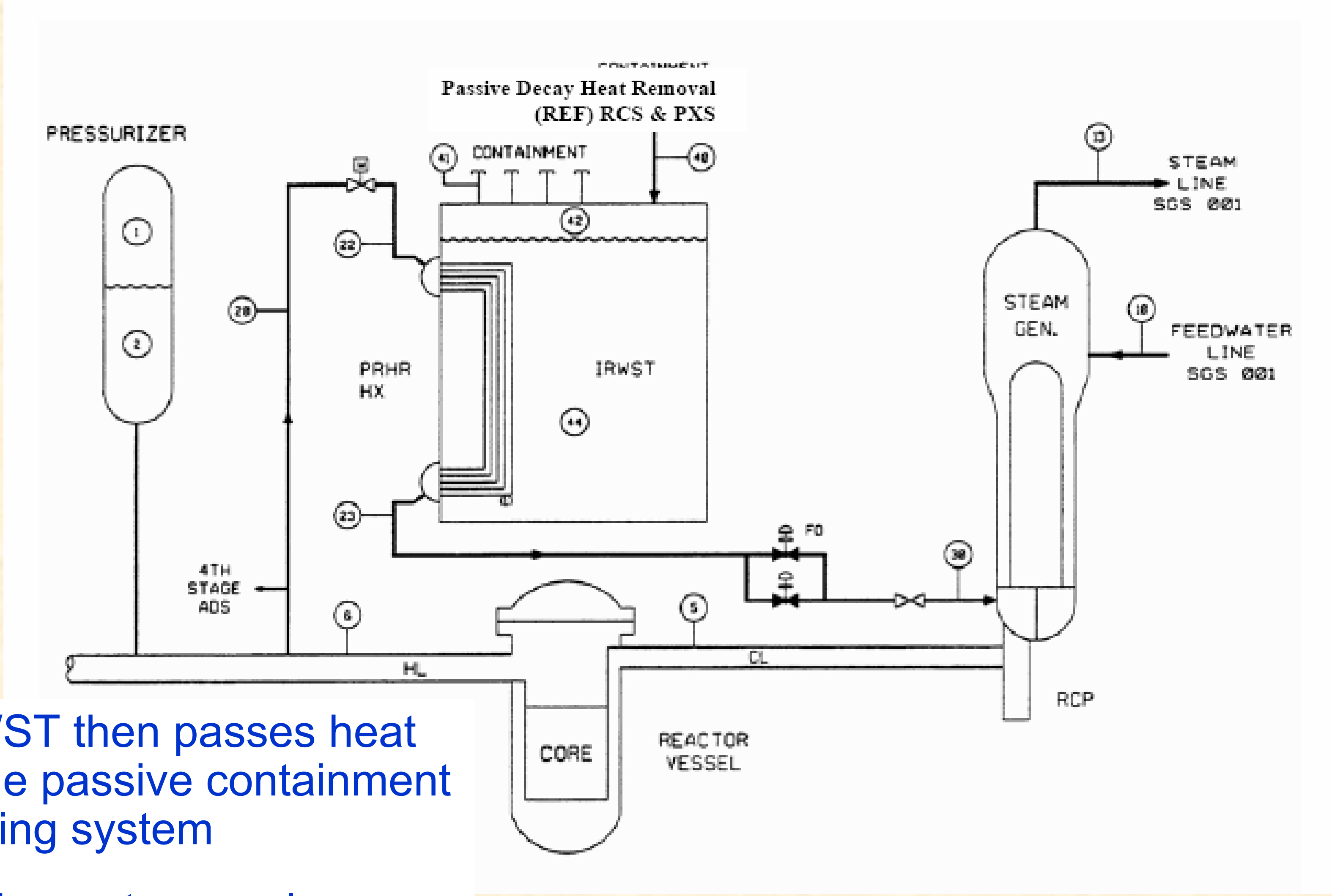
- **Passive Core Cooling System**
- **Automatic Depressurization System**
- **Passive Containment Cooling System**
- **Control Room Habitability**

Principle Source: AP-1000 DCD, Tier 2 Material, Chapter 6

Passive Core Cooling System Provides Emergency Core Cooling Following Postulated Design Basis Events

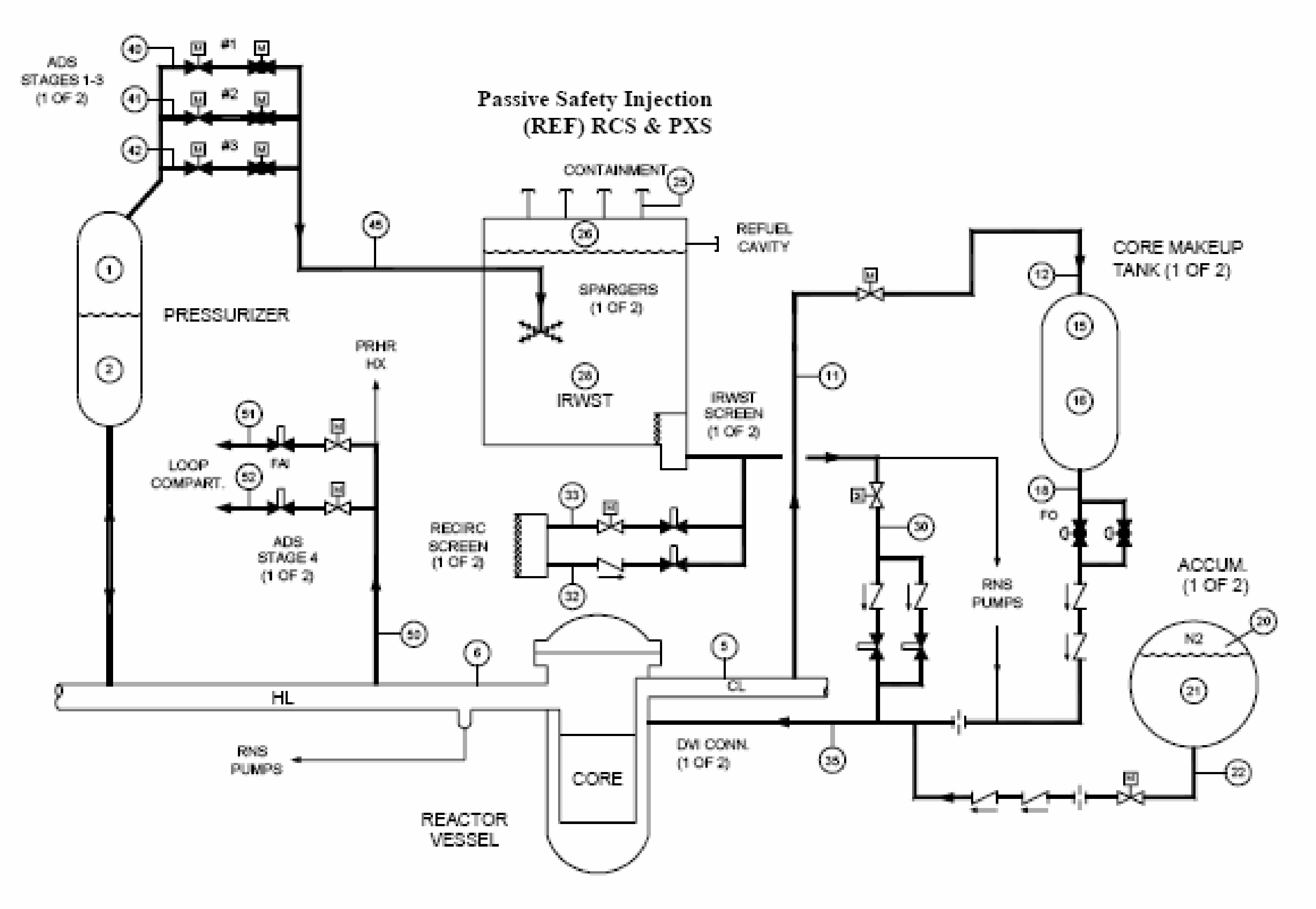
- The system provides the following functions:
  - Emergency core decay heat removal (RHR function)
  - Reactor coolant system emergency makeup and boration
  - Safety injection (SI)
  - Containment pH control (granulated TSP baskets)
- The passive core cooling system can maintain safe shutdown conditions for 72 hours after an event without operator action and without both nonsafety-related onsite and offsite power.
- Current NRC concerns about current PWR recirculation sump clogging are addressed in the AP-1000 design.

The Passive Core Cooling Uses Natural Circulation to Pass Heat to the IRWST



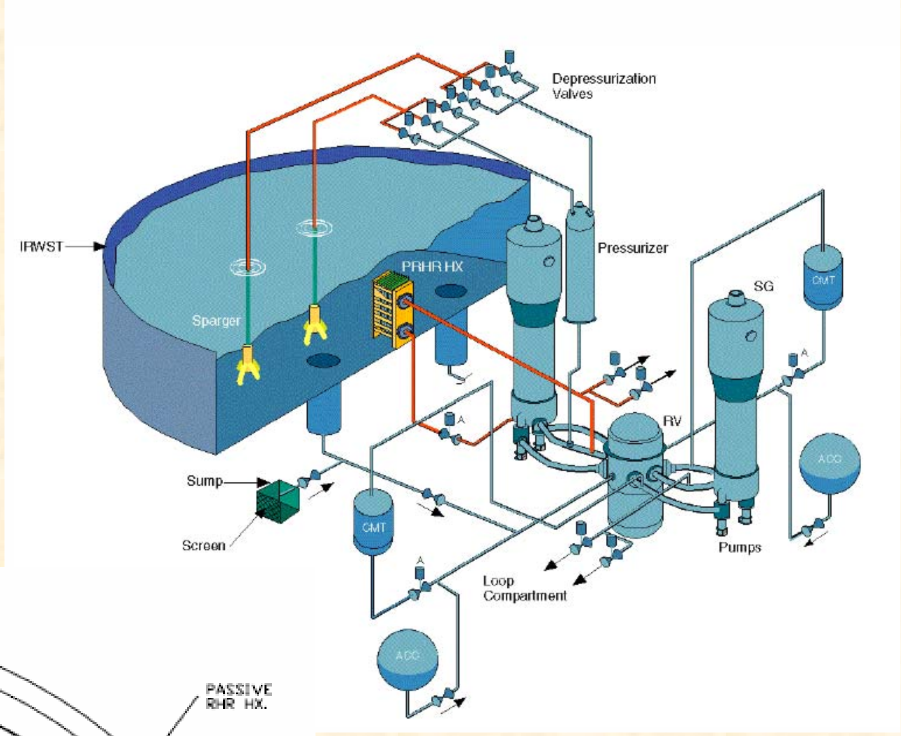
- IRWST then passes heat to the passive containment cooling system
- 30-day water supply

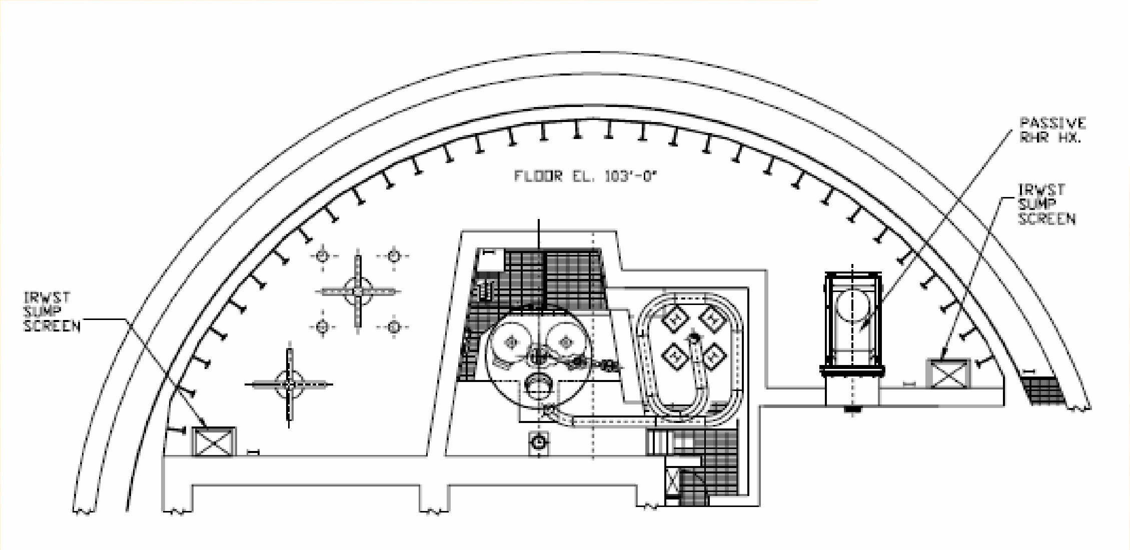
The Passive Core Cooling System Uses Several Sources of Water for SI



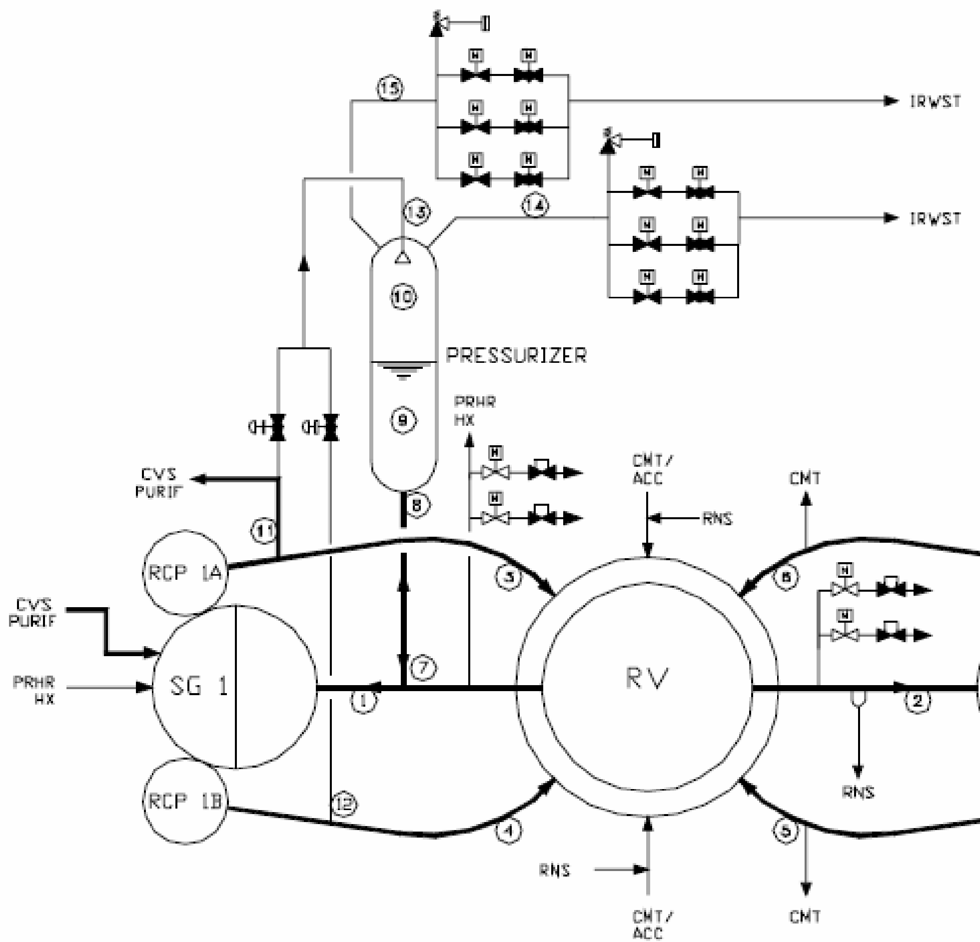
Spatial Look at Passive Core Cooling System Elements

- **Passive RHR will lower primary temperature below 420 ºF (Mode 4 – Safe Shutdown) in 36 hours**
- **Core Makeup Tank level is the key to initiating Automatic Depressurization; Accumulator Injection; and IRWST Gravity Insertion**
- **System is designed to address PWR recirculation sump screen clogging issue**



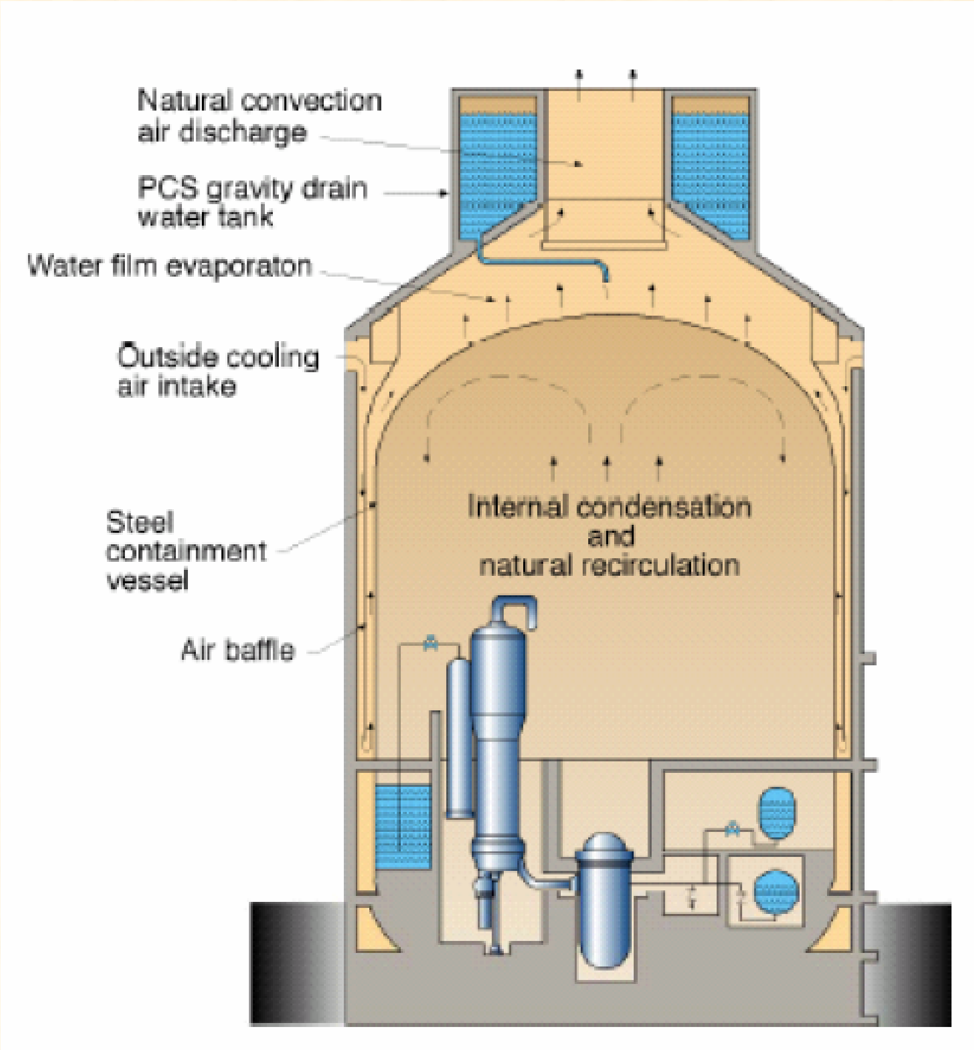


Automatic Depressurization System Reduces Severity of LOCAs and SG Tube Ruptures



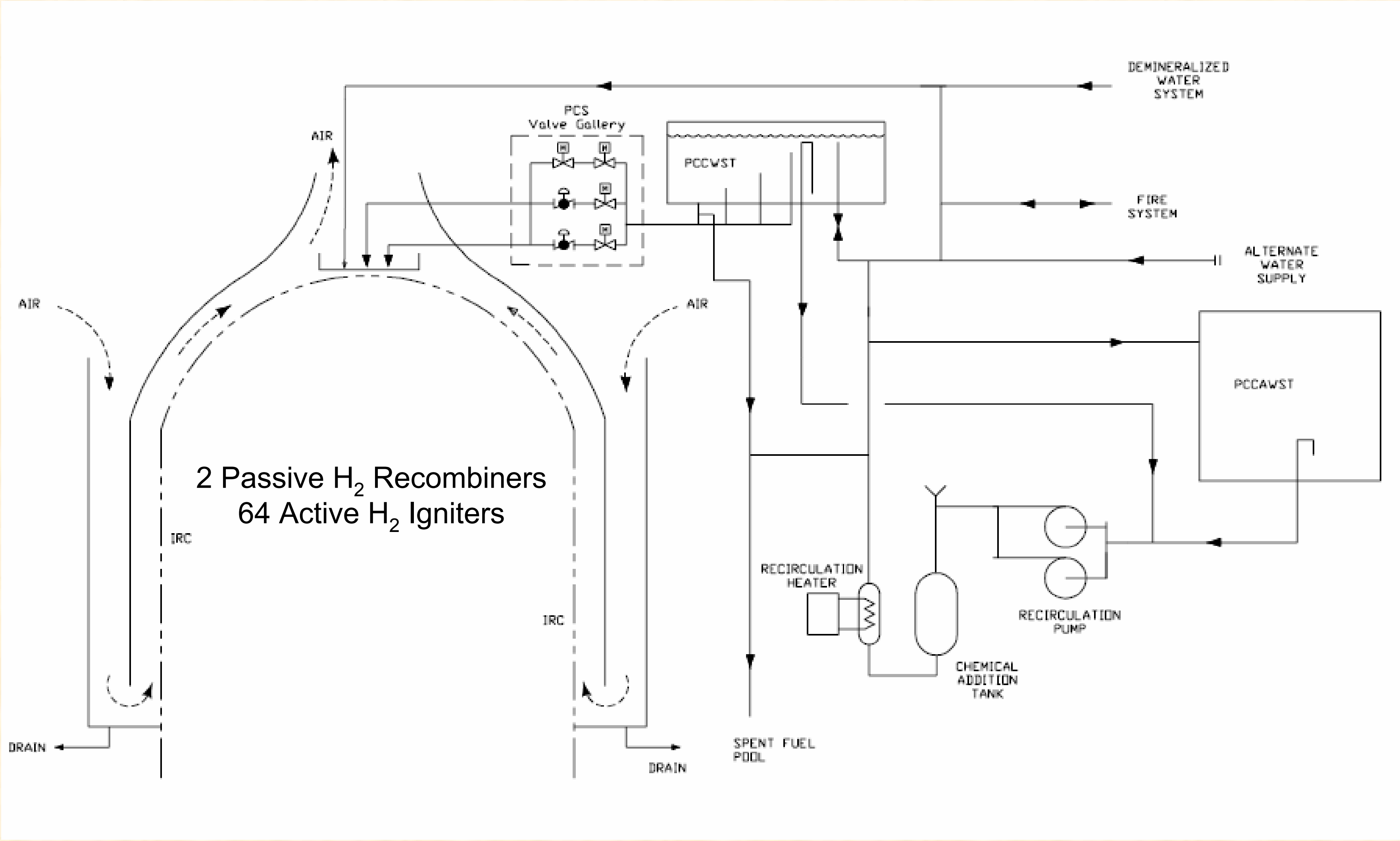
- ADS controls are arranged to open ADS valves in a prescribed sequence based on core makeup tank level and a timer
- Allows the passive core cooling system to function

Passive Containment Cooling Provides Emergency Heat Sink



- **Delivers water from the PCCWST to the outside, top of the containment vessel (72 hour supply)**
- **Provides air flow over the outside of the containment vessel by a natural circulation**
- **PCCAWST contains an inventory of cooling water sufficient for PCS containment cooling from hour 72 through day 7 (with ac power)**
- **Interconnects with Fire System and Demineralized Water System**

Passive Containment Cooling Schematic Shows System Versatility



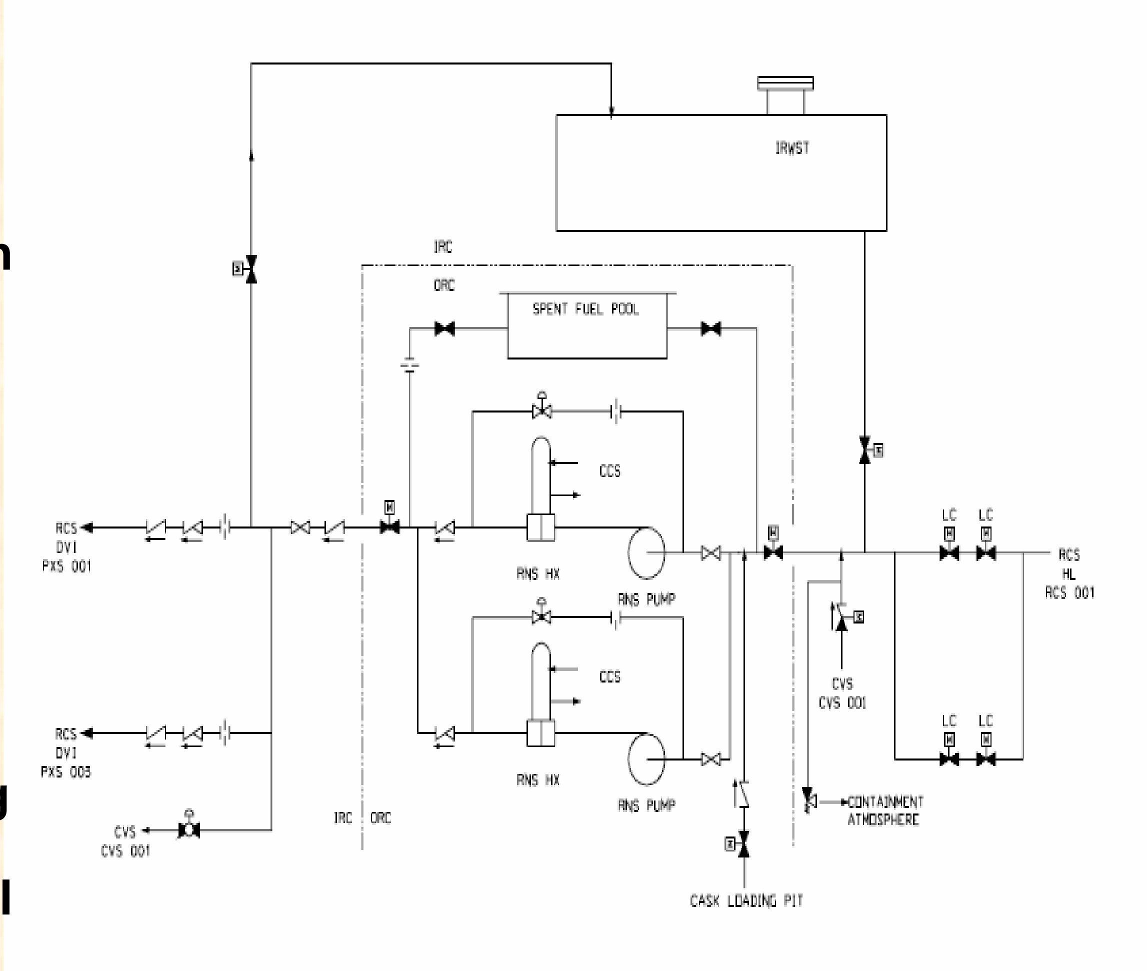
Primary Support Systems

- **Normal RHR**
- **Component Cooling Water**
- **Chemical and Volume Control**
- **Steam Generators**

Principle Source: AP-1000 DCD, Tier 2 Material, Chapters 5 & 9

Normal RHR Provides Long-term Post-Accident Makeup to the RCS

- **Normal RHR provides for:**
  - **Low temperature overpressure protection (LTOP) during shutdown operations.**
  - **Heat removal during shutdown operations.**
  - **Low pressure makeup flow from the SFS cask loading pit to the RCS for scenarios following actuation of the ADS system.**
  - **Heat removal from the in-containment refueling water storage tank.**
  - **Alternate spent fuel pool cooling**



The Component Cooling Water System is Not a Safety System

Allows the Elimination of a Standby Pump

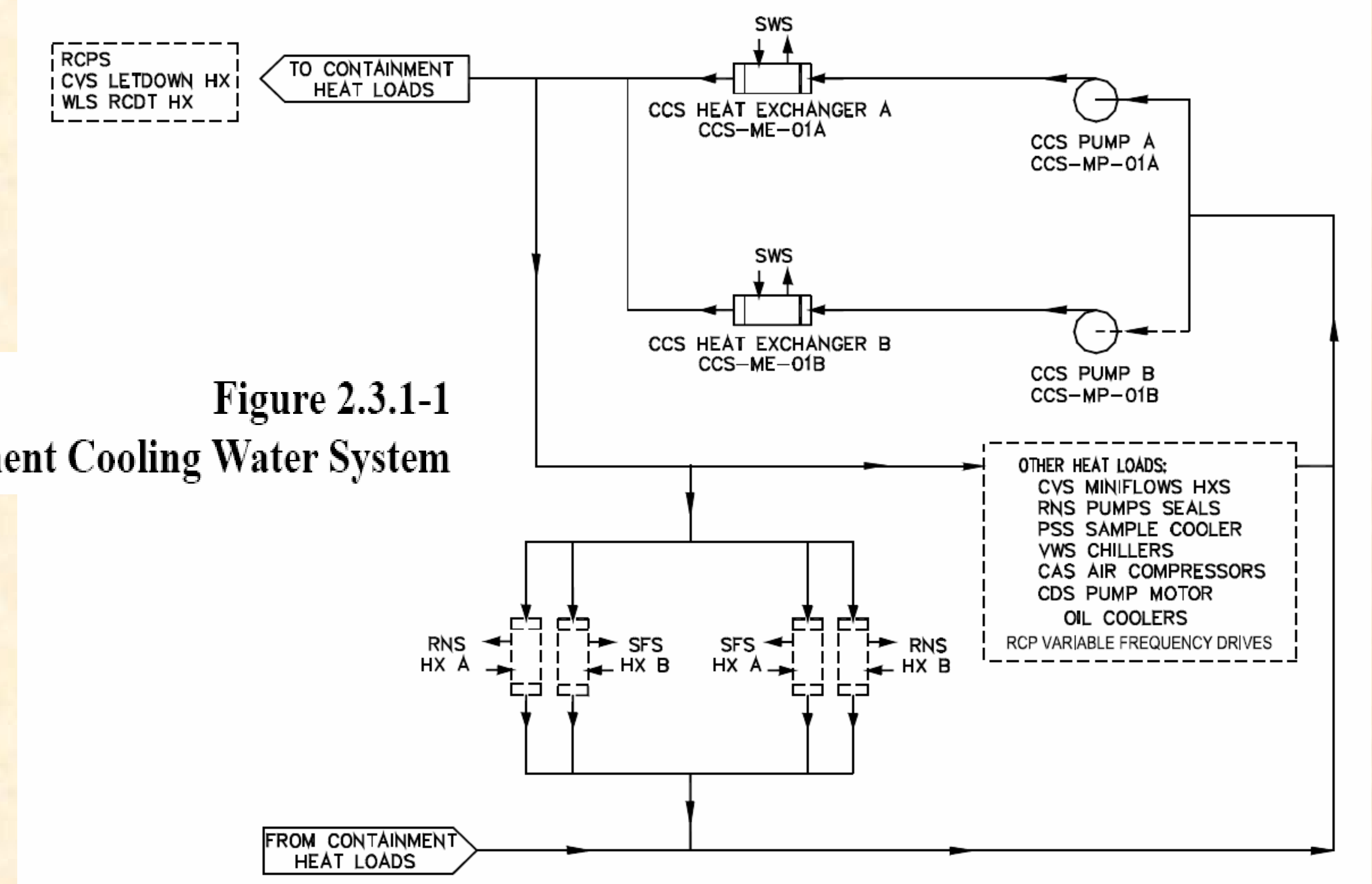


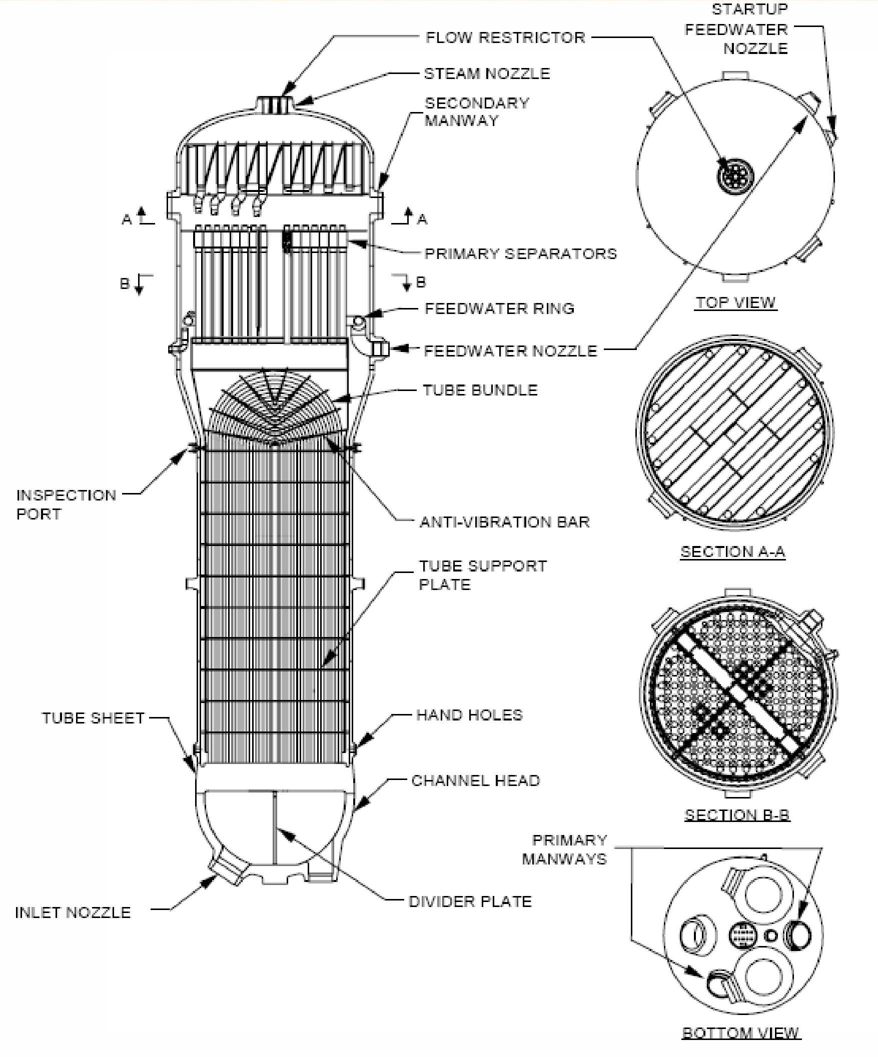
Figure 2.3.1-1
Component Cooling Water System

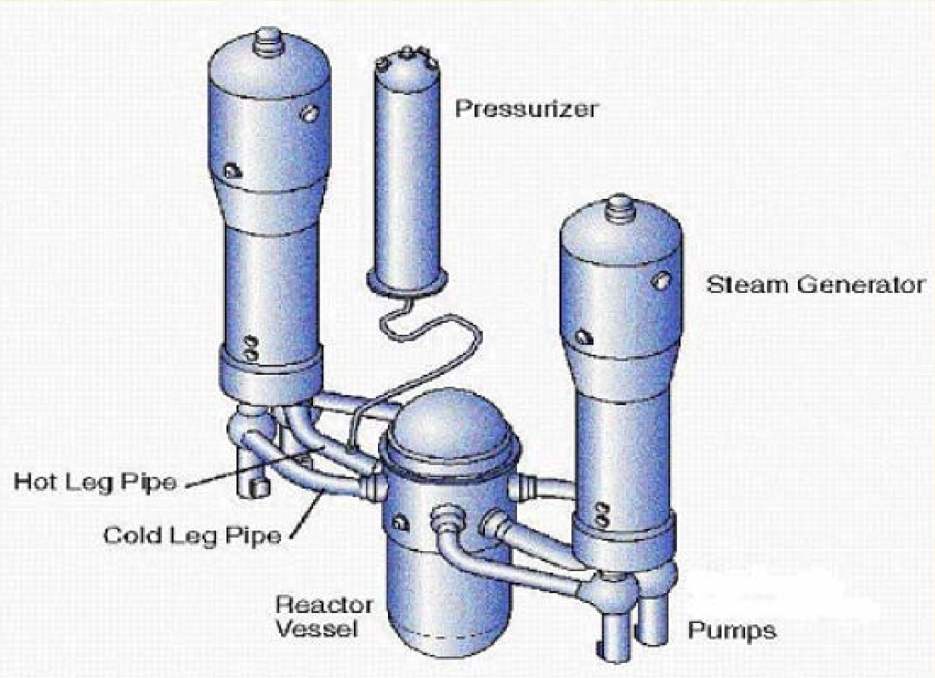
Chemical & Volume Control System (CVCS) Is Not a Safety System

Allows the Elimination of a Standby Pump

- **Pumps do not run continuously (no RCS pump seals to cool/compensate)**
- **Pumps are centrifugal instead of positive displacement as found on typical PWR**
- **Provides for:**
  - **RCS purification**
  - **RCS inventory control & makeup**
  - **RCS chemical shim**
  - **RCS oxygen control**
  - **Auxiliary pressurizer spray**
- **The system will auto-start on a low pressurizer level - the reactor coolant system makeup capability is sufficient for reactor coolant leaks up to 3/8 inch**

Steam Generator is Typical of Current Designs





- **10,025 Tubes**
- **Approximately 74 feet tall**
- **Primary Water Volume 2077 ft^3**
- **Secondary Water Volume 3646 ft^3**
- **Secondary Steam Volume 5222 ft^3**

Instrumentation & Controls

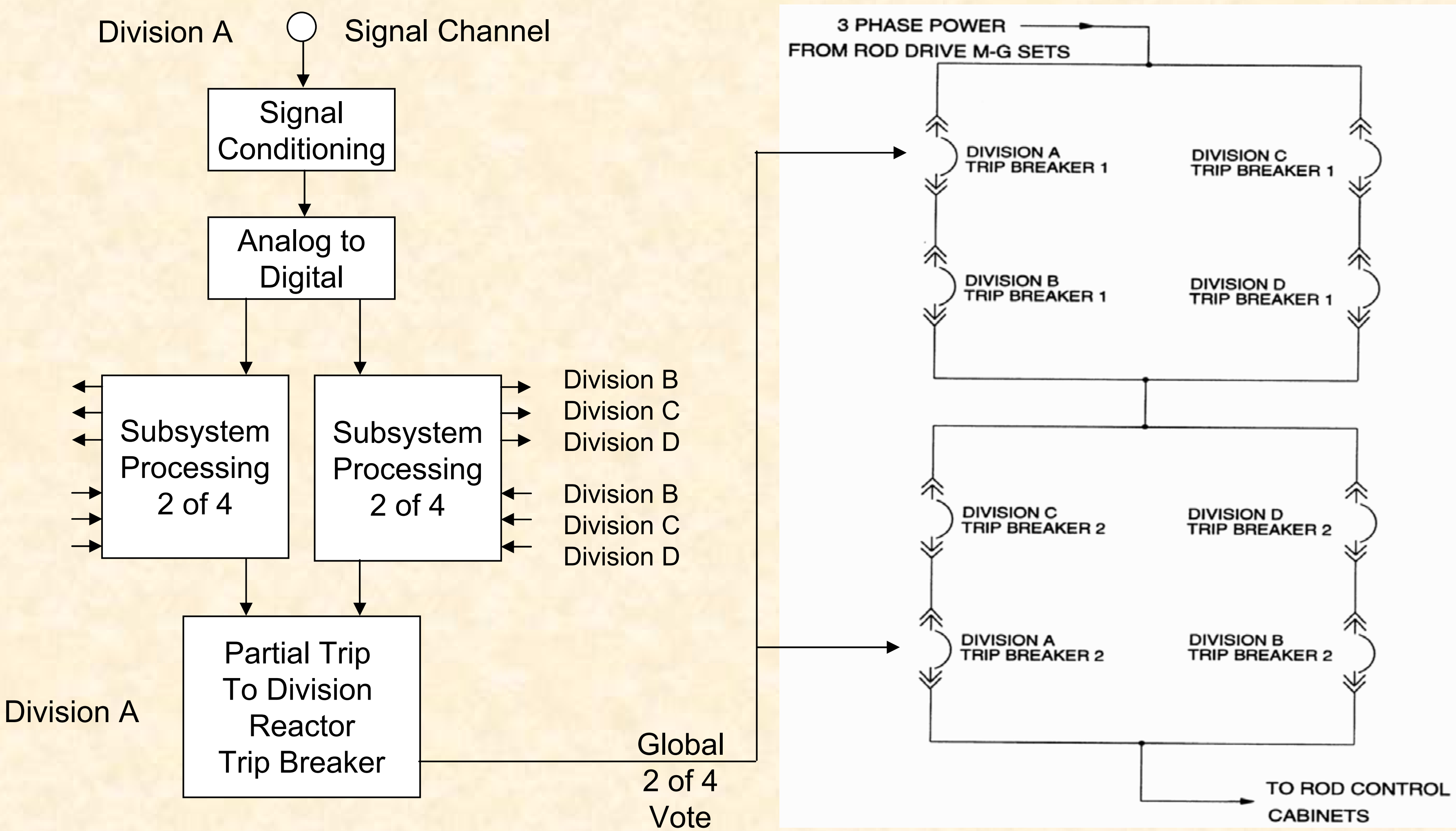
- **Normal I&C System**
- **Control Room**
- **Casualty Response**

Principle Source: AP-1000 DCD, Tier 2 Material, Chapter 7

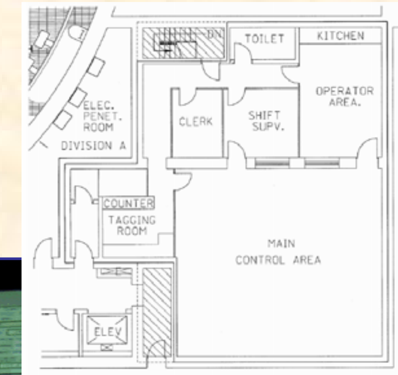
AP-1000 Uses Microprocessor, Digital Technology Based I&C

- **Multiplexed communications**
- **No Requirement for Safety AC Power**
- **Redundant Trains**
  - **4 divisions, physically separated with electrical isolation (fiber-optic)**
    - **Each with own independent battery-backed power supply**
    - **24-hour batteries for actuation, 72-hour batteries for monitoring (2 Divisions)**
- **System uses 2 out of 4 logic to process trip and safety actuation**
  - **System reverts to 2 out of 3 logic if one channel must be bypassed**
- **Improved In-Plant Testing**
  - **Built-in continuous self-testing and manual periodic testing**
- **Westinghouse Extensive Experience with Digital I&C**
  - **Operating plant upgrades and new plants (Sizewell, Temelin)**

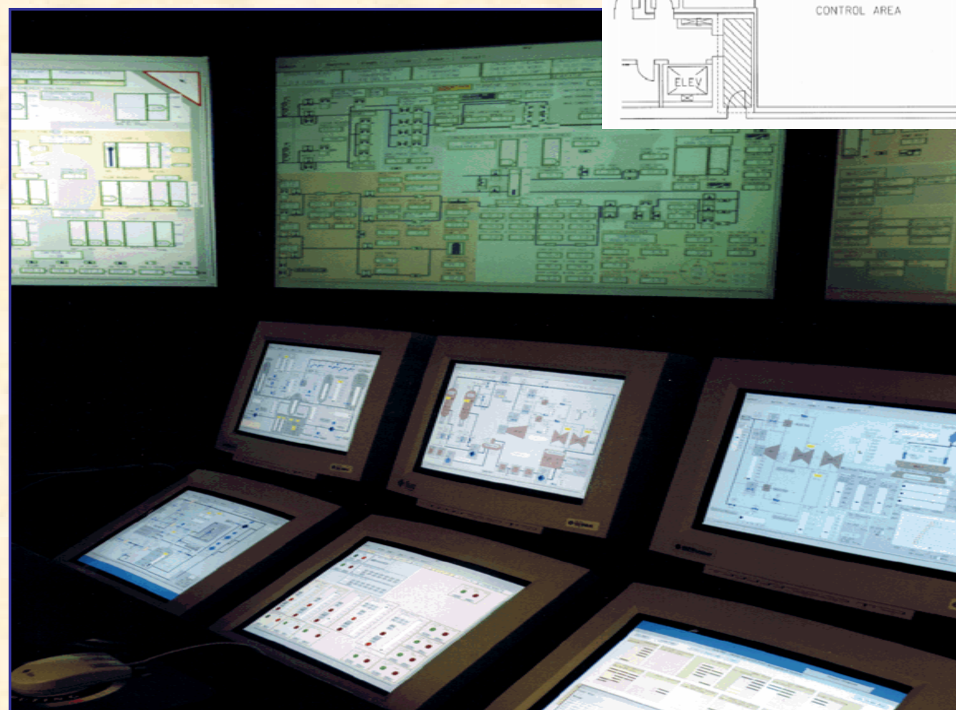
Trip Signal Flowpath



AP-1000 Control Room Does Not Look Like Current PWR Control Rooms



- Compact Control Room
  - **Designed for 1 Reactor Operator and 1 Supervisor**
- Displays
  - **Big picture awareness**
  - **Enhance crew coordination**
  - **Information spatially dedicated**



- Controls
  - **Soft controls**
    - **Dedicated display system**
    - **Non-safety systems**
  - **Few dedicated switches**
    - **PMS, Safety Controls**
    - **Diverse actuation system**
- Advanced Alarm Management
  - **Organized by function (Ex: RCS inventory control)**
  - **Alarms within each function are prioritized**

Control Room Concepts and Mockups Show Extensive Use of Digital Technology

Casualty Response Is Simplified On AP-1000

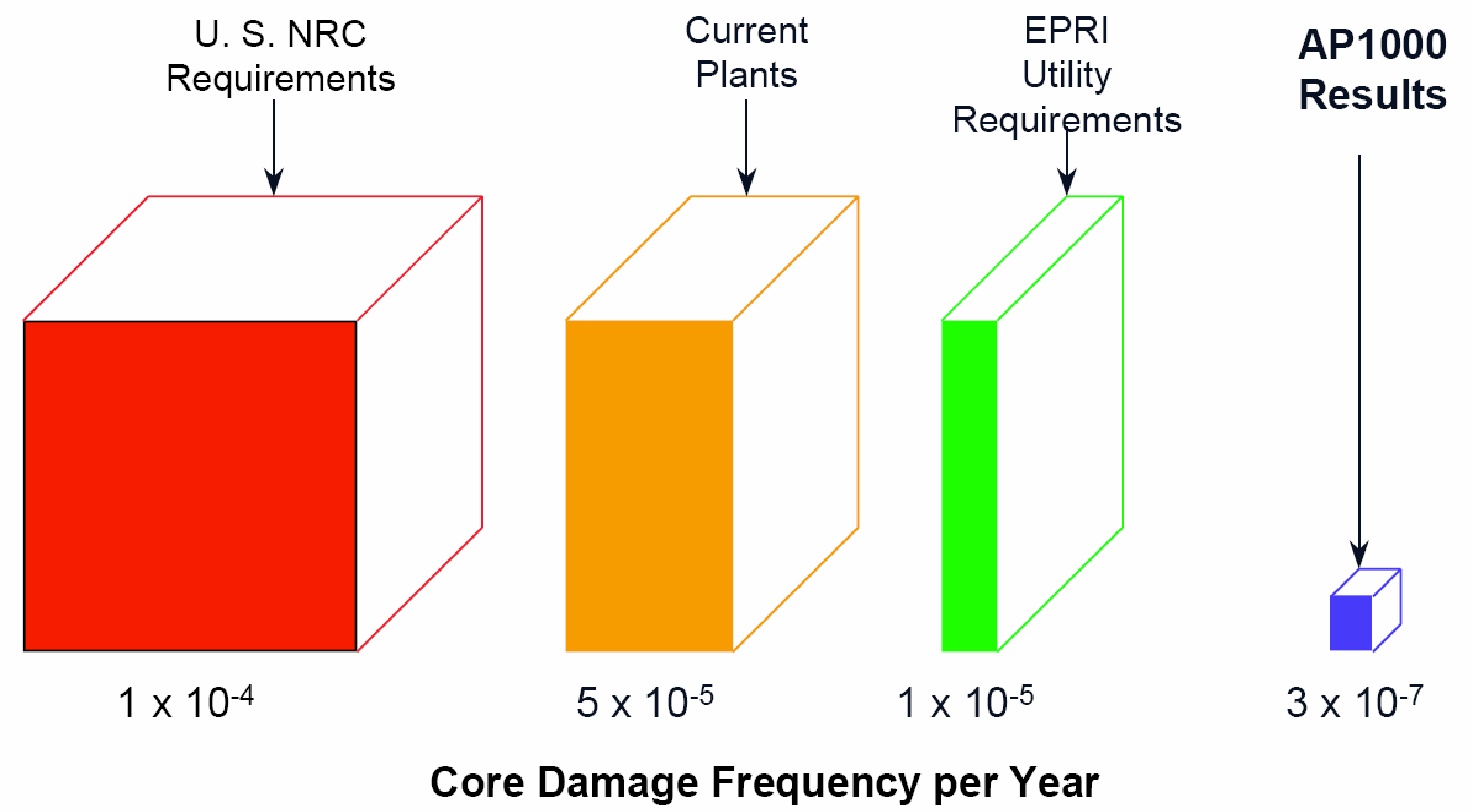
- **Plant is more self-reliant**
  - **Safety not dependent on operator immediate actions**
- **Response to a steam generator tube rupture is simplified by design**
  - **ADS system**
  - **No operator action with difficult time limits required**
- **AP-1000 plant trips and safeguards actuations are similar to current Westinghouse PWRs**
  - **Interlock functions and names are the same**
- **Computer Based Procedures**
  - **Computer & operator complement each other for a more accurate & efficient implementation of procedures**
  - **Guides the operator through procedure steps, evaluates step**
  - **Simultaneously monitors & displays relevant plant data**
  - **System brings all procedural information and needed plant data to one location**
  - **Reduces operator mental loading**

AP-1000 Summer Seminar Outline

- **PWR Primer** **(10 minutes)**
- **Design Status** **(5 minutes)**
- **Plant Overview and Key Design Features** **(20 minutes)**

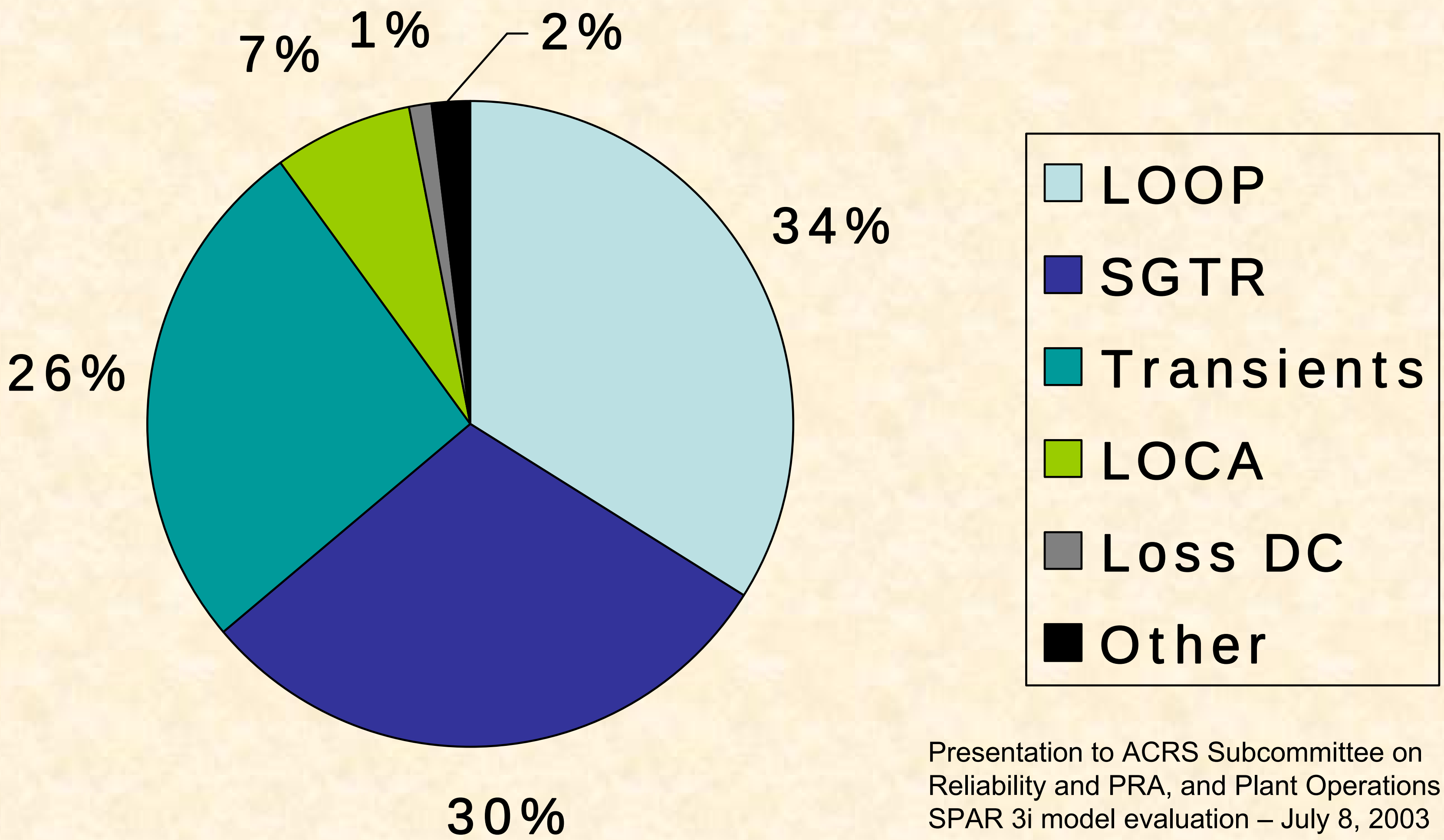
  Key Systems **(20 minutes)**
- **Accident Analysis** **(5 minutes)**
  - **Core Damage Frequency Summary**
- **Questions & Wrap-up**

AP-1000 Core Damage Frequency Comparison



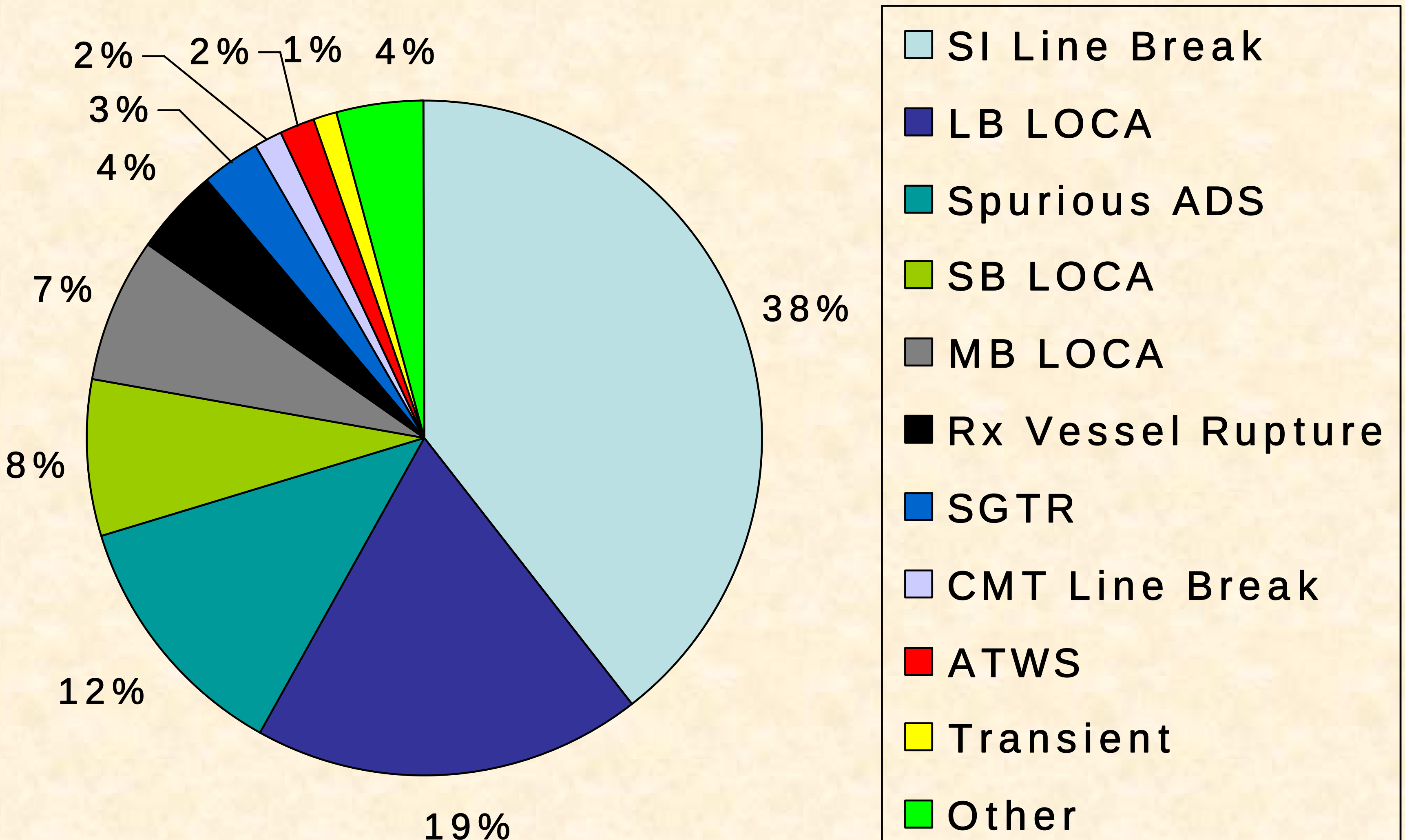
Source: Dr. Regis Matzie, BNFL Chief Technology Officer, 2003

Palo Verde Contribution of Initiating Events to Core Damage (1.79 E-05)



Presentation to ACRS Subcommittee on Reliability and PRA, and Plant Operations SPAR 3i model evaluation – July 8, 2003

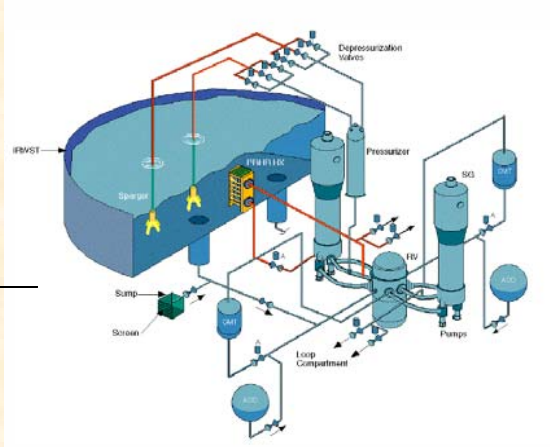
AP-1000 CONTRIBUTION OF INITIATING EVENTS TO CORE DAMAGE (2.41 E-07)



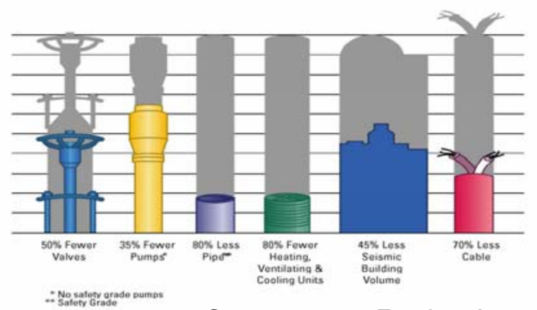
Source: AP-1000 DCD, Tier 2 Material, Chapter 19

Thank You - Questions

NRC Approval



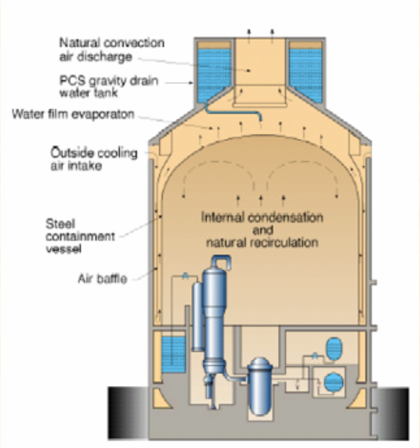
Passive Safety Systems



Component Reduction

Favorable Construction Schedule

Modular Construction



Severe Accident Mitigation