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IDENTIFICATION AND CHARACTERIZATION OF PASSIVE SAFETY SYSTEM AND INHERENT SAFETY FEATURE BUILDING BLOCKS FOR ADVANCED LIGHT-WATER REACTORS

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1. Introduction

Oak Ridge National Laboratory (ORNL) is investigating passive and inherent safety options for Advanced Light-Water Reactors (ALWRs). A major activity in 1989 includes identification and characterization of passive safety system and inherent safety feature building blocks, both existing and proposed, for ALWRs. Preliminary results of this work are reported herein.

A nuclear power plant is composed of many structures, systems, and components (SSC)-building blocks. Different designs of light-water reactors reflect differences in the designer's selection of building blocks. For example, a designer could use a containment building with either active or passive cooling systems to condense steam in a postaccident environment. Systematic identification and characterization of passive and inherent safety system building blocks is a useful step in creating new reactor options and in identifying research needed to enhance the safety of reactors now being designed.

This activity is part of a larger effort by the U.S. Department of Energy, reactor vendors, utilities, and others in the United States to develop improved LWRs. The Advanced Boiling Water Reactor (ABWR) program and the Advanced Pressurized Water Reactor (APWR) program have as goals improved, commercially available LWRs in the early 1990s. The Advanced Simplified Boiling Water Reactor (ASBWR) program and the AP-600 program are developing more advanced reactors with increased use of passive safety systems. It is planned that these reactors will become commercially available in the mid 1990s. The ORNL program is an exploratory research program for LWRs beyond the year 2000. Desired long-term goals for such reactors include: (1) use of only passive and inherent safety, (2) foolproof against operator errors, (3) malevolence resistance against internal sabotage and external assault and (4) walkaway safety. The acronym "PRIME" [Passive safety, Resilient operation, Inherent safety, Malevolence resistance, and Extended (walkaway) safety] is used to summarize these desired characteristics. Understanding existing passive and inherent safety options is a prerequisite for future work.

For this study, the International Atomic Energy Agency draft definitions of passive and inherent safety are being used [1].

2. Functional Safety Requirements for LWRs

2.1 Functional Requirements

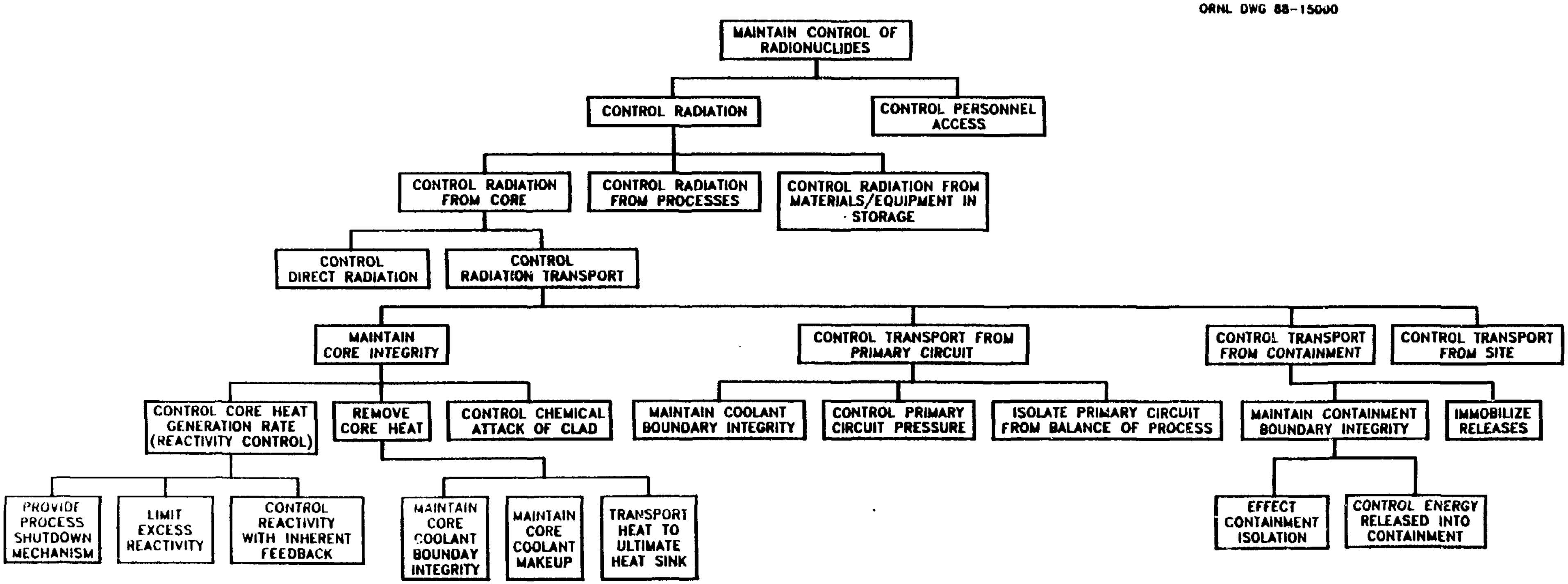
The first step in identifying passive and inherent safety SSCs for LWRs is to define the nuclear related-safety functional requirements for LWRs. This is the basis for determining whether a particular SSC is to be included in the study. For the purposes herein, only radiological safety was considered; normal industrial safety SSCs were excluded.

The highest-level functional nuclear safety requirement is control of radionuclides. From this, a multilevel, hierarchical, functional requirements diagram was created (Fig. 1). This functional requirements analysis was derived form earlier functional analysis efforts in the United States [2,3]. The primary emphasis is control of radiation from the reactor core, because almost all radionuclides in a nuclear power plant are associated with the reactor core.

Control of radiation from the reactor core has two components: *Control of Direct Radiation* and *Control of Radiation Transport*. *Control of Direct Radiation* is accomplished with radiation shielding, a passive safety mechanism. The functional requirement *Control of Radiation Transport* can be broken into four subsidiary functional requirements:

- *Maintain Core Integrity*
- *Control Transport from Primary Circuit*
- *Control Transport from Containment*
- *Control Transport from Site*

Each of these requirements was in turn broken down into lower-level, functional requirements as shown in Fig. 1 and in greater detail in Table 1. This type of functional analysis assists in identifying passive and inherent safety SSCs, clarifying what functional requirements a particular SSC fills (some SSCs fill multiple requirements), and provides a basis to judge SSCs.



FUNCTIONAL ANALYSIS REQUIREMENTS FOR LIGHT WATER REACTOR

2.2 Uses of Functional Analysis

Functional requirements analysis as a basis to categorize SSCs offers multiple benefits. First, it provides a clear, logical way to identify what each SSC accomplishes and what options are available to achieve a particular requirement.

Second, organization of SSCs by functional requirements is a way to identify missing SSC options. For example, under the first-level requirement *Maintain Core Integrity* and the second-level requirement *Remove Core Heat* is the third-level requirement *Transport Heat to Ultimate Heat Sink.* The options for heat sinks include internal plant heat capacity or dumping heat to the environment – ground, water, or air. Each option has one or more corresponding SSCs. This systematic approach leads to identification of options – sometimes options already in the literature, but in other cases, previously unidentified options.

The last benefit of using functional requirements as a method of organization is that it provides a "checklist" of safety issues to address for new concepts. For example, the functional requirement level below *Control Energy in Containment* after an accident includes *Reduce Energy Sources.* Such energy sources include radioactive decay heat, thermal mechanical energy, chemical energy, and fluid (pressure and temperature) energy. Thermal mechanical energy includes steam explosions which occur when certain molten materials drop into a bath of water. The probability of a steam explosion is strongly dependent on the physical properties of materials and the geometry of an accident. For uranium oxide fuels clad in zirconium, steam explosions are now believed to be very unlikely events because of the physical properties of the system [4]. In contrast, steam explosions are a concern with certain other materials of construction. A functional requirements approach identifies potential issues to be addressed when evaluating new technologies.

Table 1. Functional Safety Requirements for LWRs

Number	Functional Requirements
1.	Maintain Core Integrity
	1.1 Control Core Heat Generation Rate (Reactivity Control)
	1.1.1 Provide Process Shutdown Mechanism
	1.1.2 Limit Excess Reactivity
	1.1.3 Control Reactivity with Inherent Feedback
	1.2 Remove Core Heat
	1.2.1 Maintain Core Coolant Boundary Integrity
	1.2.2 Maintain Core Coolant Inventory
	1.2.3 Transport Heat to Ultimate Heat Sink
	1.2.3.1 Transport Heat
	1.2.3.2 Heat Sink
	1.3 Control Chemical Attack of Clad
2.	Control Transport from Primary Circuit
	2.1 Maintain Pressure Boundary Integrity
	2.2 Control Primary Circuit Pressure
	2.3 Isolate Primary Circuit from Balance of Process
3.	Control Transport from Containment
	3.1 Maintain Containment Boundary Integrity
	3.1.1 Effect Containment Isolation
	3.1.1.1 Containment Structure
	3.1.1.2 Containment Isolation
	3.1.1.3 Pressure Control
	3.1.2 Control Energy in Containment
	3.1.2.1 Reduce Energy Sources
	3.1.2.2 Heat Removal
	3.2 Immobilize Radionuclides
4.	Control Transport from Site

2.3 Limits to Functional Analysis

The functional requirements defined herein have been created to assist research and development; however, the functional requirements as defined for regulatory or engineering purposes may be significantly different. In normal engineering practice, many features of a reactor are fixed. Similarly, in a regulatory environment, legal precedent and national law may define requirements. These types of constraints are real but can be changed over time if there is reason to do so. For R&D programs with long time frames, a broader requirements perspective is needed.

The requirements analysis includes some requirements that may not be required for a particular design for nuclear reactor. An example is *Control Transport from Site* (evacuation planning, etc). If other lines of defense against radionuclides release are sufficiently strong, such a requirement becomes unnecessary.

3. Identification of Passive and Inherent SSCs for LWRs

A major effort has been initiated to identify passive and inherent SSCs applicable to light-water reactors. This has included worldwide literature and patent searches, reviews of safety analysis reports of current reactors, discussions with universities and reactor vendors, and review of other reactor concepts to identify technologies useful for LWRs.

Structures, systems, and components that are identified are analyzed and described using the standard format shown in Table 2. The descriptions of each technology include several technical judgements:

- The functional requirements that a particular SSC could potentially accomplish are identified.
- The current status of the technology is estimated. This can vary from standard commercial practice to a speculative concept for which no detailed engineering analysis has been done and the technical feasibility is uncertain.
- Additional functional requirements to support the proposed SSC are identified.

If several related SSCs operate on the same principles, they are included in a single description. A good example of this is suppression pools. These devices are designed to

Table 2. Structures, Systems and Components Description Format

Format	Description
Title	Title of SSC
Functional requirements	List of the functional requirements achieved by SSC
Safety type	Type of safety: inherent, passive, or active
Developmental status	The current status of this technology on a scale of 1 to 6 Status — Definition of status 1 — In commercial application in multiple light-water reactors 6 — Speculation
Reactor type	Types of reactors to which the technology could be applied: LWR, BWR, PWR
Examples of implementation	Examples of implementation. Examples may include non-LWR reactors
Description	Description of technology. This will generally include a very simple nonmathematical description of the physics of the SSC, usually followed by a summary of an actual design using summary table or figure
Alternative versions	Alternative versions or use of the technology
Status of technology	Current status of technology (discussion)
Advantages	Potential advantages of particular SSC. Advantages may include safety, cost, and operational advantages
Added requirements	Some safety systems may have additional functional requirements beyond those needed for LWR safety. Additional requirements raise questions about meeting safety goals
Comments	Self explanatory
References/contacts	References or contacts for additional information
Update Date/compiler	Last update of description/compiler of this information sheet

condense steam, remove radionuclides, and reduce pressure in the containment after a reactor accident. These devices operate by bubbling air and steam mixtures through baths of water. In the United States, boiling-water reactors have a single large suppression pool [5]. In the Union of Soviet Socialist Republics, bubbler-condenser towers are installed to condense steam in pressurized-water reactor accidents [6]. These devices consist of several hundred small suppression pools. The mechanical designs of these two types of devices are very different, but the underlying operating principles are identical.

Table 3 shows a partial list of SSCs that we have identified. Over 100 such SSCs are expected to be identified. These descriptions, organized by functional requirement, will be included in the final report prepared by ORNL.

4. Observations

4.1 Many Passive and Inherent SSCs Exist

For six of the eight second-level functional requirements (Table 2), multiple passive and inherent SSCs exist. The number of options is very large. Many of the options have been demonstrated either in other types of reactors or in other industries. Furthermore, many of the SSCs are relatively new ideals that suggest the potential for many future discoveries and advances.

The work has identified many SSCs that are applicable to both current LWRs and concepts (such as PIUS-PWR [7] or PIUS-BWR [8]) which imply more radical changes in LWR design.

4.2 Limits to Passive and Inherent Safety

For two second-level functional requirements, no passive or inherent safety SSCs have been found. The two functional requirements are

- *Isolate Primary Circuit from Balance of Plant (Function 2.3)*
- *Effect Containment Isolation (Function 3.1.1)*

These functional requirements are only important if reactor core integrity is lost. The functional requirements to maintain core integrity can be accomplished by a variety of passive and inherent SSCs.

Table 3. Partial List of Passive and Inherent Safety Structures, Systems, and Components for LWRs

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Function 1.1: Control Core Heat Generation Rate (Reactivity Control)

- Fluidized bed control rods
- Self-actuating and locking control rod initiated on low water flow or high temperature
- Reactivity control via boron concentration
- Self-controlling reactor using variable boron concentrations
- Burnable poisons to minimize reactivity shift due to variable burnup
- High-temperature ceramics, clads, and fuels for LWRs
- Light-water minimum critical mass core design
- Zirconium hydride (TRIGA) reactivity control
- Reactivity control by spectral shift
- Reactivity change with change of chemical state

Function 1.2: Remove Core Heat

- Prestress concrete reactor vessel with double liner and two-way independent structural integrity
- Steel reactor pressure vessel with no bottom penetration
- Depressurization upon loss of coolant
- Reinforced concrete backup container for steel pressure vessel
- Continuous/simultaneous pump pressurizer
- PIUS Emergency core-cooling system
- Fluidic in-vessel emergency core-cooling system
- Pressure-activated valve emergency core-cooling system
- Jet pump emergency core-cooling system
- Passive safety and shutdown system (PSSS) coolant cooling system
- Natural circulation coolant for maximum coolant availability
- Natural air circulation cooling of coolant

Table 3. (continued)

Function 1.3: Control Chemical Attack of Clad

Reduction of coolant/clad chemical reactions under severe accident conditions

Function 2.1: Maintain Coolant Boundary Integrity

Function 2.2: Control Primary Circuit Pressure

Rupture disks (GAM)

Function 2.3: Isolate Primary Circuit from Balance of Plant

Function 3.1: Maintain Containment Boundary Integrity

Filtered vented containment

Double liner containment

Containment structures

Underground reactor containment system

Low thermal interaction of molten core and liquid water

Heat pipes for reactor containment cooling or reactor core decay heat removal (Dec. 1988/RLP)

High-conductivity, high-heat-loss containment

Ice containment cooling system

Containment pressure control by water spray

Containment pressure control by bubble and condenser or suppression pool

Vacuum containments

Function 3.2: Immobilize Releases

Core melt source term reduction system

Inherent reduction of postaccident source term by high-humidity environment

Function XX: Other

Concrete shielding

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[a] Functional requirements not associated with *Control Radiation Transport* from reactor

In theory, a passive device could be used to isolate the primary circuit or containment if it could be initiated (triggered) by the radioactivity in the fluid stream. In practice, all current isolation devices need external signals to determine whether they should be activated. The importance of these two or any other functional requirements depends upon how well other functional requirements are met. Consider the following example. The impact of the failure to *Effect Containment Isolation* (Function 3.1.1) after an accident involving a core melt depends on two other functional requirements:

- *Control Energy in Containment* (Function 3.1.2)
- *Immobilize Releases* (Function 3.2)

If a passive water spray system washes the containment of radionuclides (*Immobilize Releases*), maintains low-containment pressure by steam condensation (*Control Energy in Containment*), and covers the molten core with water, the impact of the loss of one function (*Containment Isolation*) is greatly reduced.

4.3 Technologies from Other Reactor Types

The same issues of passive and inherent safety apply to all reactor types. Our examination of the literature has identified many technologies being developed for other reactors that may be applicable to LWRs. An example is the invention and development of gravity-assisted control rods for liquid-metal reactors that self-initiate reactor shutdown based on high coolant temperatures, high fluid flow rate, or low liquid flow rate [9]. Such mechanisms may be applicable as backup shutdown rods for advanced LWR concepts.

4.4 Technologies from Other Fields

Many possible SSCs have been identified that are commercial technologies in other fields but have not been applied to LWR safety. In most cases, these are relatively new technologies. An example is the heat pipe. Heat pipes are sealed tubes containing a liquid which boils and transfers heat by a vaporization-condensation cycle from the hottest to the coldest parts of the sealed pipe. Heat pipes could be used for emergency core cooling, containment cooling, or other purposes. Heat pipes have been considered and used for special reactors such as space reactors but only one early study was identified in which heat pipes were considered for LWRs [10]. The particular application was passive containment cooling.

Heat pipes are a good example of changing conditions making a passive technology that was previously bypassed potentially attractive. Consider the following:

First, recent probabilistic risk assessments show that loss of containment cooling may be a significant accident initiator [11]. Higher equipment room temperatures increase equipment failure rates for both normal operating equipment and emergency equipment. Heat pipes are one high-reliability technical solution.

Second, in the last 15 years the experience base for the technology has increased because heat pipes are being used for building temperature control, solar heating, and temperature control of foundation structures for the Alaska Pipeline. In this last application, over 100,000 heat pipes are in use, with a very high record of reliability.

Last, the technology has advanced. For example, heat pipes can be designed to begin operation at a preset temperature. For certain reactor applications such as containment cooling in cold climates, such a feature would prevent freezing temperatures in containment.

Whether these changes are sufficient to make the technology the preferred choice for ALWRs is not known. What is clear is that changing technologies and changing requirements can make previously unused technologies worth reevaluation.

5. Conclusions

At ORNL, we are preparing a report identifying passive and inherent safety SSCs for LWRs. Based on the progress to date, we see the following benefits:

- a better understanding of current passive and inherent design options for safety SSCs,
- a systematic approach to identify promising directions for future research, and
- a method to identify technologies that may have been previously rejected for LWRs, but are now promising because of either changing requirements or improvements in the technology.

6. References

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IDENTIFICATION AND CHARACTERIZATION OF PASSIVE AND INHERENT SAFETY SYSTEM BUILDING BLOCKS FOR ADVANCED LIGHT-WATER REACTORS

DR. CHARLES FORSBERG
UNITED STATES OF AMERICA

INTERNATIONAL ATOMIC ENERGY AGENCY
TECHNICAL COMMITTEE MEETING ON PASSIVE SAFETY FEATURES IN CURRENT AND FUTURE WATER-COOLED REACTORS

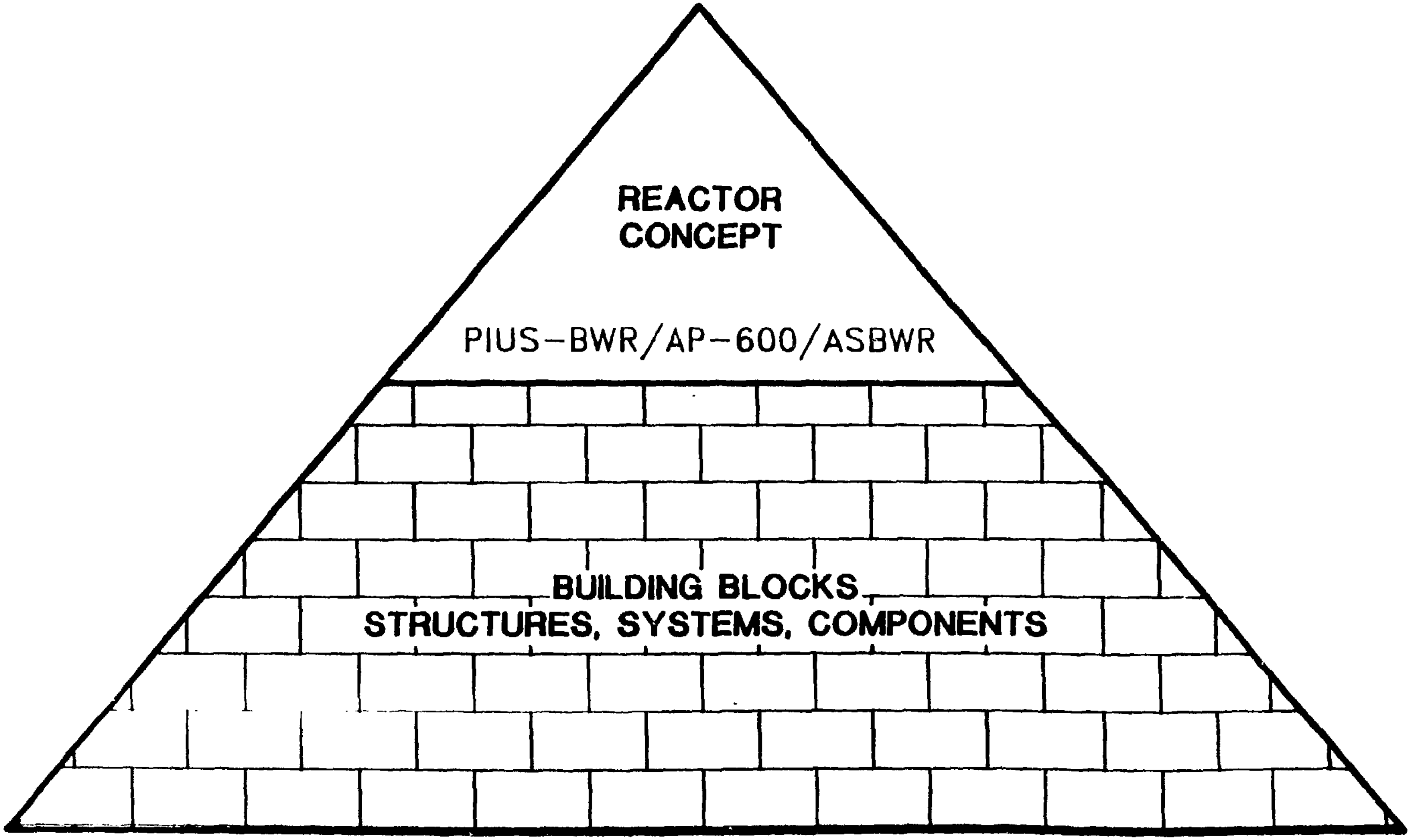
MARCH 21-24, 1989

MOSCOW, U.S.S.R.

UNITED STATES PROGRAMS IN LIGHT-WATER REACTORS

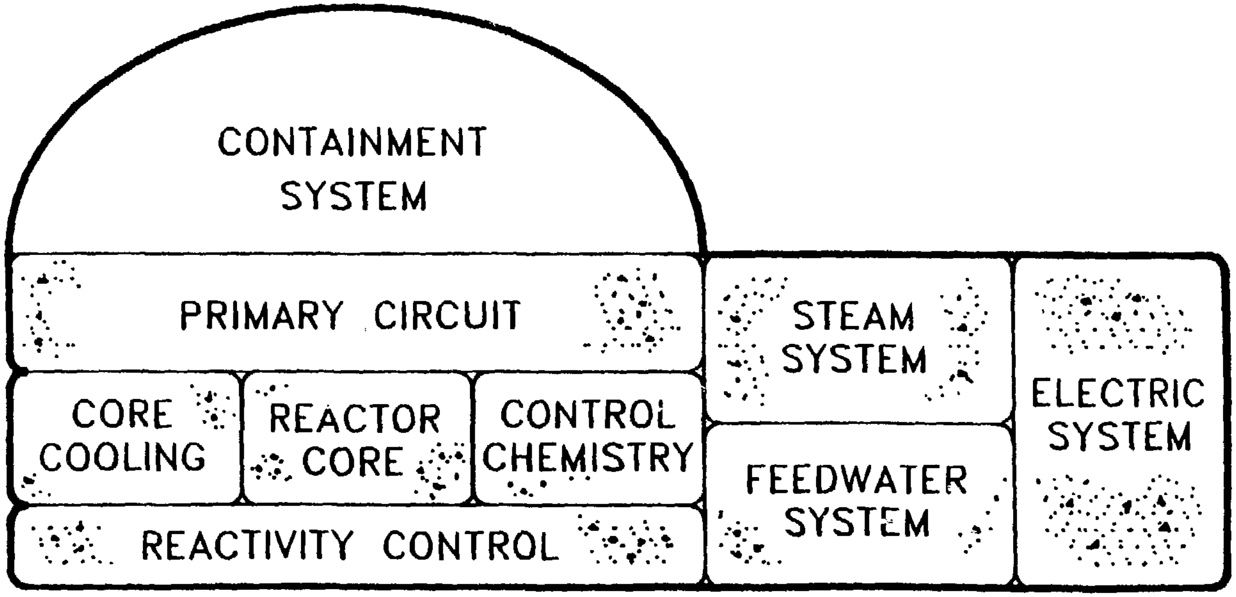
PROGRAMS	COMMERCIAL TIME FRAMES
ADVANCED BOILING-WATER REACTOR ADVANCED PRESSURIZED-WATER REACTOR	~1990
ADVANCED SIMPLIFIED BOILING-WATER REACTOR ADVANCED PASSIVE -600	~1995
DEVELOPMENTAL LIGHT-WATER REACTOR	POST-2000

ORNL DWG 89-7549



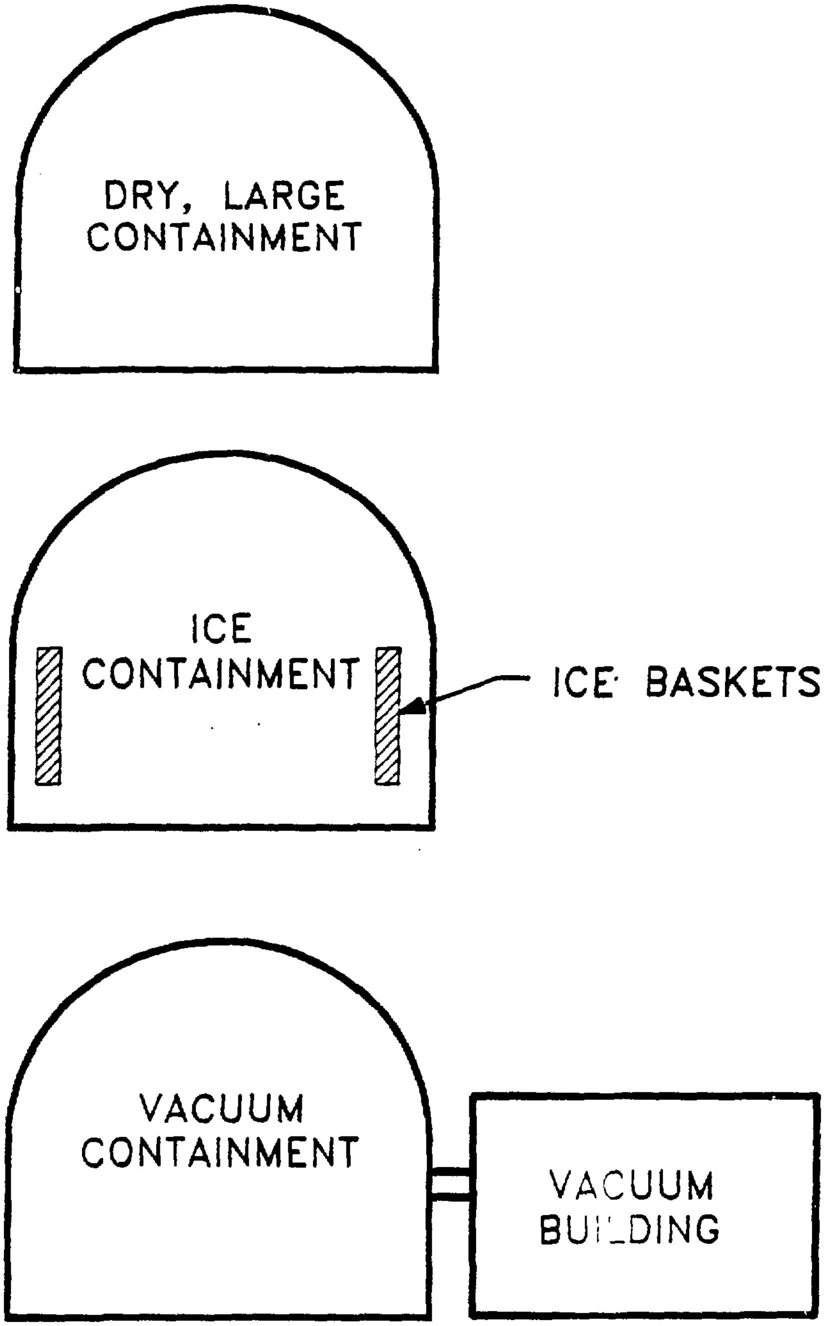
TWO COMPLEMENTARY APPROACHES TO STUDY PASSIVE/INHERENT SAFETY IN WATER-COOLED REACTORS

ORNL DWG 89-7550



ALL REACTORS ARE COMPOSED OF BUILDING BLOCKS -STRUCTURES, SYSTEMS, AND COMPONENTS-

ORNL DWG 89-7551



EXAMPLES OF CONTAINMENT SYSTEM BUILDING BLOCKS

BENEFITS FROM IDENTIFICATION AND CHARACTERIZATION OF PASSIVE AND INHERENT SAFETY SSCs

- BETTER UNDERSTANDING OF BENEFITS AND COSTS OF PASSIVE AND INHERENT SAFETY

- ASSIST IN DEFINING THE MOST PRODUCTIVE DIRECTIONS OF RESEARCH

- SYSTEMATIC EVALUATION OF OLDER PASSIVE AND INHERENT TECHNOLOGIES THAT MAY BE DESIRABLE BECAUSE OF
  - CHANGING REQUIREMENTS
  - IMPROVED TECHNOLOGIES

APPROACH TO STUDY

- DEFINE FUNCTIONAL SAFETY REQUIREMENTS FOR LIGHT-WATER REACTORS

- DEFINE APPROACH TO MEET REQUIREMENTS
  - PASSIVE AND INHERENT SAFETY
  - IAEA DRAFT DEFINITIONS

- SEARCH FOR SSCs MEETING ABOVE REQUIREMENTS

- DESCRIBE, ANALYZE, AND CATEGORIZE EACH SSC

- ANALYZE CHOICES OF SSCs FOR EACH FUNCTIONAL REQUIREMENT

WHAT ARE FUNCTIONAL SAFETY REQUIREMENTS FOR LWRs?

- FUNCTIONAL REQUIREMENTS DEFINE WHAT BUILDING BLOCKS (SSCs) ARE REQUIRED
- FUNCTIONAL REQUIREMENTS FOR REACTOR SAFETY ARE INDEPENDENT OF TECHNOLOGY
- FUNCTIONAL REQUIREMENTS ARE THE BASIS FOR CATEGORIZING BUILDING BLOCKS (SSCs)

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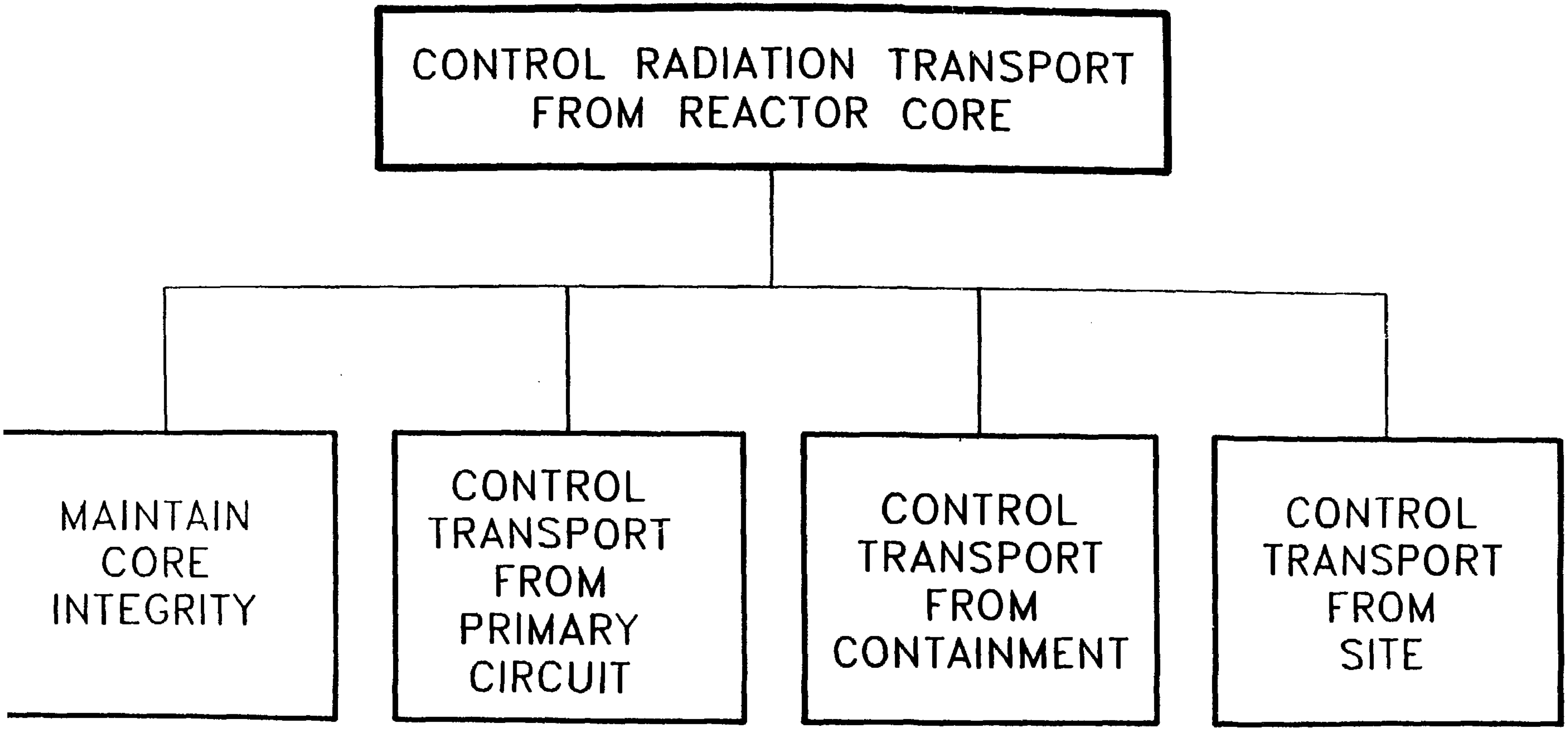
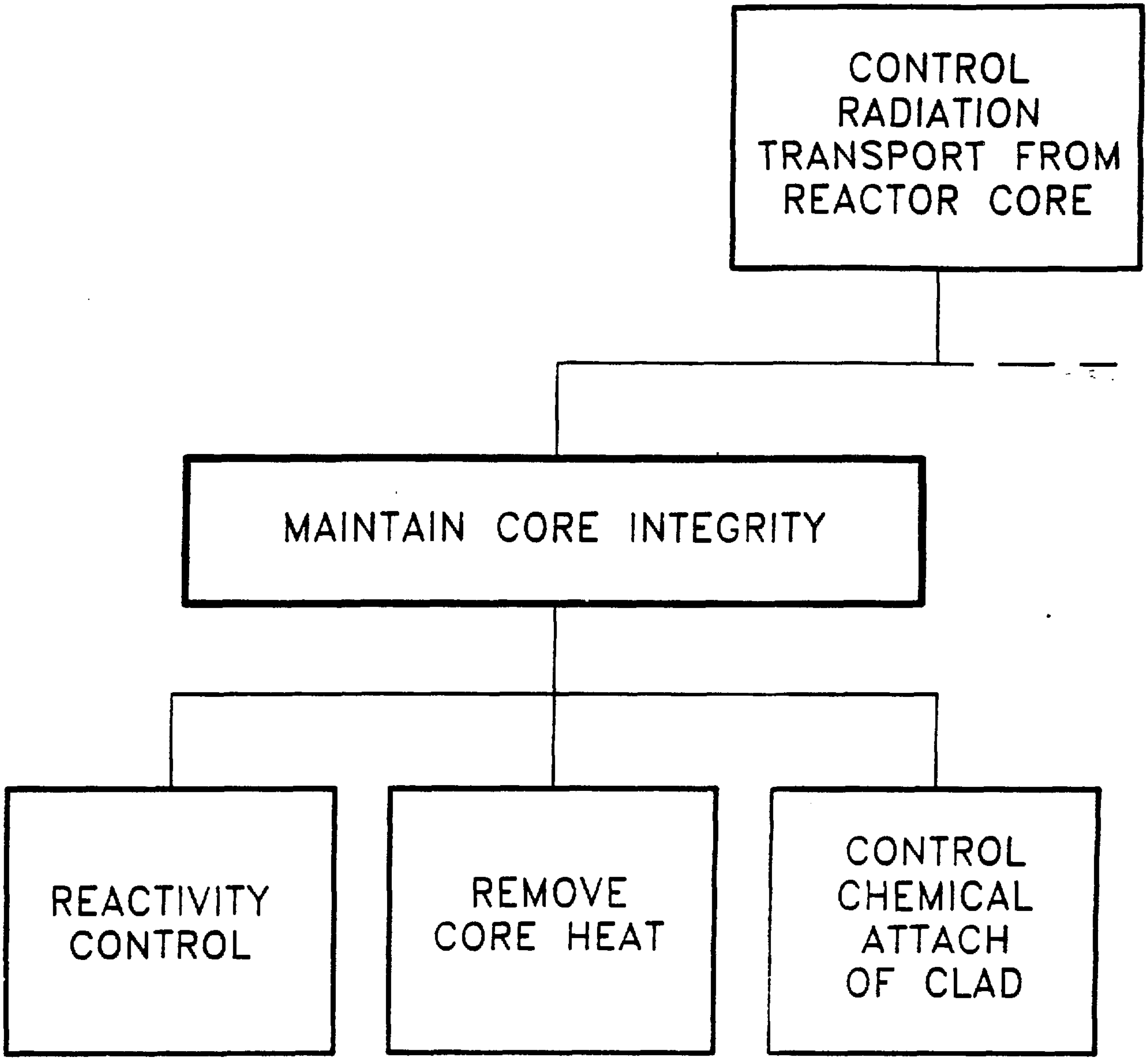


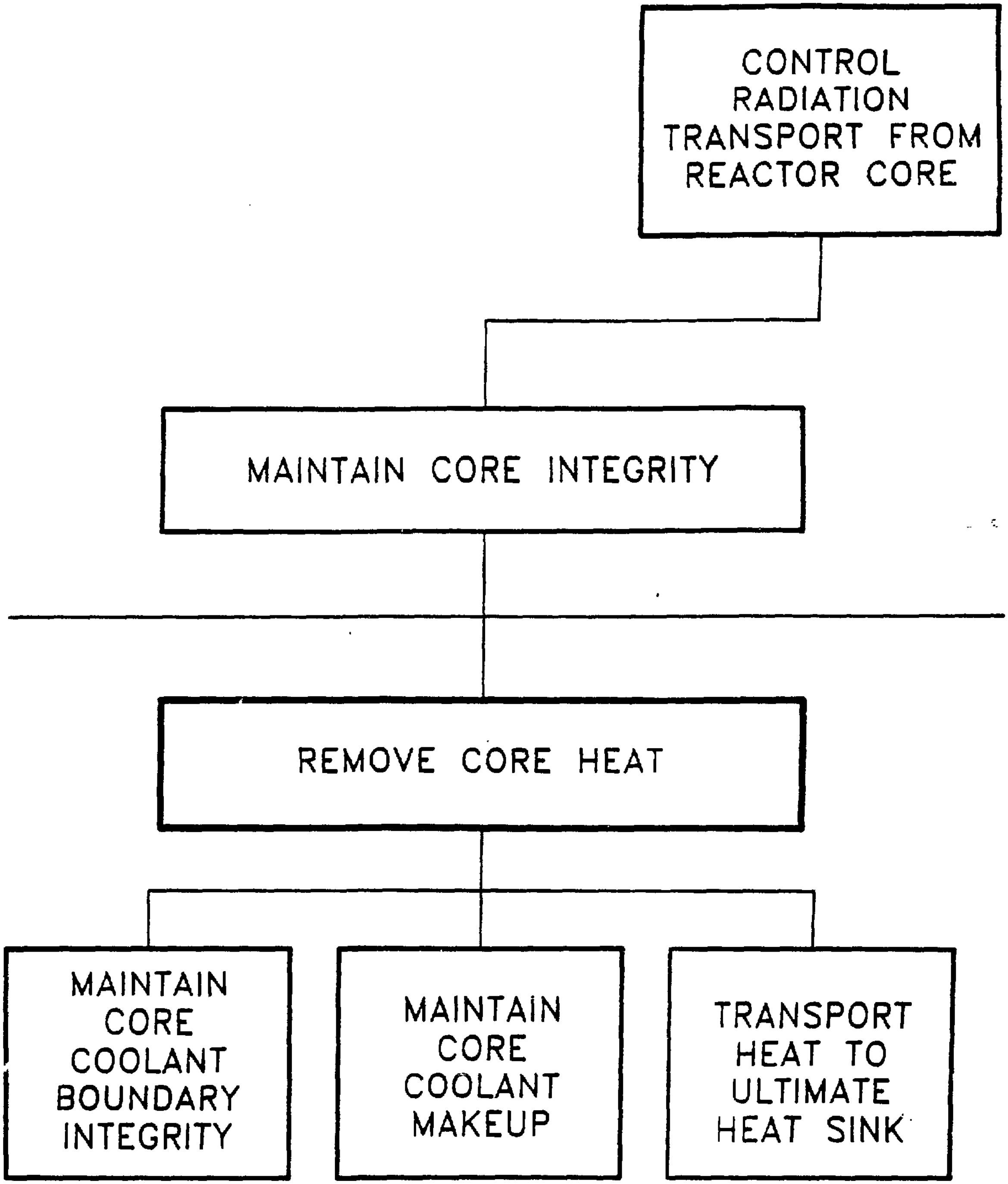
FUNCTIONAL BLOCK DIAGRAM FOR LWRs

ORNL DWG 89-7553



SECOND-LEVEL FUNCTIONAL BLOCK DIAGRAM
-MAINTAIN CORE INTEGRITY-

ORNL DWG 89-07554



THIRD-LEVEL FUNCTIONAL BLOCK DIAGRAM
-REMOVE CORE HEAT-

SEARCH FOR PASSIVE AND INHERENT SSCs

- WORLD LITERATURE AND WORLD PATENT SEARCH
- DISCUSSIONS WITH VENDORS AND UNIVERSITIES
- REVIEW OF COMMERCIAL REACTOR SAFETY ANALYSIS REPORTS
- REVIEW OF OTHER REACTOR CONCEPTS

STANDARD DESCRIPTION OF SSC

- TITLE
- FUNCTIONAL REQUIREMENTS
- SAFETY TYPE (PASSIVE OR INHERENT)
- DEVELOPMENTAL STATUS (COMMERCIAL TO SPECULATIVE)
- APPLICABLE REACTOR TYPES
- EXAMPLES OF IMPLEMENTATION
- DESCRIPTION OF TECHNOLOGY
- ALTERNATIVE VERSIONS

STANDARD DESCRIPTION OF SSC (CONTINUED)

- STATUS OF TECHNOLOGY - COMMENTS
- ADVANTAGES
- ADDED REQUIREMENTS
- COMMENTS
- REFERENCES

BENEFITS OF FUNCTIONAL ANALYSIS

- **LOGICAL WAY TO APPROACH IDENTIFICATION OF SSCs**
- **FIND "MISSING" SSCs**
- **CHECKLIST OF SAFETY ISSUES TO CONSIDER**

FUNCTIONAL ANALYSIS AIDS IDENTIFICATION OF SSCs

EXAMPLE: FUNCTIONAL REQUIREMENT TO TRANSPORT HEAT TO ULTIMATE HEAT SINK

HEAT SINK OPTIONS	EXAMPLE SSC
HEAT CAPACITY	FIVES (PIUS-BWR)
HEAT TO ENVIRONMENT	
AIR	AIR COOLER
WATER	COOLING POND
GROUND	GROUND-COUPLED COOLING COILS

SSCs WITH SAME OPERATING PRINCIPLES INCLUDED IN SINGLE DESCRIPTION

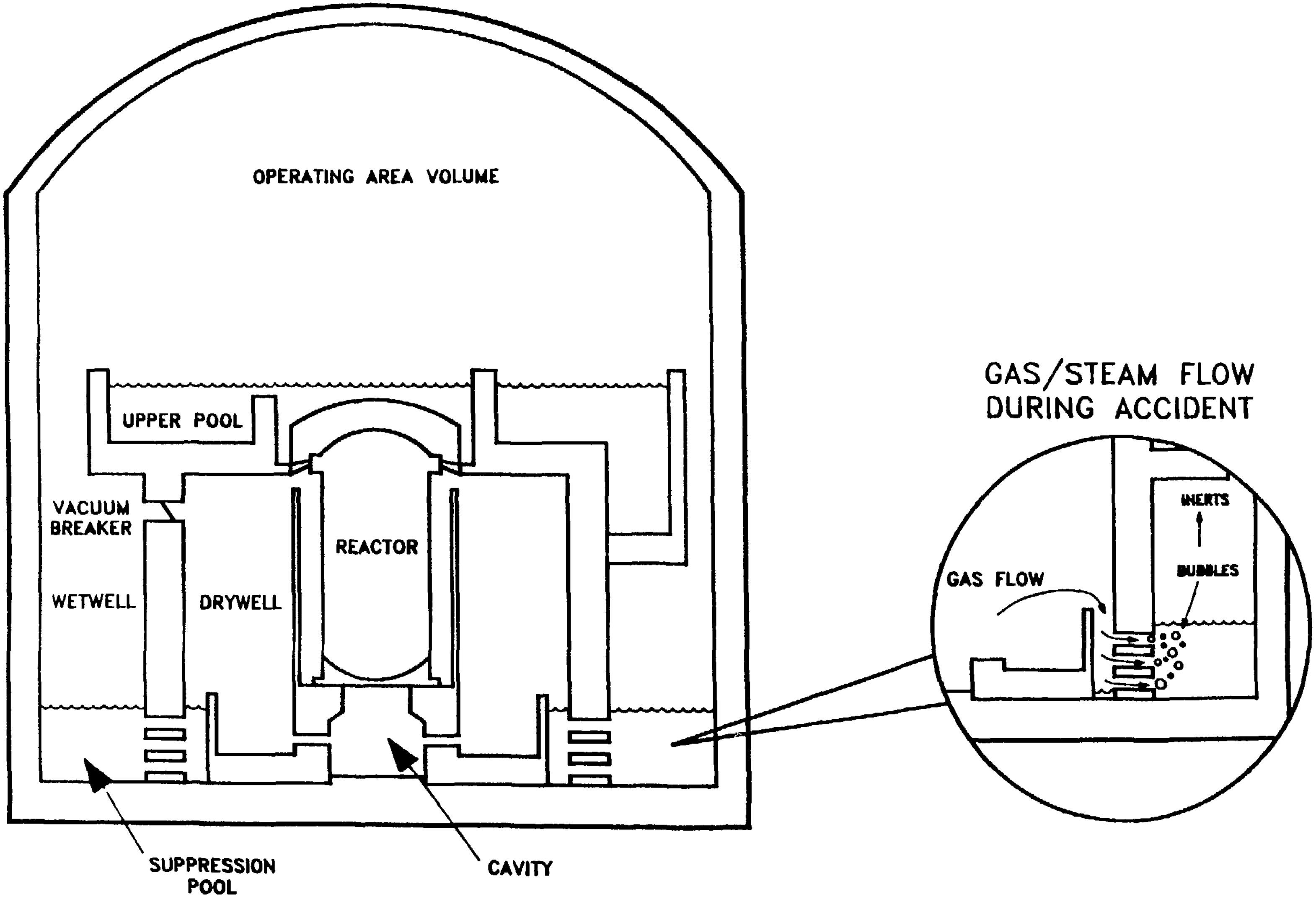
- **EXAMPLE:** SUPPRESSION POOL AND BUBBLER-CONDENSER TOWER

- **FUNCTION:**
  3.1.2: CONTROL ENERGY TO CONTAINMENT
  3.2: IMMOBILIZE RELEASES

- **FUNCTIONAL DESCRIPTION:** CONDENSE STEAM IN POSTACCIDENT CONTAINMENT BY BUBBLING STEAM AND AIR MIXTURE THROUGH POOL OF WATER

- **EXAMPLE IMPLEMENTATION**
  1. USA, BWR, SUPPRESSION POOL
  2. U.S.S.R., PWR, BUBBLER-CONDENSER TOWER

ORNL DRG 89-00053



OPERATION OF BWR MARK III SUPPRESSION POOL

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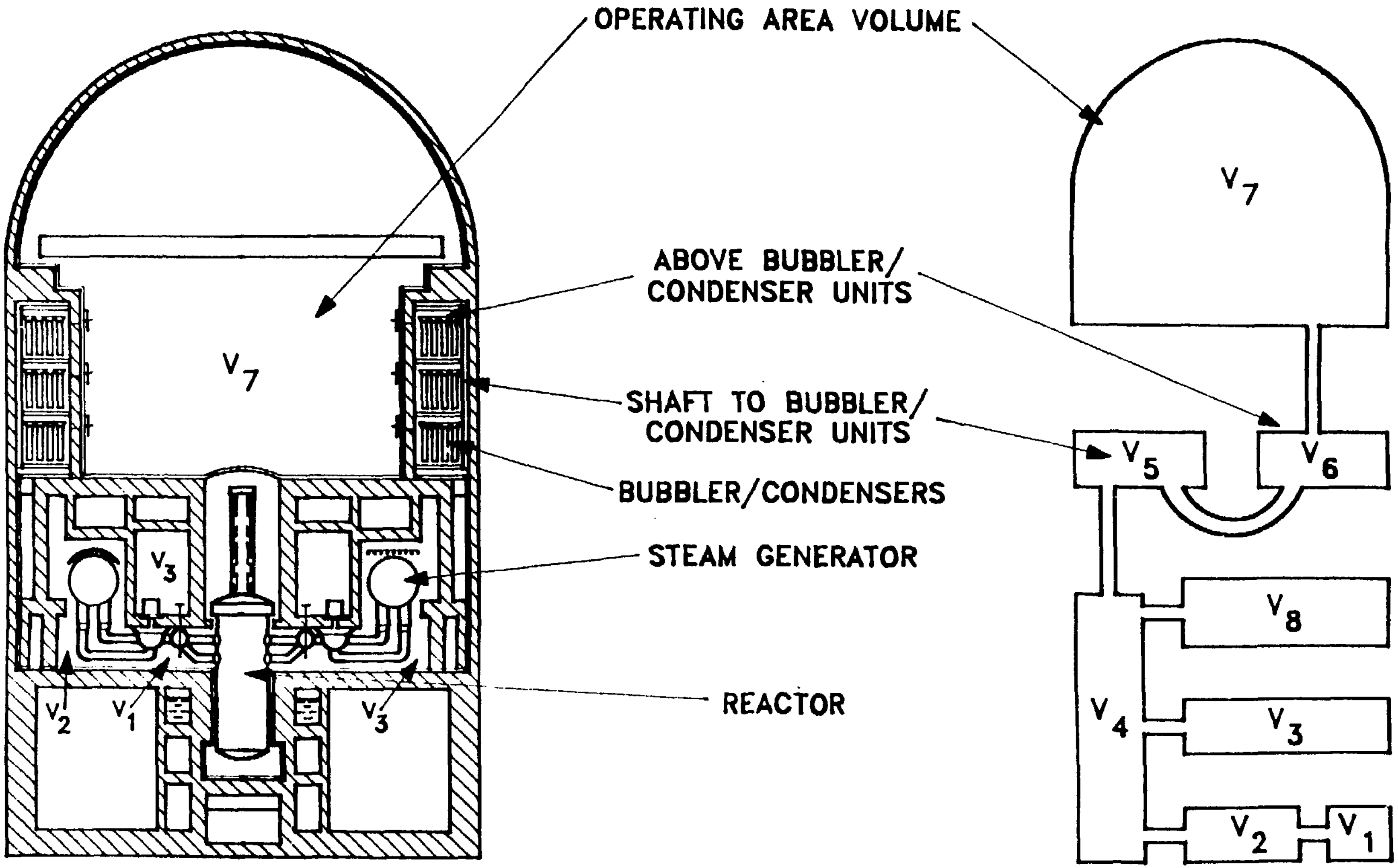
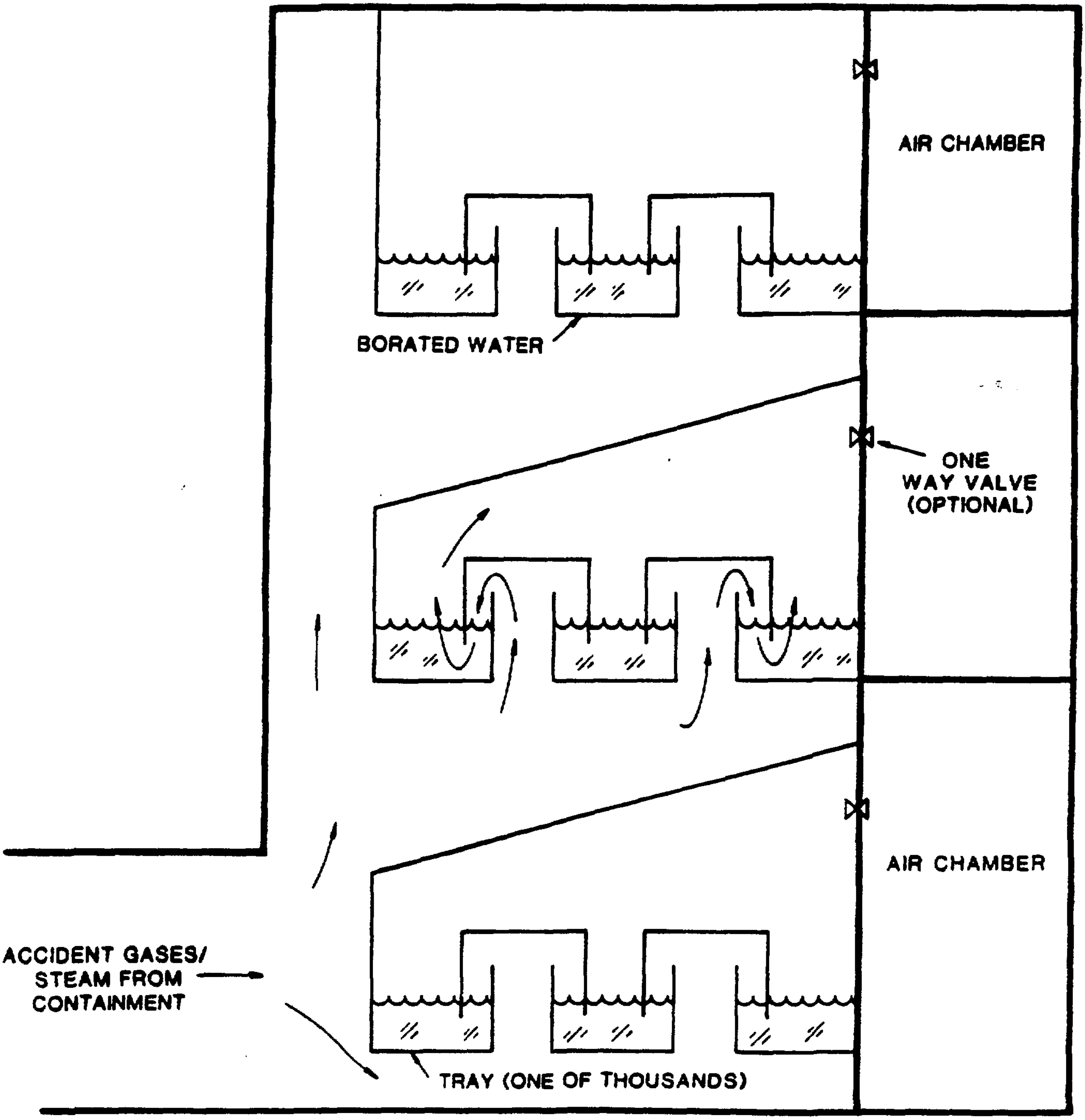


SCHEMATIC OF BUBBLER/CONDENSER CONTAINMENT CONCEPT (ELEVATION VIEW) IN SOVIET VVER-440, MODEL V213 REACTORS

ORNL DWG 86-360

VVER-440 BUBBLER/CONDENSER TOWER



OBSERVATIONS - MANY PASSIVE AND INHERENT SSCs EXIST

- OVER 100 SSCs IDENTIFIED TO DATE
- MULTIPLE OPTIONS FOR 6 OF 8 SECOND LEVEL FUNCTIONAL REQUIREMENTS
  - MAINTAIN CORE INTEGRITY
    - REACTIVITY CONTROL
    - REMOVE CORE HEAT
    - CONTROL CHEMICAL ATTACK OF CLAD
  - CONTROL TRANSPORT FROM PRIMARY CIRCUIT
    - MAINTAIN COOLANT BOUNDARY INTEGRITY
    - CONTROL PRIMARY CIRCUIT PRESSURE
  - CONTROL TRANSPORT FROM CONTAINMENT
    - IMMOBILIZE RELEASES

OBSERVATION: NO PASSIVE AND INHERENT SSCs FOR SOME FUNCTIONAL REQUIREMENTS

- NO PASSIVE AND INHERENT DEVICES TO:
  - ISOLATE PRIMARY CIRCUIT FROM BALANCE OF PLANT
  - EFFECT CONTAINMENT ISOLATION

- THEORETICAL POSSIBILITY SUCH DEVICES COULD EXIST
  - MUST BE TRIGGERED ON RADIOACTIVITY IN FLUID

- CAN COMPENSATE FOR THESE FUNCTIONAL REQUIREMENTS BY STRENGTHENING OTHER FUNCTIONS
  - EXAMPLE: WATER SPRINKLER IN CONTAINMENT
    - CONDENSE STEAM AND LOWER PRESSURE
    - WASH OUT RADIONUCLIDES

OBSERVATION: MANY PASSIVE AND INHERENT SSCs AVAILABLE FROM OTHER REACTOR TYPES

- EXAMPLE: CONTROL ROD DROP MECHANISM

- INITIATED BY:
  - LOW WATER FLOW
  - HIGH WATER FLOW
  - HIGH TEMPERATURE

- DEVELOPED FOR: LIQUID METAL-FAST BREEDER REACTOR

OBSERVATION: KNOWN PASSIVE AND INHERENT SSCs FROM OTHER INDUSTRIES MAY BECOME ATTRACTIVE BECAUSE OF CHANGING CONDITIONS AND TECHNOLOGY

EXAMPLE: HEAT PIPE

- FUNCTIONAL USES
    - CORE COOLING
    - CONTAINMENT COOLING

- NEW PERSPECTIVE FROM PROBABILISTIC RISK ASSESSMENTS
    - CONTAINMENT COOLING FAILURE RAISES TEMPERATURES
    - HIGH TEMPERATURES INDUCE EQUIPMENT FAILURE
    - MORE RELIABLE CONTAINMENT COOLING DESIRED

- IMPROVED TECHNOLOGY
    - EXPERIENCE ON ALASKAN PIPELINE (100,000 UNITS)
    - CAN ACTIVATE AT SET TEMPERATURES

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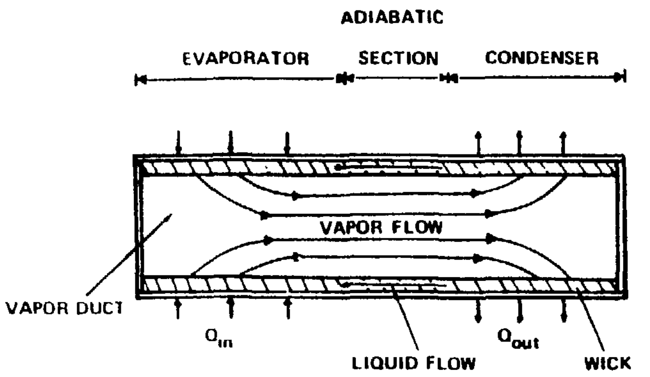
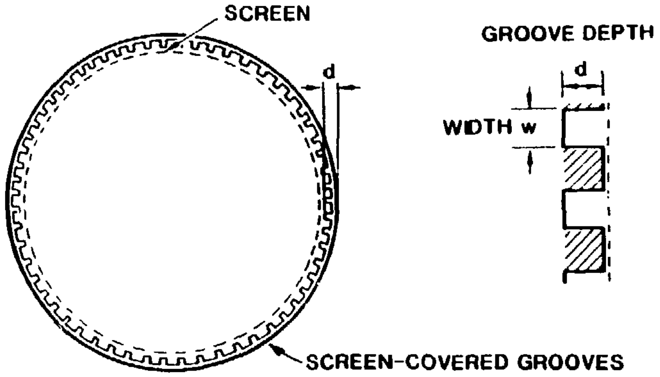
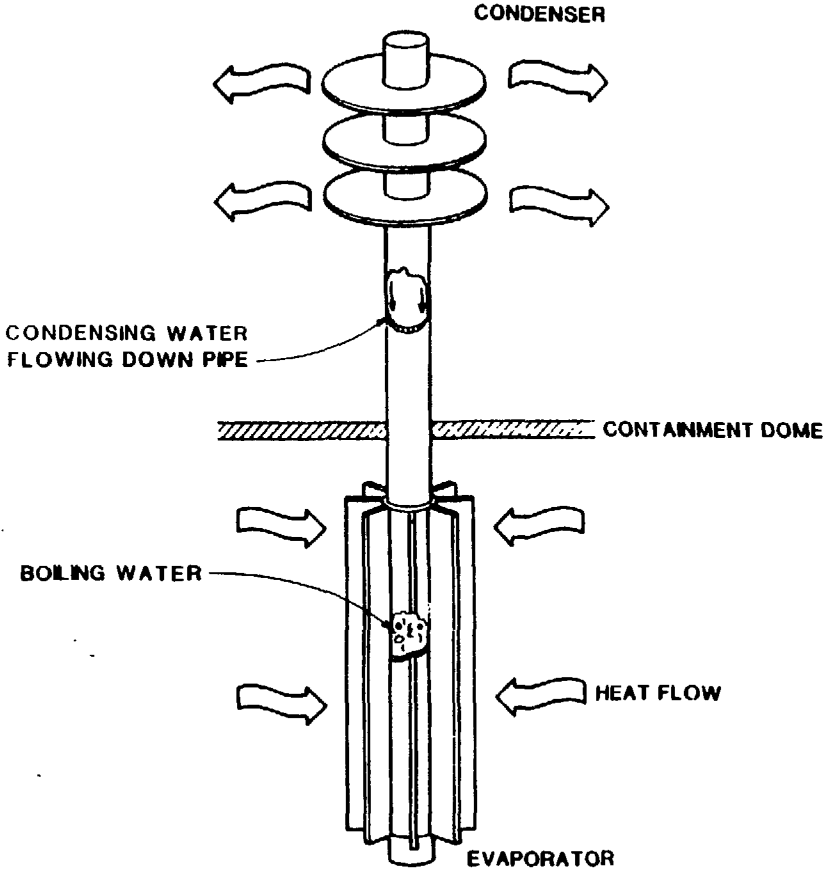


(a) PRINCIPLES OF HEAT TRANSFER IN A HEAT PIPE



(b) DETAILS OF WICK TYPE HEAT PIPE



(c) DETAILS OF AN AIR-COOLED GRAVITY-ASSISTED HEAT PIPE

HEAT PIPE CONFIGURATION

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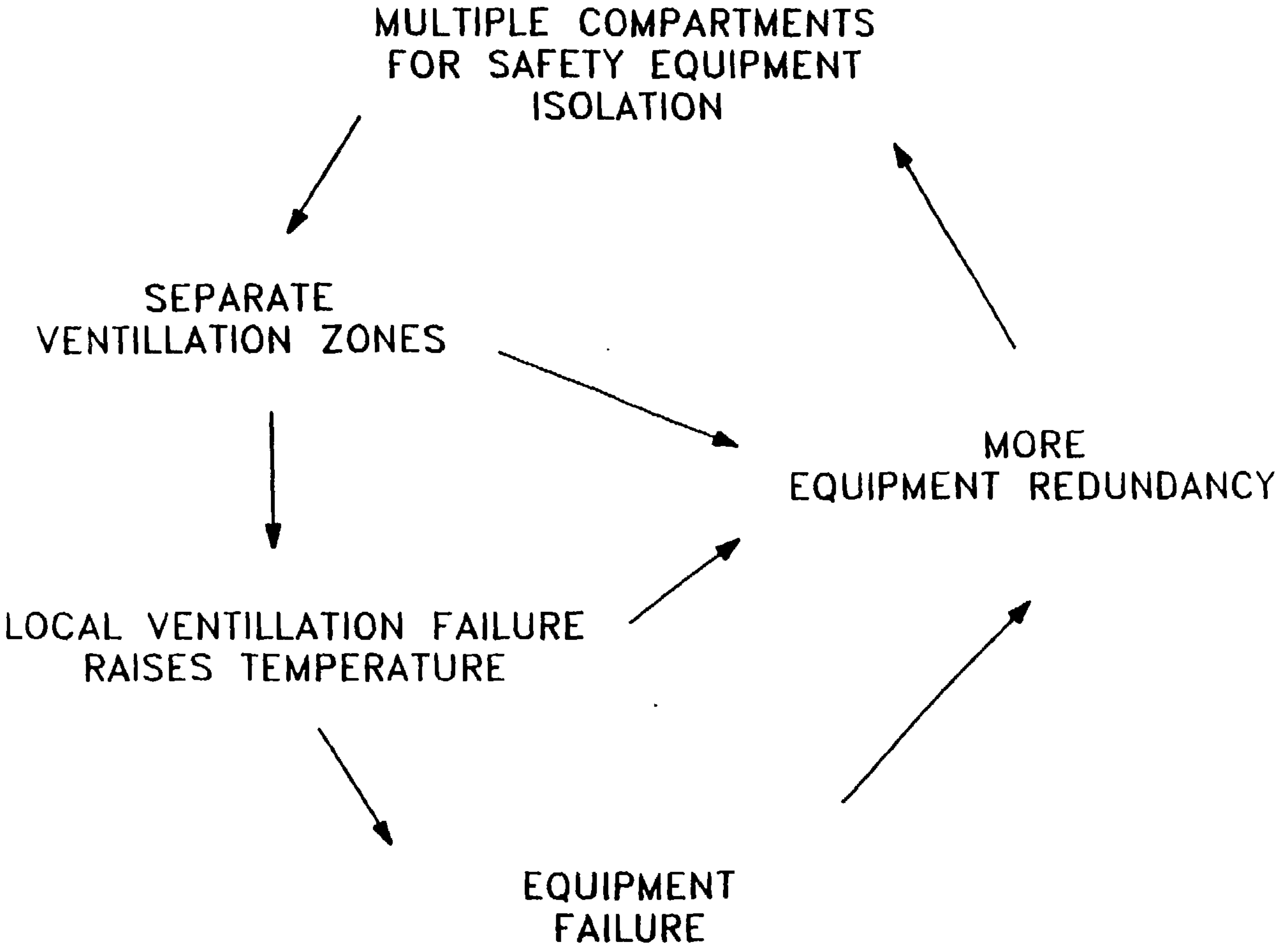

MULTIPLE COMPARTMENTS
FOR SAFETY EQUIPMENT
ISOLATION

SEPARATE
VENTILLATION ZONES

MORE
EQUIPMENT REDUNDANCY

LOCAL VENTILLATION FAILURE
RAISES TEMPERATURE

EQUIPMENT
FAILURE

NORMAL OPERATION CONTAINMENT COOLING PROBLEM

BENEFITS FROM PASSIVE AND INHERENT SSC STUDY

- CREATES BETTER UNDERSTANDING OF OPTIONS
- MAJOR AIDS IN IDENTIFYING PROMISING DIRECTIONS OF RESEARCH
- IDENTIFIES OLD, UNUSED TECHNOLOGIES FOR WHICH CHANGING REQUIREMENTS OR TECHNOLOGY MAKE A PARTICULAR TECHNOLOGY ATTRACTIVE