

CHAPTER 3: CANDU CONTAINMENT DESIGN AND OPERATION

MODULE A: OVERVIEW OF NEGATIVE PRESSURE CONTAINMENT

MODULE OBJECTIVES:

At the end of this module, you will be able to describe:

- 1. The different containment designs implemented in pressurized heavy water reactors**
- 2. Features of the CANDU design relevant to containment**

1.0 CANDU DESIGNS

1.1 Multi-unit plants with vacuum building:

In service dates: 1971-1992, all built in Ontario, Canada for Ontario Hydro

Pickering A and B: 8 units, 2 control rooms, one vacuum building.

Bruce A and B: 8 units, 2 control rooms, one vacuum building

Darlington: 4 units, one control room, one vacuum building

Output 540 - 940 MWe.

Operate at 9-10 MPa, reactor outlet header 290-310C, outlet header may boil 2% quality

Steam pressure 5 MPa.

Structural and ACU cooling for reactor buildings, no internal spray

Cylindrical reactor building volume ~ 60,000 m³, vacuum building ~80,000 m³, plus connecting duct ~30,000 m³

Once-through dousing spray in vacuum building, no recirculation

Subatmospheric reactor buildings.

Retrofitted with hydrogen igniters

1.2 CANDU 6

Single-unit plants with no vacuum building

Output 700 MWe, operate at 10 MPa, 312 C outlet header, may be 2-4% reactor outlet header quality

In service dates: 1983-2003

Wolsong 1,2,3,4 (Korea)

Gentilly-2 (Canada)

Point Lepreau (Canada)

Cernavoda 1,2 (Romania)

Embalse (Argentina)

Qinshan 1,2 (China)

Cylindrical reactor building free volume ~50,000 m³, reinforced prestressed concrete, .6 cm steel liner, double dome

Dousing tank under the dome, 1500 m³, chilled to 28C, serves for dousing spray and ECC injection

Six dousing spray headers, with two independent initiation systems, deliver 4.5 m³/s when pressure increases to 4.5 kPa(g), spray stops at 7 kPa(g).

Not a passive spray system, requires spray valves to open. No spray recirculation.

Igniters: 44 at 11 locations, 3-channel logic to start them

Gross leakage monitoring system, designed to detect a sudden breach in containment of a size that would lead to 5% volume/day leakage. System does continuous computer analysis of data for pressure, temperature, humidity for each room. (flows too?)

Buttonup at 3.5 kPa(g) or high radioactivity in stack or near core.

Subatmospheric normally but not after right after an accident like a CANDU with a vacuum building; expect ~35 kPa(g) at end of dousing

Acceptance leak rate is .5%/day at design pressure.

Design pressure 224 kPa(a), max expected pressure for large steam line break + total dousing failure

Redundancy: for containment availability, it is sufficient to have one igniter at each location, 4/6 spray headers, 12/16 air coolers, water in dousing tank.

1.3 CANDU 9

None built, CANDU-9 is new design

Output 900 MWe, operate at outlet header 10 MPa, 310 C, 2% quality

Single-unit, no vacuum building

No spray dousing

Cylindrical reactor building with larger free volume 110,000 m³

Design pressure 310 kPa(a), note higher value because no spray

Steel liner, post-tensioned prestressed concrete.

Thicker base slab (3 m, compare 1.7 m for older designs)

Energy management by air coolers, condensation on structures

Hydrogen management by igniters, recombiners, plus forced ventilation designed specifically for hydrogen dispersion

Gross containment leakage monitoring system (GCLM) analyzes flows, pressures, temperatures within reactor building to check for inadvertent openings in containment envelope.

2.0 COMMON FEATURES RELEVANT TO CONTAINMENT AND ACCIDENTS

Heavy water for coolant and moderator; 10% mass difference between heavy and light water affects thermodynamic properties only slightly

Tritium generated when heavy water absorbs a neutron, requires periodic removal

Dual reactor shutdown systems; accident analysis assumes failure incredible.

Positive void coefficient causes brief power increase during LOCA before reactor shutdown

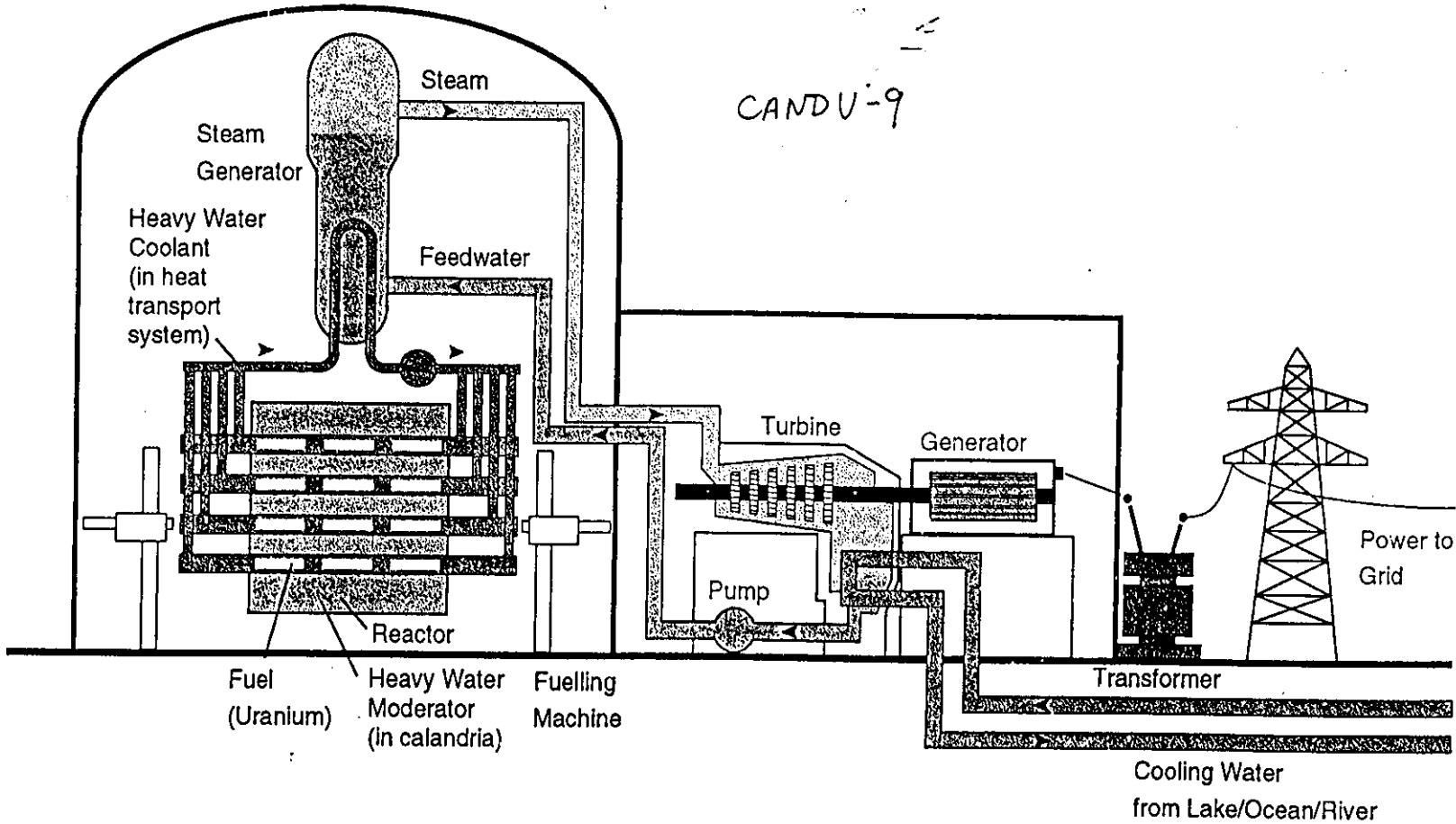
Fuel bundles in several hundred horizontal pressure tubes rather than pressure vessel, pressure tubes enclosed in cold moderator tank (calandria)

Coolant circulates in two loops (each connected to half the pressure tubes), isolated from each other during accident, not likely to lose inventory from both loops.

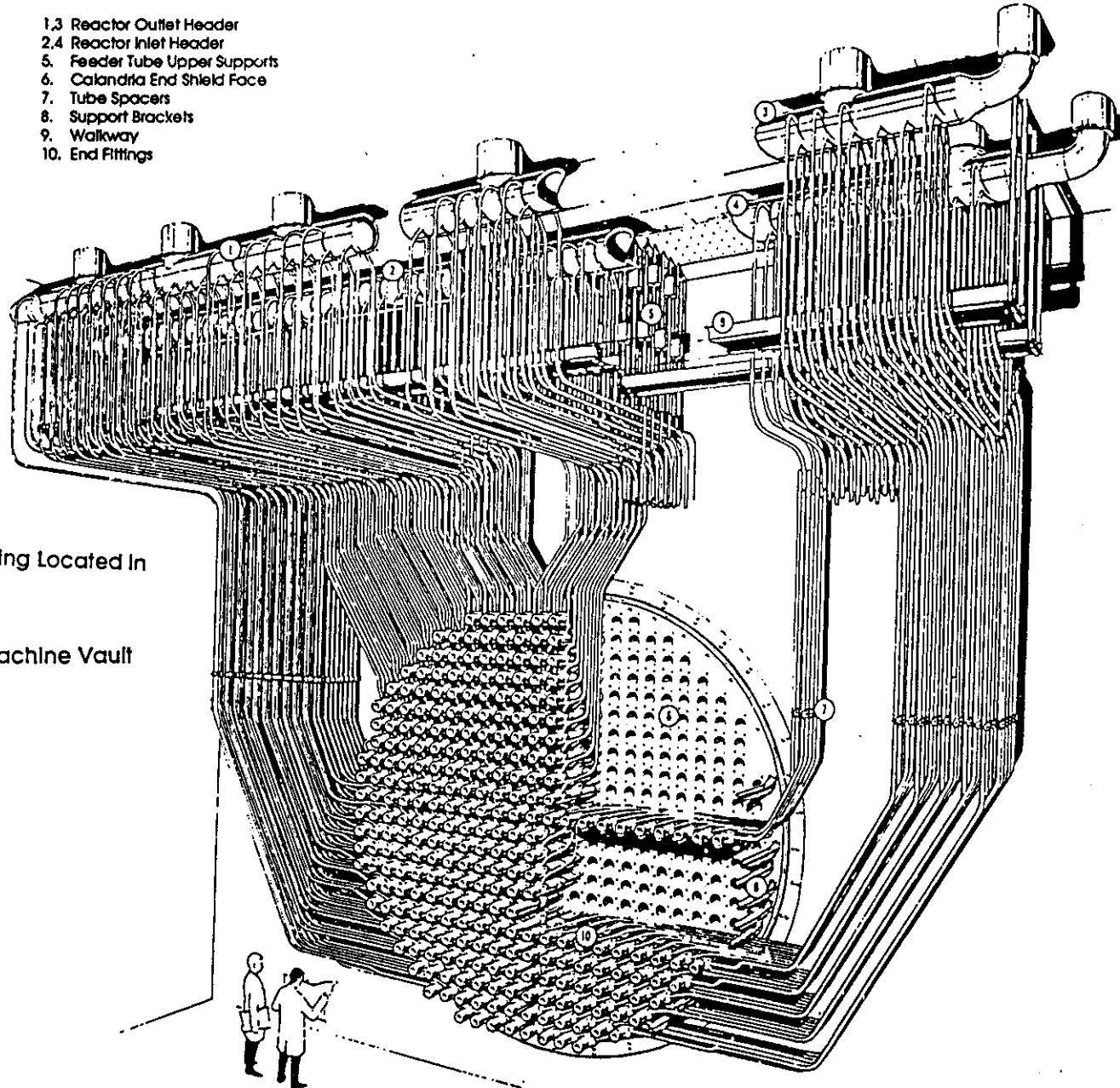
High and low pressure ECC; high pressure for initial injection from a tank, switch to different pumps for recovery mode. Gravity injection from tank also possible if tanks fail.

100-150 tons natural uranium fuel, hence chain reaction stops if bundles no longer correctly spaced 30 cm apart and surrounded by heavy water, i.e. if core structures collapse

Daily refuelling: spent fuel must be passed by the fuelling machine through a special containment penetration.



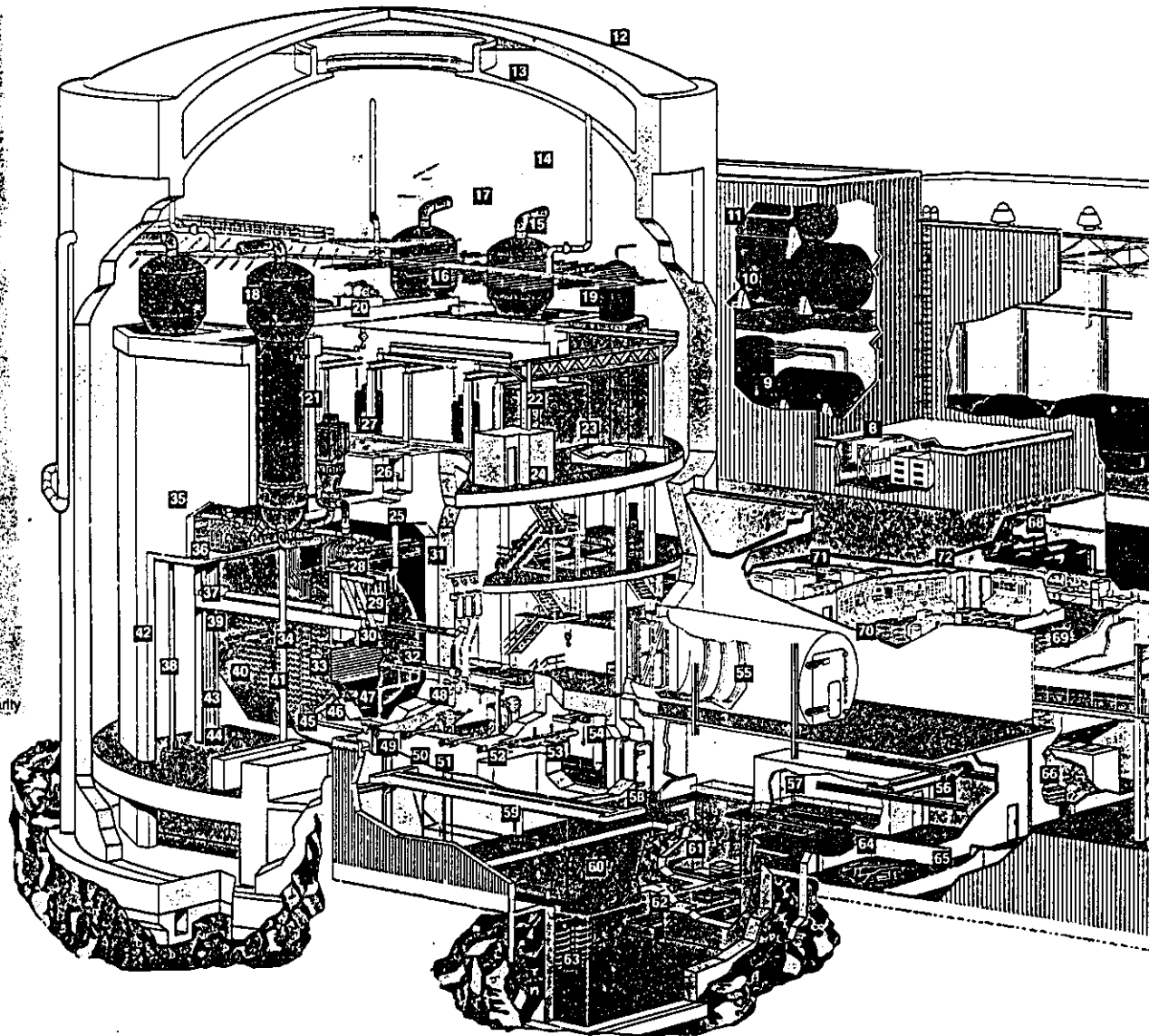
- 1.3 Reactor Outlet Header
- 2.4 Reactor Inlet Header
5. Feeder Tube Upper Supports
6. Calandria End Shield Face
7. Tube Spacers
8. Support Brackets
9. Walkway
10. End Fittings



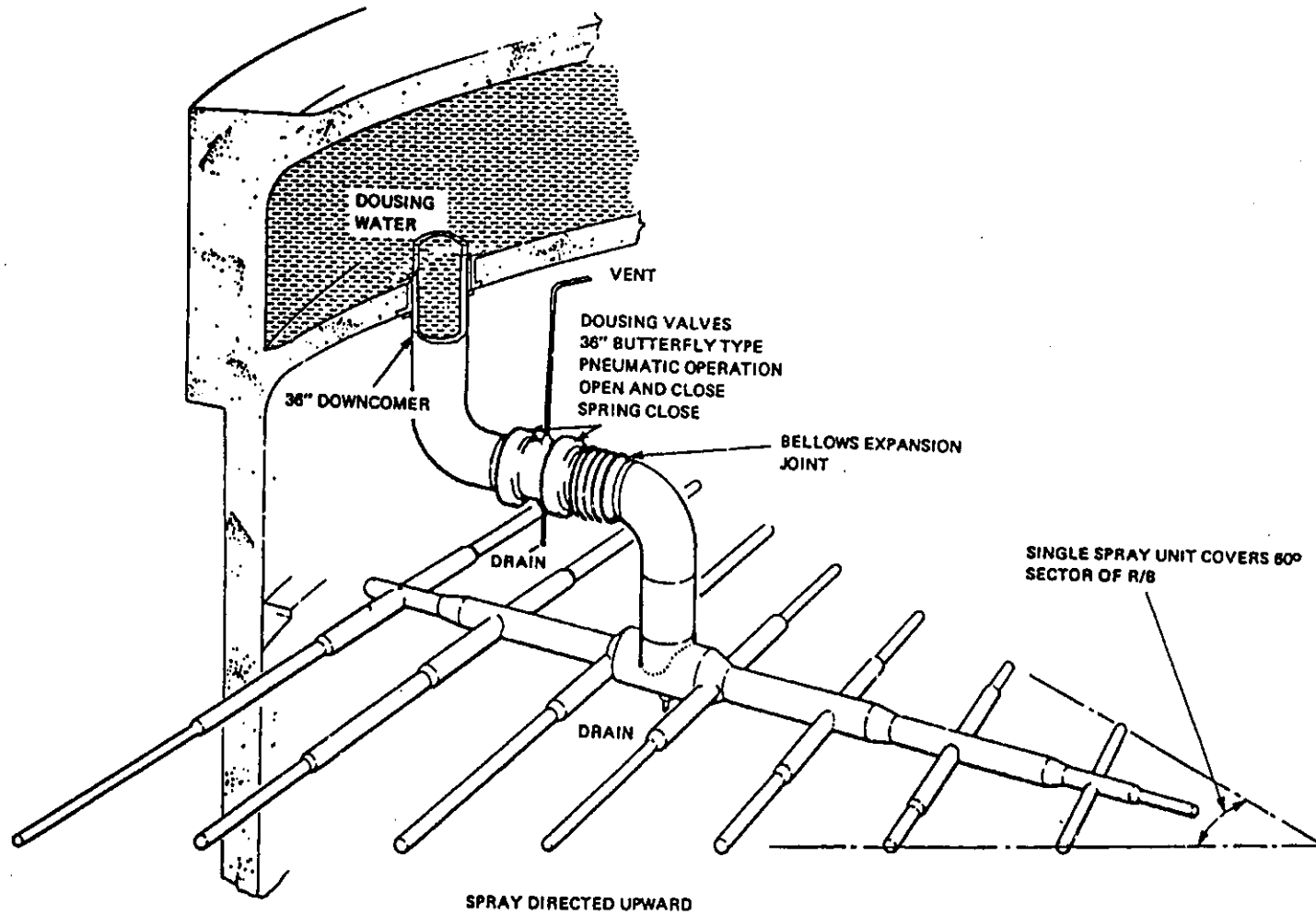
Major Reactor Piping Located In

CANDU Fuelling Machine Vault

1. Diesel room
 2. Water treatment plant
 3. Crane hall
 4. Turbine building
 5. Turbine building crane
 6. Generator
 7. Condenser
 8. Battery room
 9. Boiler feed water tanks
 10. Deserator storage tank
 11. Deserator
 12. Reactor building
 13. Dousing tank
 14. Dousing water supply pipes
 15. Dousing water valves
 16. Dousing water spray nozzles
 17. Main steam pipes
 18. Steam generators
 19. Pressurizer
 20. Crane
 21. Heat transport pumps
 22. Bleed condenser
 23. Bleed cooler
 24. Hatch
 25. Reactor vault
 26. Pressure relief pipes
 27. Reactivity mechanism deck
 28. Reactivity mechanism guide tubes
 29. Calandria
 30. Poison injection nozzles
 31. Poison tanks
 32. Ion chambers
 33. Fuel channel assemblies
 34. End shield
 35. Headers
 36. Feeder pipes
 37. Fueling machine bridge
 38. End shield support columns
 39. Fueling machine
 40. Fueling machine catenary
 41. Fuel channel and rings
 42. Steam generator support column
 43. Feeder pipe insulation cabinet
 44. Fueling machine shielding door
 45. End shield cooling
 46. Fueling machine track
 47. Moderator inlet pipe
 48. New fuel transfer mechanism
 49. New fuel port
 50. Fueling machine service ports
 51. Rehearsal facility
 52. Spent fuel ports
 53. Spent fuel elevator
 54. Entrance to spent fuel area
 55. Airlock
 56. Cranes
 57. Spent fuel shipping area
 58. Spent fuel handling area
 59. Spent fuel bay gantry
 60. Spent fuel bay
 61. Spent fuel storage trays
 62. Storage tray conveyor
 63. Storage tray stack
 64. Fueling machine maintenance area
 65. Decontamination room
 66. New fuel storage
 67. Tool crib
 68. Vapour recovery equipment
 69. Office
 70. Control room
 71. Control equipment room
 72. Computer room
- Some items have been moved for clarity

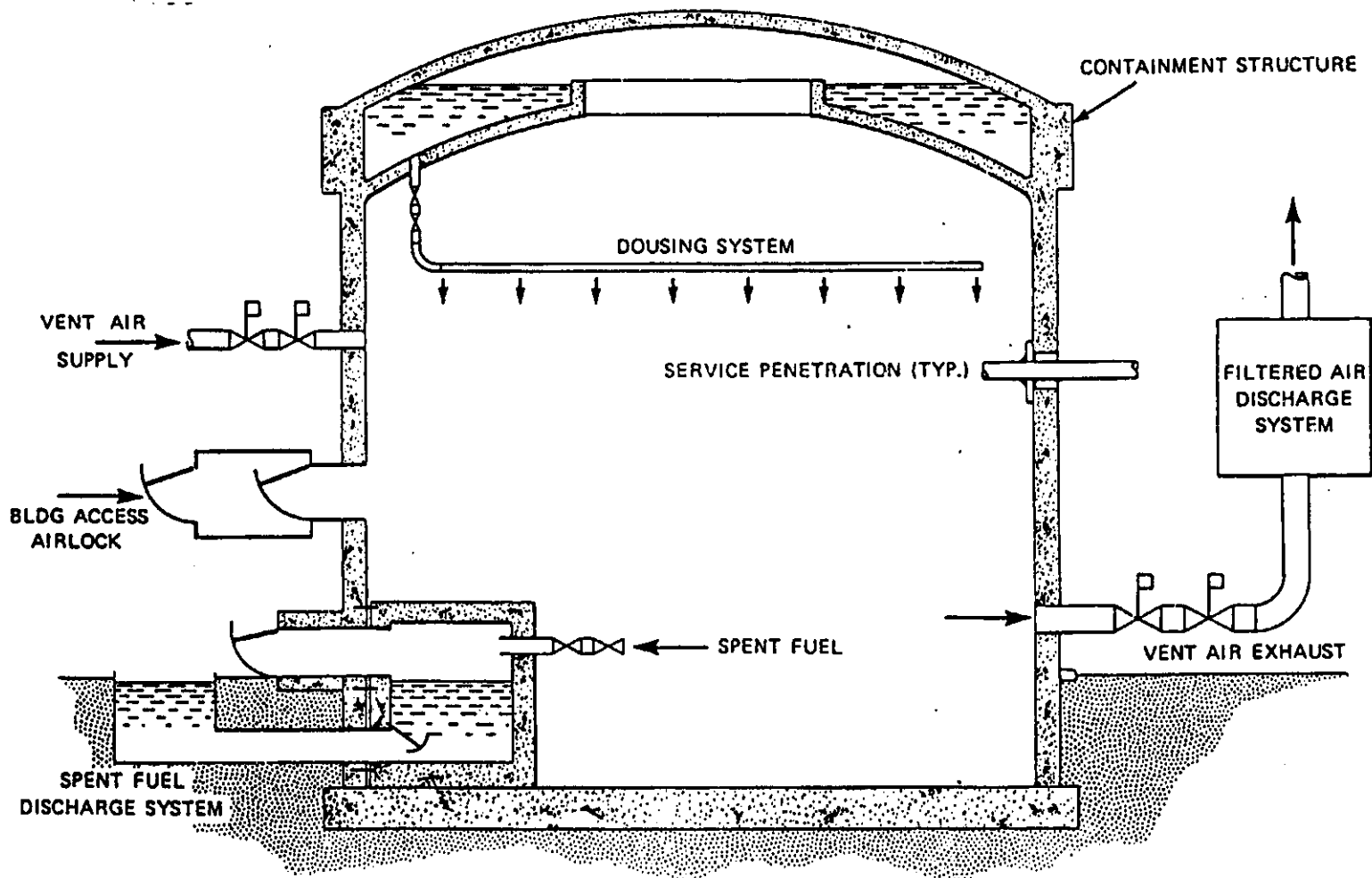


CANDU 6



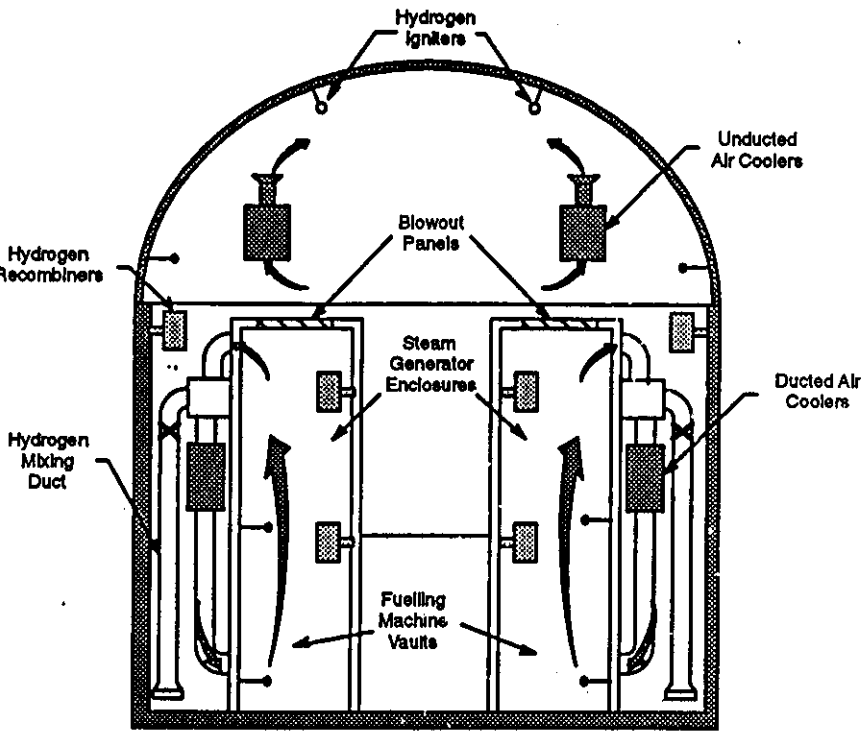
CANDU 6

One of Six Independent Spray Units

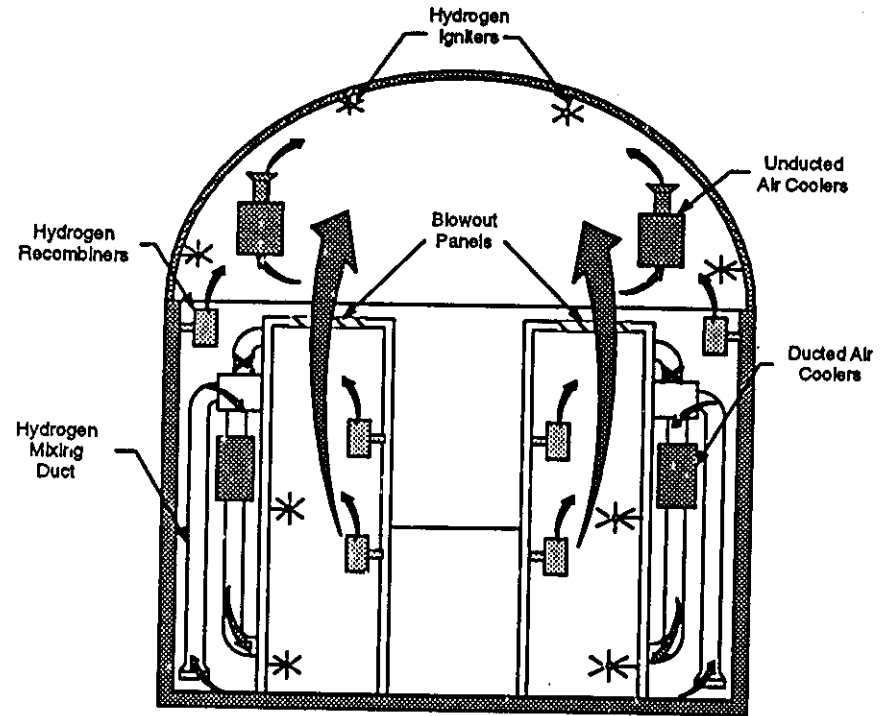


CANDU 6

Reactor Containment System



Hydrogen Control System – normal reactor operation.



Hydrogen Control System – accident mode operation.

CANDU 9

CHAPTER 3: CANDU CONTAINMENT DESIGN AND OPERATION

MODULE B: REACTOR BUILDING AND DOUSING SYSTEM

MODULE OBJECTIVES:

At the end of this module, you will be able to describe:

- 1. The structure of the reactor building for a multi-unit CANDU**
- 2. The design and operation of the sumps**
- 3. The design and operation of the vacuum building and passive spray system**

1. REACTOR BUILDING STRUCTURES

Rooms are normally separated by barriers that open on high pressure differential

1.1 Boiler room

Largest free volume, about 35,000 m³, thanks to dome, 25 m high

Contains boilers (steam generators)

Lines from steam generators to turbine (superheated steam at 250C, 5MPa), could cause highest pressure break

Lines from feedwater pumps to boiler inlets (subcooled water at 187C and 5mpa), another potential break.

Pumps for the main coolant loop, major heat source during normal operation, can also leak

Residual cooling system (shutdown cooling) pumps, heat exchangers

Some cold high pressure equipment: boiler emergency cooling system, pressurized tank

Air coolers, seismically qualified, near ceiling

{ TC "1.0 Introduction" \ 1 }

Dome thickness about .4 m, walls and floor about 1.5 m

Note complex structure of supports, cranes, walkways, see figure in module 5B.

1.2 Fuelling machine vaults and service rooms underneath

On either side of the horizontal core, below the boiler room floor

Much smaller, about 3000 m³ each, very thick internal walls for shielding and support

Contain the equipment for online-refuelling (potential leak)

Twelve main headers for coolant system with fluid at 270C and 9 MPa.: reactor inlet, reactor outlet, pump suction

Several hundred connecting pipes (feeders) between the individual fuel channels and the main headers

Large air coolers on seismically qualified brackets

Concern is small size of rooms relative to size of break flow. Note very thick walls.

Service rooms underneath are where break flow accumulates.

1.3 Moderator rooms

Near floor of building, low because of moderator pump suction

Volume about 2000 m³.

Contain moderator pumps, heat exchangers, ion exchange columns, coolers

Moderator is cool, low pressure system, (65C, several hundred kPa) but water is high activity

Breaks in HX cooling water pipes must be considered. Cold, but could flood equipment.

Significant as place that must not be flooded during LOCA, as volume at lowest pressure during normal operation

1.4 Accessible areas

Volume about 30,000 m³.

Remainder of reactor building at floor level between core and outer walls

Shielded from core radiation, accessible to personnel when reactor at full power.

Miscellaneous low-pressure, low-temperature, non-radioactive equipment

No significant break flows or radionuclides sources expected here.

Significant as a free volume, and as a large surface area where water from the break spreads out

2.0 REACTOR BUILDING SUMPS

2.1 Requirements:

All liquid from any large break must reach floor level in the reactor building for ECC recirculation pump suction

Must be adequate suction for these pumps when ECC tank is empty

Small break flows must drain to sumps/tanks for liquid recovery systems

No flooding of critical equipment: moderator pumps essential, (ECC pumps are outside reactor building)

No accumulations on upper floors: can't clean up after break, puts loads on structures

Normal small D2O losses from equipment such as valves, pumps (packing, stuffing boxes) and piping that must be drained or vented during normal operation are collected by separate systems

Moderator collection

RCS collection

Miscellaneous collection

(Radio)active drainage

Systems are separated according to degree of purity/radioactivity of D2O.

The collected D2O ends up in small tanks that the operator can pump out at his discretion.

These systems do not play a role during break scenarios, but may give early warning of leaks

Abnormal D2O or H2O losses have different origins:

Hot pipe breaks, cold pipe breaks from service water

Condensation (will be a lot during a main steam line break)

Relief valve flows (some relief valves vent to containment atmosphere/sumps, e.g. the moderator cover gas)

Abnormal losses are managed by different systems of piping, pumps and valves as well as sumps, pits and by the design of the floors and walls of the reactor building.

RCS liquid recovery

Emergency coolant injection,

Active drainage,

Reactor building liquid recovery

Reactor building floors and walls.

Older design (1971) was retrofitted to facilitate descent of water to floor

2.2 Operation

Once break flow from the main RCS loop reaches the lowest level, the fuelling machine service room sumps, they can be pumped back into the RCS system either by:

D2O recovery, which can pump limited amounts of D2O back into the RCS D2O storage tank

ECl system in recovery mode, which can pump back more water (~700 kg/s), using

the moderator pumps, from the sumps through the moderator heat exchangers back into the RCS headers (PNGSA, the older station)

the ECC recovery pumps, through the recovery heat exchangers (all other CANDUs)

Eventually, since flow from the break will match the rate at which water is pumped back in, sump level must stabilize.

If the D2O recovery system is involved (very small break), the operator controls level by switching the recovery pump on and off to control sump level for the recovery pump NPSH and to maintain adequate inventory in the D2O storage tank.

If the ECI system has activated, level reaches a steady state value after the high pressure ECI system has pumped the 800 m³ ECI storage tank contents into the broken RCS loop, from which it falls into the sumps.

Level will stabilize at a depth of 1 m in this case; it will spread from the fuelling machine service rooms over the entire reactor building floor into the accessible area.

If the water accumulating under the vaults is not from the main RCS loop, it is not pumped out of the sump (where would it be pumped into?) and sump level will continue increasing.

The operator will try to valve out the break.

If the break flow cannot be stopped immediately, it is not of great concern because the service room floors are designed so that water accumulating under the fuelling vaults will eventually burst through rupture panels and spread into the accessible area with its huge surface area.

Calandria vault is where breaks from the calandria (moderator) piping will accumulate. Can be valved in to ECI recovery suction.

The moderator room is physically separate from the sumps discussed earlier.

Water could accumulate there only as a result of breaks in the moderator piping or in the service water supply to the heat exchangers. Service water flow is large, ~1000 L/s.

The great concern is that the moderator pumps might be flooded by rising level in the moderator room.

The moderator room is therefore well provided with instrumentation, as well as with two active drainage pumps which pump out this room into the accessible area

2.3 Detailed sump descriptions

Boiler room

The bathtub-sized boiler room sump (1.86 m² , 1.5m deep) is in the middle of the sloping boiler room floor.

Two 25 cm pipes travel vertically downward to the east and west FM service room sumps.

Foils at the bottom ends of the pipes (intended to separate room atmospheres) require about four meters of water accumulating in the pipes before water bursts through to the fuelling machine service rooms below.

There is no level transmitter in the sump, only a beetle (alarms in control room)

Given the very large pipe capacity, water does not overflow significantly from the sump onto the surrounding floor.

Break flows that do not reach the central sump run to the east and west sides of the boiler room, and flow through holes made in the curbs at the edge of floor onto the walkon panels several feet below, or down stairwells eventually to the FM vaults.

The walk-on panels can open only upward in response to high pressure in the FM vault, not downward in response to falling water.

Water cannot accumulate significantly there because it will flow over the panels to the stairwells, or through gaps on each side left by panels which were removed to prevent accumulation.

There are small drain lines, from the east and west walkon panels to two very small tanks with beetles but no other alarms.

These two tanks drain through a common line, where another beetle is located, into a third tank, which does have a high level alarm in the control room.

Fuelling machine vaults and service rooms

Equipment in the vaults includes the RCS feeders, main RCS inlet and outlet headers, the fuelling machines and the vault coolers.

The moderator cover gas rupture discs also relieve to the vaults, in case a pressure tube bursts inside the moderator

The fuelling machine vaults, where breaks may occur, are designed for minimum holdup; water passes almost immediately through piping and openings in the vault floor into the service room sump below.

Water may also enter the service room sumps from piping leading down from the boiler room sump and the boiler room stairwells. From the service room sump it travels along the D2O recovery piping to the D2O recovery tank, and continues through the mirror image D2O recovery piping to the service room sump on the opposite side.

The east and west service rooms are each connected to the accessible area by a trench of 3.3 m² area running under the wall separating the rooms from each another. A vertical vapour barrier midway across a trench normally prevents air flow between the rooms.

After water reaches 1.3 m in either sump, it bursts through the vapour barriers in the trenches between the service rooms and the accessible area.

Accessible area sumps

Three small sumps (.8 m²) at widely separated locations in the accessible area.

The active drainage pumps in the sumps have only local handswitches and are not normally placed in auto mode. During LOCA, the operator is not required to start them.

Each sump has a level switch connected to a control room annunciation.

These annunciations are expected when the moderator room is pumped into one of these small sumps or accessible area level rises enough to flow into the sumps.

Moderator room sumps

Several sumps under pumps and heat exchangers.

Three level switches, with control room indicating lamps associated with each of the two pumps that pump out the moderator room to accessible area.

One level switch, is connected to an alarm and a main control room alarm window indicating very high level in the moderator room.

Two submersible pumps with emergency power backup are intended to prevent flooding of the moderator pump motors on high level in the moderator room.

The pumps have four-position handswitch in the control room and status lamps. There is logic to automatically start the AUTO or STANDBY pumps on high or very high level.

3.0 VACUUM BUILDING AND PRESSURE RELIEF DUCT

3.1 Description of duct and dousing system

The pressure relief duct connects the eight reactor buildings to the vacuum building through pressure regulating valves (at the vacuum building) and bursting panels/valves (at each reactor building).

Pressure relief duct is a rectangular cross-section elevated structure, runs length of station behind reactor buildings.

Normally kept at atmospheric pressure and temperature, normally isolated from vacuum building and reactor buildings.

The vacuum building and dousing system consists of:

A cylindrical flat-topped concrete structure standing apart from the reactor buildings.

The 10,000 m³ Emergency Service Water (ESW) open tank near the top of the main chamber, the source of dousing water and other emergency needs:

An emergency supply to the low pressure service water system of Units 1 and 2 (several hundred L/s)

An emergency supply of water to the high pressure service water system for Units 1 to 4 (several hundred L/s).

An emergency supply of water to the recirculation cooling water system (cools a few smaller loads not supplied with service water) for Units 1 to 8.

A supply of water for the dousing system which is used to condense steam which has entered the

vacuum building after an accident.

A supply of water for sealing the vacuum ducts prior to testing of a given pressure relief valve.

A large cylindrical main chamber, $8.24 \times 10^4 \text{ m}^3$ below the tank and the upper chambers

Two small upper chambers (each 485 m^3). Each chamber is a 33.5 m long concrete box located on the roof of the vacuum building.

The chambers each have a 0.91 m high concrete weir which runs the length of the chamber and separates the 14 suction pipes from 14 vertical downcomers.

Twenty-eight vertical suction pipes leading from the bottom of the emergency storage tank to two upper vacuum chambers.

Twenty-eight downcomers (14 per upper chamber). The downcomers pass through the emergency storage tank and have U-bends, the outlets of which are connected to one of seven spray headers.

U-bends are filled with water (vacuum building seal) to separate the main and upper chambers. The U-bends in the dousing system are filled with water.

A trickle supply flow is provided which, if the system is leak tight, will cause an overflow into the small overflow lines attached to each header.

Sight glasses (instrumentation for visual inspection) on the overflow lines, located in the vacuum building basement, are used to confirm that the U-bends and headers are full of water.

If no water in the U-bends, no dousing occurs when main chamber pressure rises!

Seven spray headers and piping to permit ESW to be sprayed into the main chamber at 30 m³ /s.

The spray headers span the top of the vacuum building (below the emergency storage tank) in order to provide a uniform spray distribution and hence maximize dousing.

The headers have holes located on their top side, the holes being sized for efficient droplet production.

Seven vacuum pumps for the three chambers to keep all the chambers at about 1/10 atmospheric pressure.

Vacuum pumps automatically stop on high boiler room pressure and dampers close (buttonup)

Not needed after LOCA

Control from secondary control area

Normally one runs for each chamber, others on standby

Heaters for ESW temperature control. Must not freeze.

Very small circulating pumps to maintain a seal between the upper and lower chamber, and pump water from the vacuum building floor back to the ESW tank (very small capacity, only one douse possible during LOCA).

Instrumentation for seal flow (critical!), tank and floor level, temperature, pressure vacuum pump status

3.2 Operation of dousing system

Passive, no moving parts, rising pressure in main chamber initiates dousing.

Water from the emergency storage tank is sprayed through holes in the dousing headers.

These holes are designed to break the water up into fine droplets which enhances the heat transfer with the steam and air as the droplets fall to the vacuum building floor.

As the water in the storage tank is cooler than the steam, the steam gives up its heat to the water and partly condenses.

Experiment shows heat transfer is about 95% effective, i.e. most droplets are at ambient temperature when they hit the floor after a 3-second fall.

Consider a steady rise in main vacuum chamber pressure as caused by a moderate LOCA.

Upper chambers are isolated by the U-bend water seals, so a pressure difference will exist between the main and upper vacuum chambers.

Consequently, water will be pushed up the suction pipe and downcomers, ie, the gas pressure difference will tend to be balanced by the hydrostatic head of the water.

When the main vacuum building pressure is high enough (about 60 kPa(a) when the ESW tank is full), the water in the suction pipes will reach the top of the weir.

More precise to state that it flows over the weir and into the spray headers once the pressure difference between upper and lower chambers reaches 37 kPa(d). (The upper chamber air is compressed by rising water level, so its pressure rises together with main chamber pressure, but not as fast.)

Increasing main chamber pressure further causes water to flow over the weir and into the downcomers.

The water that had been backing up in the downcomers will now be "pushed" into the dousing header and out through the spray holes, ie, dousing would commence.

For a large LOCA or large main steam break dousing flows in the order of 38,500 kg/s are expected - 25 minutes of flow.

Dousing will continue until the driving pressure difference is insufficient to raise the water to the top of the weir, happens as ESW level drops or main chamber pressure falls.

Dousing is not necessarily continuous, could be on/off for some break sizes.

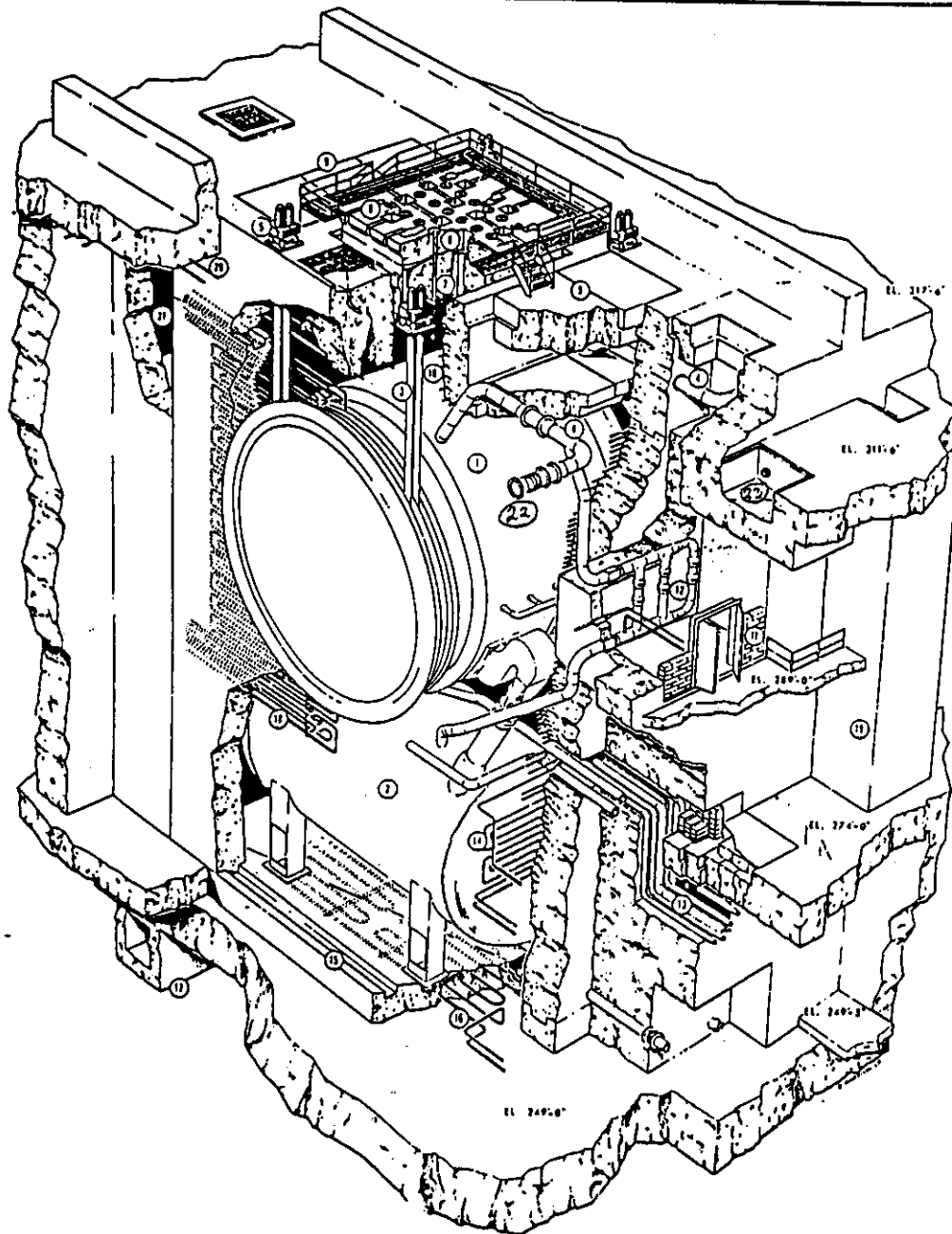
What the drawings do not show is that the upper chamber air could be entrained by the dousing flow

Air is eventually removed from the upper chamber, a siphon may be established.

Dousing may then continue until the ESW tank is emptied, regardless of main chamber pressure.

A full douse (empty tank) is expected only for large steam line breaks and the largest LOCAs.

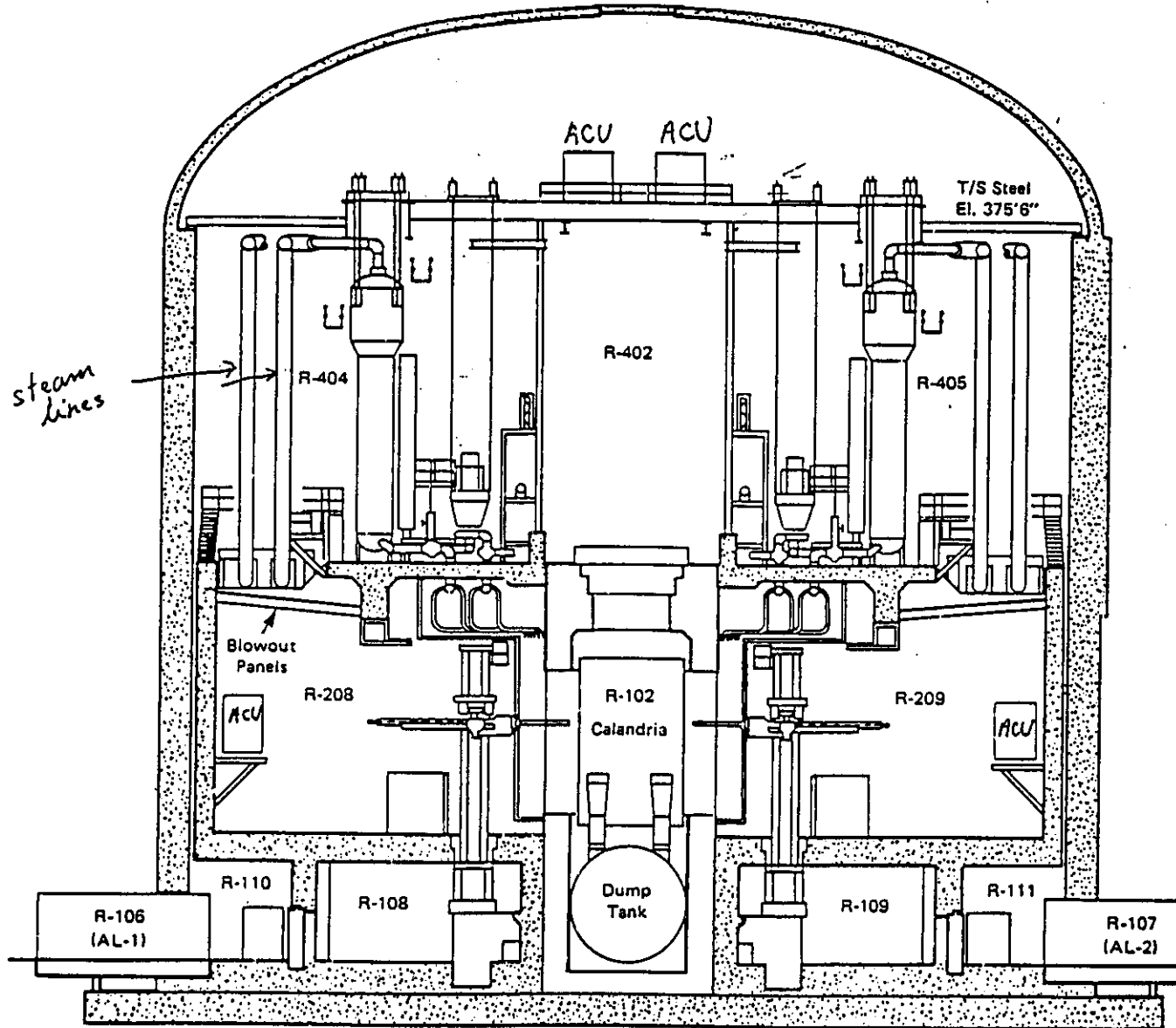
The vacuum building will be subatmospheric except briefly during the largest steam line breaks.



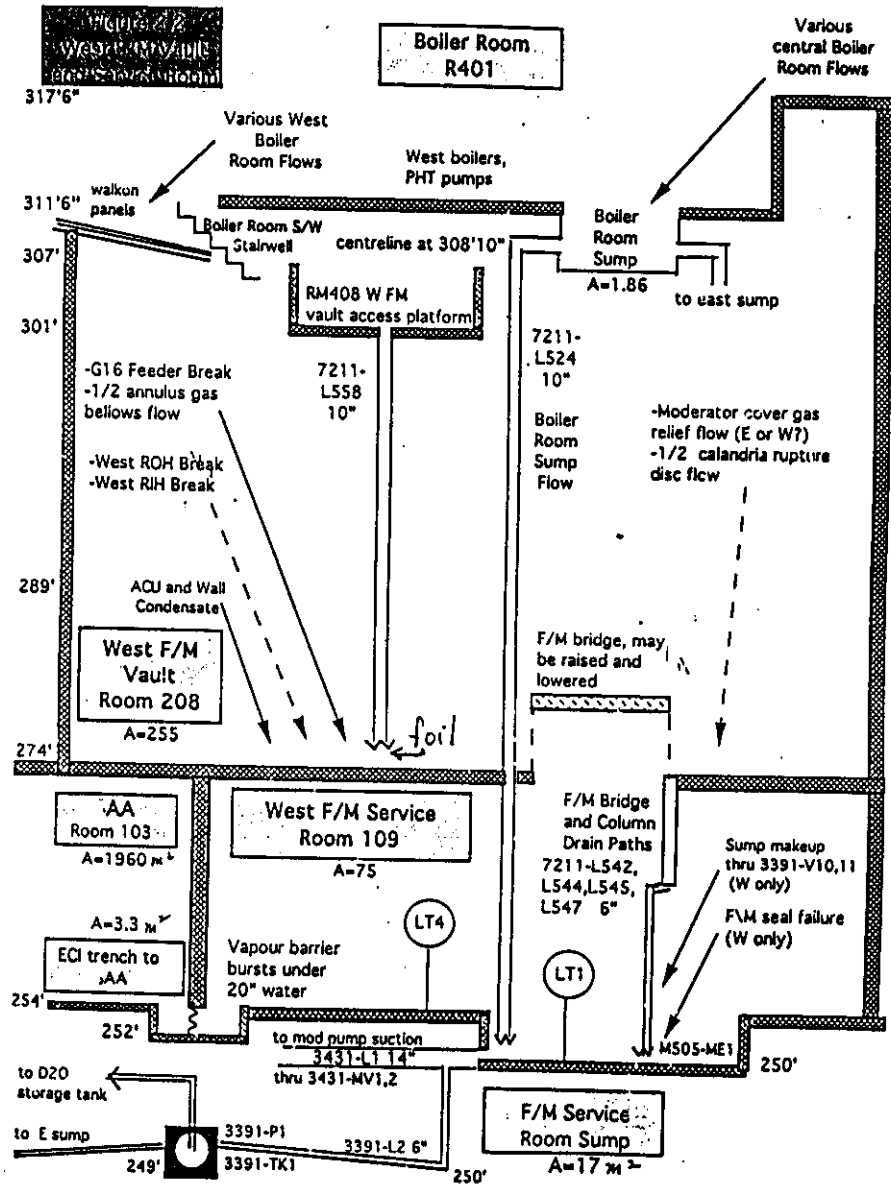
- 1 CALANDRIA
- 2 DUMP TANK
- 3 CALANDRIA SUPPORT RODS
- ④ HELIUM BALANCE AND BLOW OFF LINES
- 5 CALANDRIA VERTICAL ADJUSTMENT
- 6 CALANDRIA VAULT REACTIVITY MECHANISM PLUG
- 7 CALANDRIA VAULT REACTIVITY MECHANISM PLUG COOLING PIPES
- 8 REACTIVITY CONTROL MECHANISM PENETRATIONS
- 9 CALANDRIA VAULT HATCHES
- 10 CALANDRIA VAULT ROOF BIOLOGICAL SHIELD COOLING
- 11 HEAVY CONCRETE BLOCK WALL
- 12 HELIUM VALVE CHAMBER
- 13 CALANDRIA VAULT PIPING
- 14 NORTH WALL BIOLOGICAL SHIELD COOLING

- 15 CALANDRIA VAULT FLOOR
- 16 CALANDRIA VAULT FLOOR BIOLOGICAL SHIELD COOLING
- ⑬ SPENT FUEL TRANSFER DUCT
- 18 EAST WALL BIOLOGICAL SHIELD COOLING
- 19 PIPE CHASE
- 20 FUELLING MACHINE VAULT COOLING
- 21 CALANDRIA VAULT BOILER ROOM INTER SPACE
- ⑭ Calandria rupture disk
- ⑮ Boiler room sump

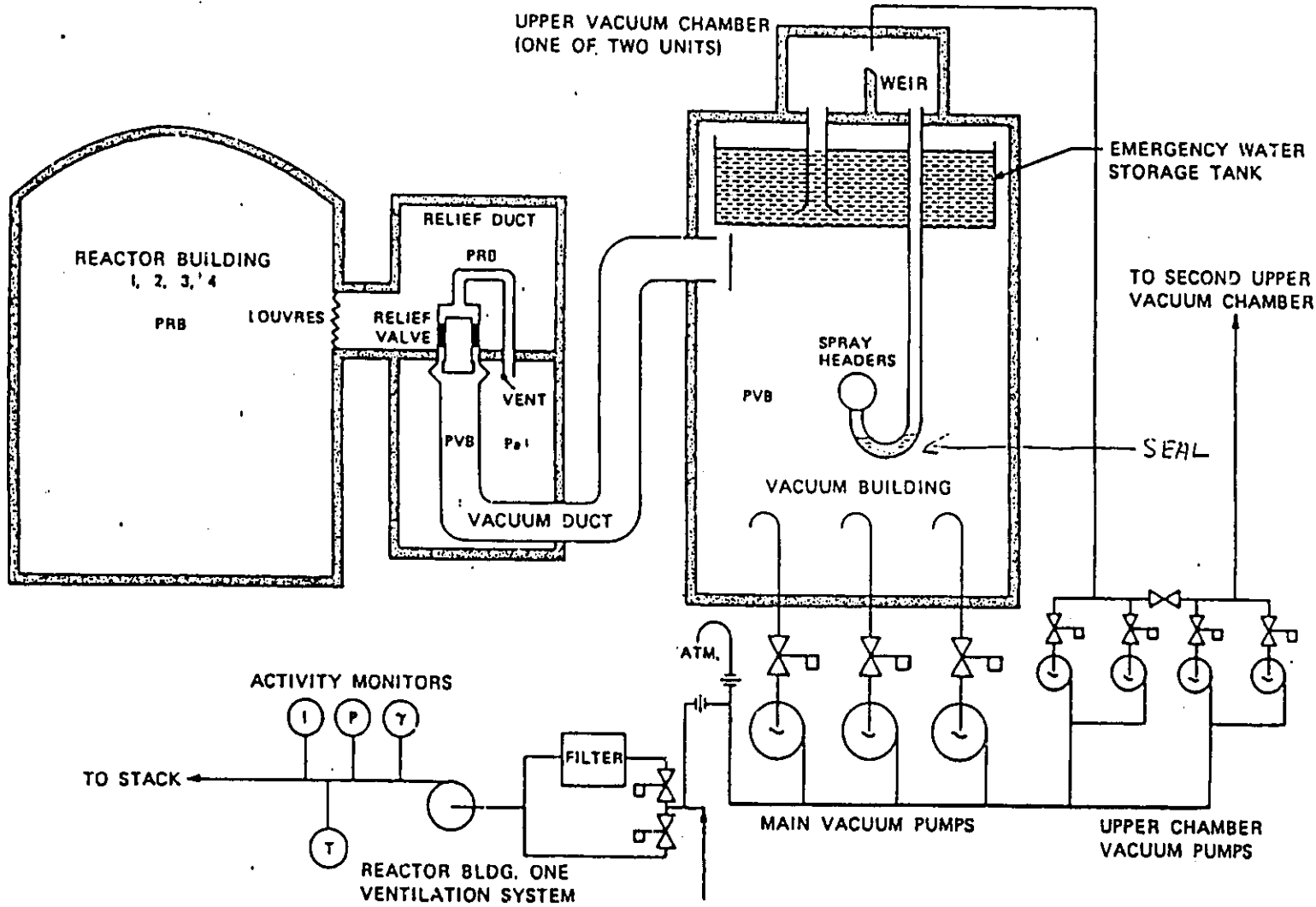
PNGS-A



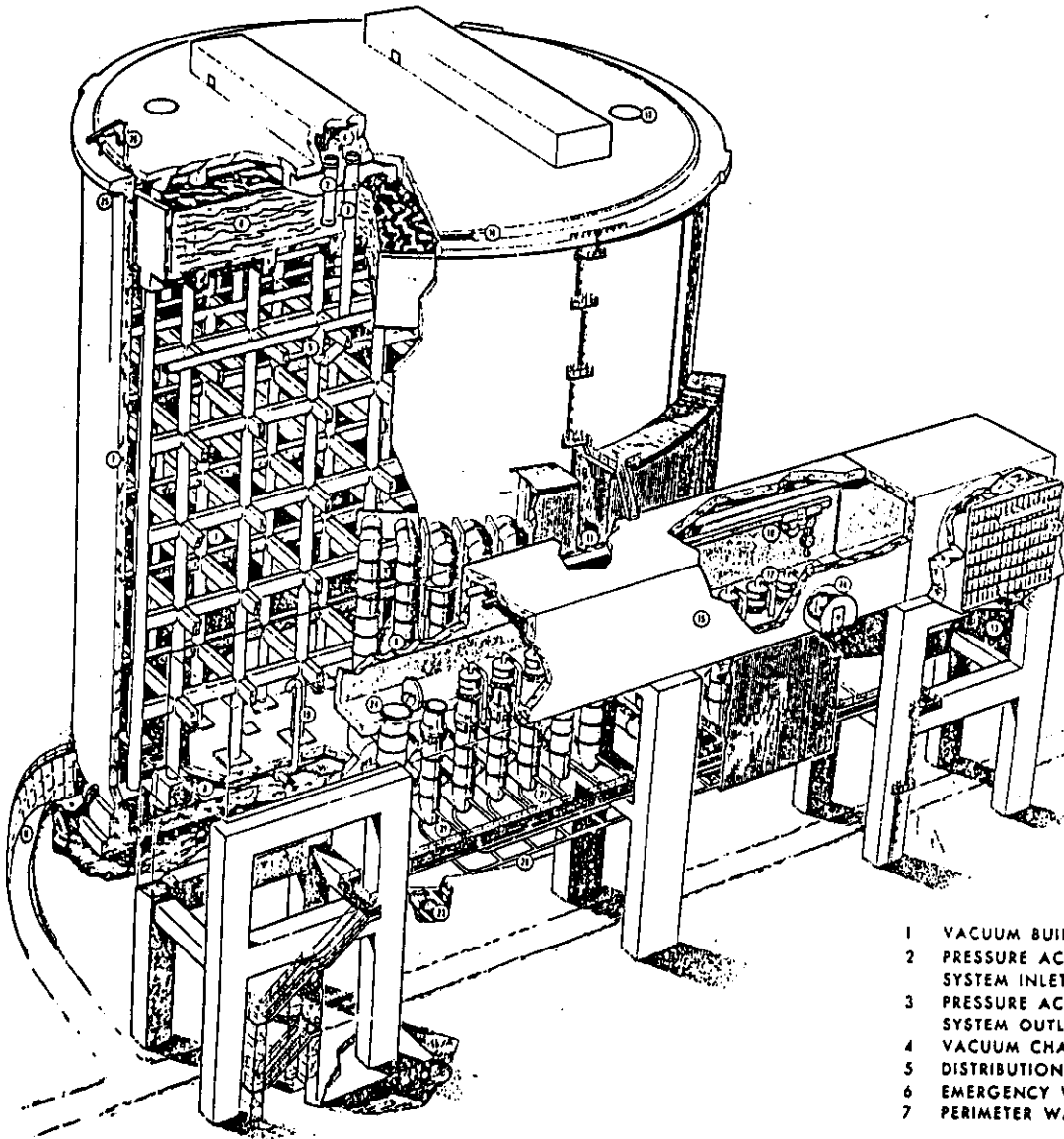
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Flowpaths from pipe breaks to sumps



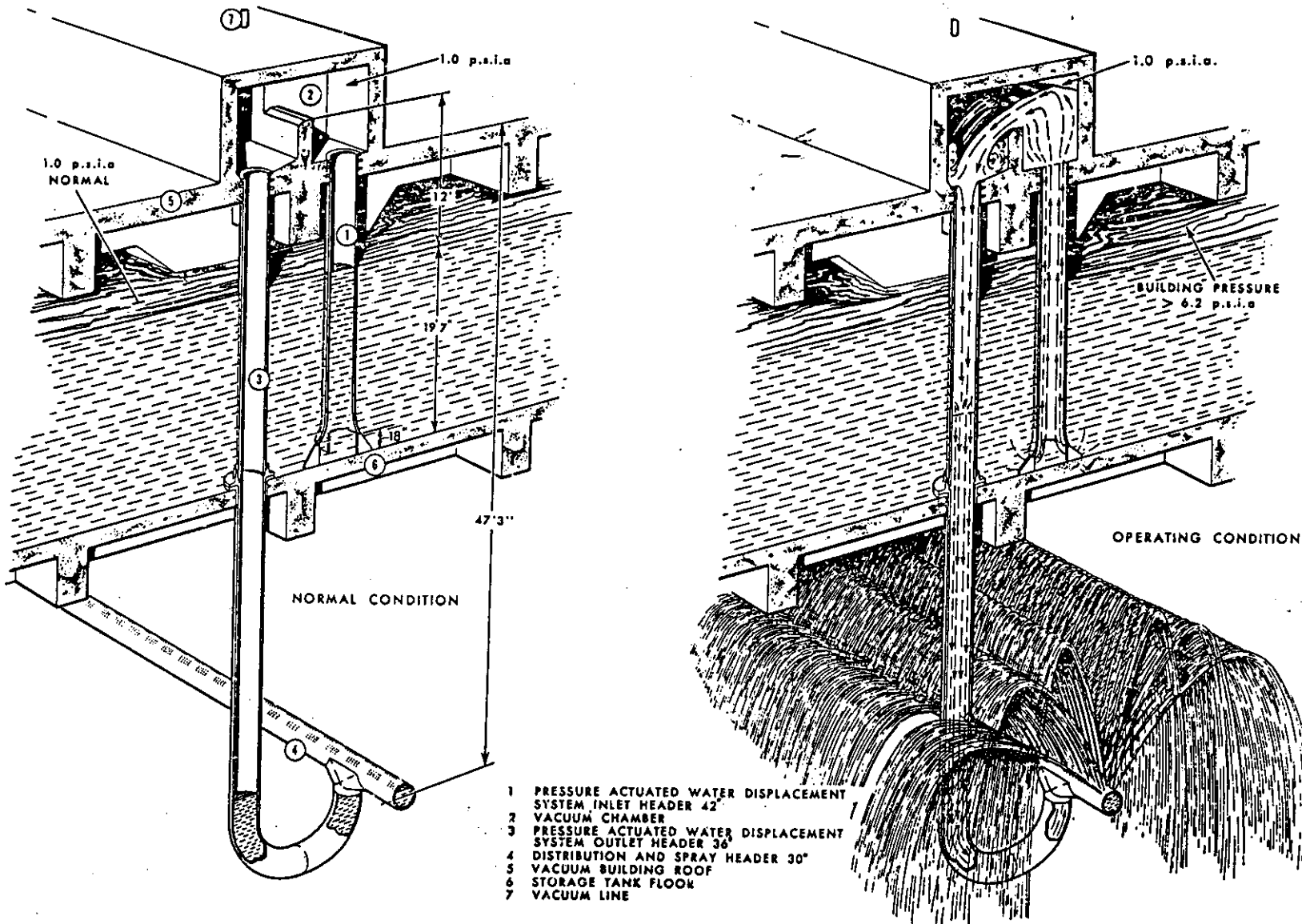
PICKERING NEGATIVE PRESSURE CONTAINMENT



- 1 VACUUM BUILDING INTERNALS
- 2 PRESSURE ACTUATED WATER DISPLACEMENT SYSTEM INLET HEADER
- 3 PRESSURE ACTUATED WATER DISPLACEMENT SYSTEM OUTLET HEADER
- 4 VACUUM CHAMBER
- 5 DISTRIBUTION AND SPRAY HEADER
- 6 EMERGENCY WATER STORAGE TANK
- 7 PERIMETER WALL

- 8 BASEMENT
- 9 VACUUM DUCTS
- 10 MONORAIL AND HOIST
- 11 EMERGENCY WATER LINE
- 12 PRESSURE RELIEF VALVES
- 13 SHIELDING WALLS
- 14 PERSONNEL AIRLOCK
- 15 PRESSURE RELIEF DUCT
- 16 ROOF/WALL SEAL
- 17 WATER TANK ACCESS HATCH
- 18 BASEMENT ACCESS RAMP
- 19 VACUUM PUMP SUCTION HEADER
- 20 VACUUM DUCT DRAIN PIPE
- 21 VACUUM DUCT FILL PIPE
- 22 REACTOR BUILDING PRESSURE RELIEF LOUVRES
- 23 SERVICES TUNNEL
- 24 EQUIPMENT AIRLOCK
- 25 PERIMETER WALL MONORAIL
- 26 JIB CRANE
- 27 ROOF HOIST

VACUUM BUILDING AND RELIEF DUCT



VACUUM BUILDING SPRAY SYSTEM

CHAPTER 3: CANDU CONTAINMENT DESIGN AND OPERATION

MODULE C: VENTILATION, COOLING AND VAPOUR RECOVERY

MODULE OBJECTIVES:

At the end of this module, you will be able to describe:

- 1. The functions of the ventilation and vapour recovery system**
- 2. The operation of drier beds**
- 3. Approximate leakage rates for instrument air, vapour and air into the reactor building**
- 4. The locations and capacities of the air coolers**
- 5. The operation of the containment isolation system**

1.0 VENTILATION AND VAPOUR RECOVERY

{ TC "1.0 Introduction" \ 1 } Two types of ventilation systems in the reactor building: normal once-through ventilation, and vapour recovery.

Vapour recovery

- Areas which are liable to heavy water leakage are isolated from other areas and are placed in a closed loop circuit with a vapour recovery system to dry the air.
- Permits recovery of D₂O (\$400/kg) which has leaked from systems and has vapourized.
- Prevents buildup of tritium vapour in the reactor building plus other airborne radionuclides
- The Boiler Room, West and East Fuelling Machine Vaults have high-pressure hot piping (boilers, RCS headers, pressure tubes) and many fittings that could leak.
- Moderator Room (moderator pumps, heat exchangers, ion exchange columns) piping is low pressure (<800 kPa) and low temperature (~70C) but moderator coolant has far more tritium than the RCS.
- Pressures are adjusted by dampers in ducts between rooms, to make the most contaminated room at the lowest pressure.

Once-through ventilation system

- The remainder of the reactor building is referred to as the Accessible Area
- Accessible to personnel while reactor is at power, due to shielding around the core.

- **Accessible Areas are less likely to experience heavy water leakage**
- **Ventilated using a one pass system with the air flow from outside**
- **Air passes through the Accessible Areas and exits through the reactor building stack without being dried.**
- **Stack has filters for iodine and particulate, plus radiation monitoring equipment**
- **This stack and the filters are not the same as the emergency filtered discharge system that operates after an accident.**

Vapour Recovery System{ TC "1.1.1 Vapour Recovery" \ 1 }

- **{ TC "1.1.1.2 Vapour Recovery Circuits" \ 1 } Three separate room drier circuits: F/M Vaults, Boiler Room, and Moderator Rooms, as well as the stack (or exhaust) drier.**
- **Each drier has a fan and desiccant (drying) beds**
- **During normal operation, the 3 circuits are isolated from one another.**
- **For the room driers, the air flow is directed in a closed loop so that both intake and exhaust are connected to the same room.**
- **Each circuit has a small exhaust flow (bleed) to maintain the differential pressure between the dried rooms and accessible areas.**
- **For the stack drier the exhaust is directed entirely to the stack.**

- **Boiler Room Drier Circuit:** one drier, maintained about .005-.01 kPa below accessible areas by a damper
- **Moderator Drier Circuit:** similar, maintained at lowest pressure
- **F/M Vault Drier Circuit:** one drier, maintained about .005-.01 kPa below accessible areas by a damper
- **Two stack driers, but only one drier is in service at any one time and a manual damper isolates the other.**
 - **Dry the air exhausted to the stack before passing through filters**
 - **Provide a bleed flow from the boiler room to maintain it at a negative pressure relative to the accessible areas.**
 - **Stack dampers close on high Boiler room pressure, as part of containment isolation.**

Molecular sieve desiccant drier design and operation{ TC "1.1.1.3 Drier Operation" \1 1 }

- **System components:** two parallel desiccant beds, the adsorption and regeneration fans, regeneration heaters and condensers.
- **Fan capacity is 1-2 m³/s.**
- **One bed is in adsorption mode (remove vapour from air), while the other is in regeneration mode (remove vapour from bed).**
- **Adsorption mode**

- **Adsorption fans direct moist air from the area being dried over the desiccant bed and then either to the stack (exhaust drier) or back to the dried area (room driers).**
- **When the bed becomes saturated, water can no longer be adsorbed from the air.**
- **Regeneration mode**
 - **To regenerate the desiccant, dry, hot air is passed through it and the water is released into the air.**
 - **A condenser cools the effluent air from the desiccant bed to condense the released water vapour.**
 - **The dried, cooled air leaving the condenser is then returned to the desiccant via the heater in a closed loop to extract more vapour.**
 - **The condensate collection system takes the condensate produced by the room dryers and stores it in one of three collection tanks**
- **Dewpoint (humidity) measurements at the inlet and outlet of the bed in adsorption mode indicate when it is time to switch over.**
- **The individual inlet dewpoints are displayed by green chart recorder pens with a display range of -80 to +20 C.**
- **Normal inlet dewpoint is -25 C, so vapour partial pressure is about .1 kPa in the dried rooms**

Reactor building ventilation system{ TC "1.1.2 VENTILATION" \L 1 }

Functions

- **supplies outside air to the normally accessible areas and conditions this air to a comfortable temperature and humidity;**
- **maintains the reactor building pressure slightly subatmospheric (-.7 kPa for accessible areas)**
- **maintains differential pressure between the various rooms within the reactor building to induce air flows from rooms of lower air contamination to rooms of higher air contamination**
- **N.B. During LOCA, panels between these rooms burst or open to equalize pressure and prevent hydrogen buildup**
- **ensures reactor building containment isolation**
- **controls airborne radionuclide release to environment during normal operation through stack by means of filters**

Ventilation Circuits{ TC "1.1.2.2 Ventilation Circuits" \1 }

- **Air enters the RB ventilation system via fixed louvres in the south wall of the Reactor Auxiliary Bay.**
- **Passes through an air conditioning unit, two inlet isolating dampers and is then proportioned to various non-D₂O rooms through distribution duct network.**
- **Each of these small rooms is then connected to the main exhaust, where the air is exhausted from the reactor building to the stack by one of the two 100% service fans at ~3 m³/s.**
- **It is this exhaust flow which creates the subatmospheric conditions in the reactor building.**
- **Since normally the inlet opening and thus the flow resistance remain constant, the negative pressure in the reactor building accessible areas with respect to the outside atmosphere will depend mainly on the exhaust flow rate.**
- **From the accessible areas exhaust flow goes directly to the ventilation system.**
- **Bleed air flows from the dried rooms enters the ventilation system via control dampers that maintain the dried rooms at the desired**
- **The containment isolation dampers of the ventilation system will close (or box-up) to isolate the reactor building on detection of high or low pressure conditions, or high radioactivity.**
 - **These dampers (at inlet and stack) are simultaneously actuated and close within 2 seconds.**
 - **Isolation dampers are in pairs as per IAEA design requirements**
 - **Dampers are pneumatically actuated**
 - **Additional normally closed dampers near the inlet can be opened if the system is isolated and the RB pressure becomes undesirably negative. Such dampers are called vacuum breakers.**

Stack Filters

- Two sets in parallel, each with a HEPA (particulate) and charcoal (iodine)
- Moisture separators (demisters), prefilters, preheaters
- Charcoal filter cannot absorb iodine if relative humidity > 64%, hence preheater

Leakages { TC "2.1 Leakages" \ 1 }

Must consider: instrument air leakages; leakages to and from outside atmosphere; and constant vapour inleakages from equipment.

Instrument Air Leakage { TC "2.1.1 Instrument Air Leakage" \ 1 }

- Whenever a pneumatic device activates, e.g. a pneumatic valve strokes, the high pressure instrument air that provides energy for movement must be exhausted to containment atmosphere.
- Instrument air system draws air in from outside reactor building.
- According to containment test C-12 (a regularly scheduled containment integrity test) nominal consumption is about 150 scfm of instrument air = 0.07 kg/s,
- Sufficient to pressurize the reactor building from -0.5 kPa(g) to +1 kPa(g) in approximately 3 hours if containment is isolated, assuming no leaks.

Leakages from outside atmosphere. { TC "2.1.2 Leakages from and to atmosphere." \ 1 }

- In and out leakages are linearly proportional to the difference between the constant atmospheric pressure and the room pressure.
- Atmospheric air inleakages will add to the constant instrument air inleakage
- Can be inferred from the known bleed flow for each room.
- Inleakages are about .25 kg/s per kPa, with most into the boiler room.
- Outleakage flow can be inferred from Containment Test C-12 .
- According to test C-12, during a boxup, and assuming no inleakage, the Boiler Room pressure is expected to rise from -0.5 kPa to 1.0 kPa above atmosphere in approximately 3 hrs.
- In reality at positive ΔP , outleakage from the R/B will slow the pressure response causing the boiler room pressure rise to eventually level out as the instrument air inleakage balances this air outleakage.
- Boiler room pressure must exceed 0.75 kPa(d) in < 1.5 hrs to pass the test C-12.
- Infer max outleakage of about .25 kg/s per kPa.

Vapour inleakage{ TC "2.1.3 Vapour inleakage" \l 1 }

- Vapour inleakage for the dried areas (Boiler Room, F/M Vaults, Moderator Room) can be inferred from drier bed cycling times, condensate tank filling rates.
- About .003 kg/s total, mostly from boiler room equipment

Hydrogen considerations

- Newest CANDU-9 design changes switches the ventilation system flowpaths during LOCA specifically to sweep hydrogen away from the small rooms near the core, up in to the larger free volume near the dome to dilute hydrogen and make it pass by igniters/recombiners
- Older designs were retrofitted with igniters, and removed some panels between vaults and boiler room to improve natural circulation during LOCA

2. AIR COOLERS

During normal operation must limit the temperature <36 C in all areas; remove waste heat from boilers, RCS, moderator, moderator and RCS pumps, piping, lights, etc..

During accidents, condense vapour and increase their cooling load by a factor of about 10-15.

The Boiler Room is cooled by six ACUs, all handswitches "ON" for normal operation.

Each of the Fuelling Machine Vaults has four ACUS, two normally ON, the others to be turned on during LOCA.

An ACU is comprised of a cold water coil and a fan motor assembly.

For the units in the Boiler Room and F/M Vaults, cooling water is supplied from the high pressure service water system, and the fan motors are supplied with Class 3 power (diesel generator backup, never without power for more than 10 minutes while generators start up.)

Some of the service water pumps are also supplied from Class 3, so important loads like the ACUs always have sufficient cooling flow.

These ACUs are also seismically qualified, and on seismically qualified brackets

For ACUs in other Reactor Building areas, some have their water supply from high and others from low pressure service water, although their fan motors are all supplied with Class 4 power (lowest reliability, for nonessential devices that can safely be left without power for an indefinite period).

These ACUs are not essential for energy management during LOCA and are not qualified.

Each ACU has both inlet and outlet service water valves, which under normal operating conditions are left fully open.

A constant flow of cooling water flows through the coils of all units at all times during normal service water operation, even when the fans are shutdown by the handswitch in the control room.

Each bank of the four F/M Vaults ACUs has its own separate service water supply header.

Since the inlet and outlet valves on each cooler are fully open, the amount of water flowing to the cooler coils are controlled by a valve in the water supply header for the bank. Two control valves are used, 7134-MV510 is for the east header and 7134-MV514 for the west header.

Normally their control room handswitches are in the "AUTO" positions and the valves are approximately 70% open.

If vault pressure increases >3.4 kPa(d), these valves open fully, doubling the cooling water flow (happens independent of containment isolation or ECC logic).

Total nominal capacity is about 3000 kW, cooling flow about 200 L/s, most heat removed in vaults and boiler room.

3. Containment isolation system (box-up, buttonup)

Three initiation methods: manual activation (operator in control room), automatic on high activity in ventilation ducts, automatic on high/low boiler room pressure.

Channelized safety system: 2 channels for radiation, 3 for boiler room pressure

System isolates if 1/2 radiation channels alarms, or 2/3 pressure channels alarms

Boxup signal seals in: if pressure and activity return to normal after initiating boxup, system stays isolated (characteristic of safety systems)

Operator must explicitly reset the boxup signal

Possible to test one channel at a time without causing full boxup response.

Radiation monitoring:

10 monitors altogether, one from each channel in each duct through containment boundary

Gamma-sensitive scintillation meter with 2-second response time

High activity setpoint is 1750 counts per sec, normal value is 100-200

Setpoint chosen so 15 minutes of release at that rate would result in the public getting half the allowed dose, i.e. .4 TBq of I-131, or 600 TBq of noble gases

Activity could be due to problem with removal of spent fuel, not necessarily LOCA

Boiler room pressure:

Three meters, alarm setpoint +1.7 kPa(g) (normal pressure is -.5 kPa(g))

Effects of buttonup signal

Hydrogen igniters start

Isolation dampers close (inlet, outlet)

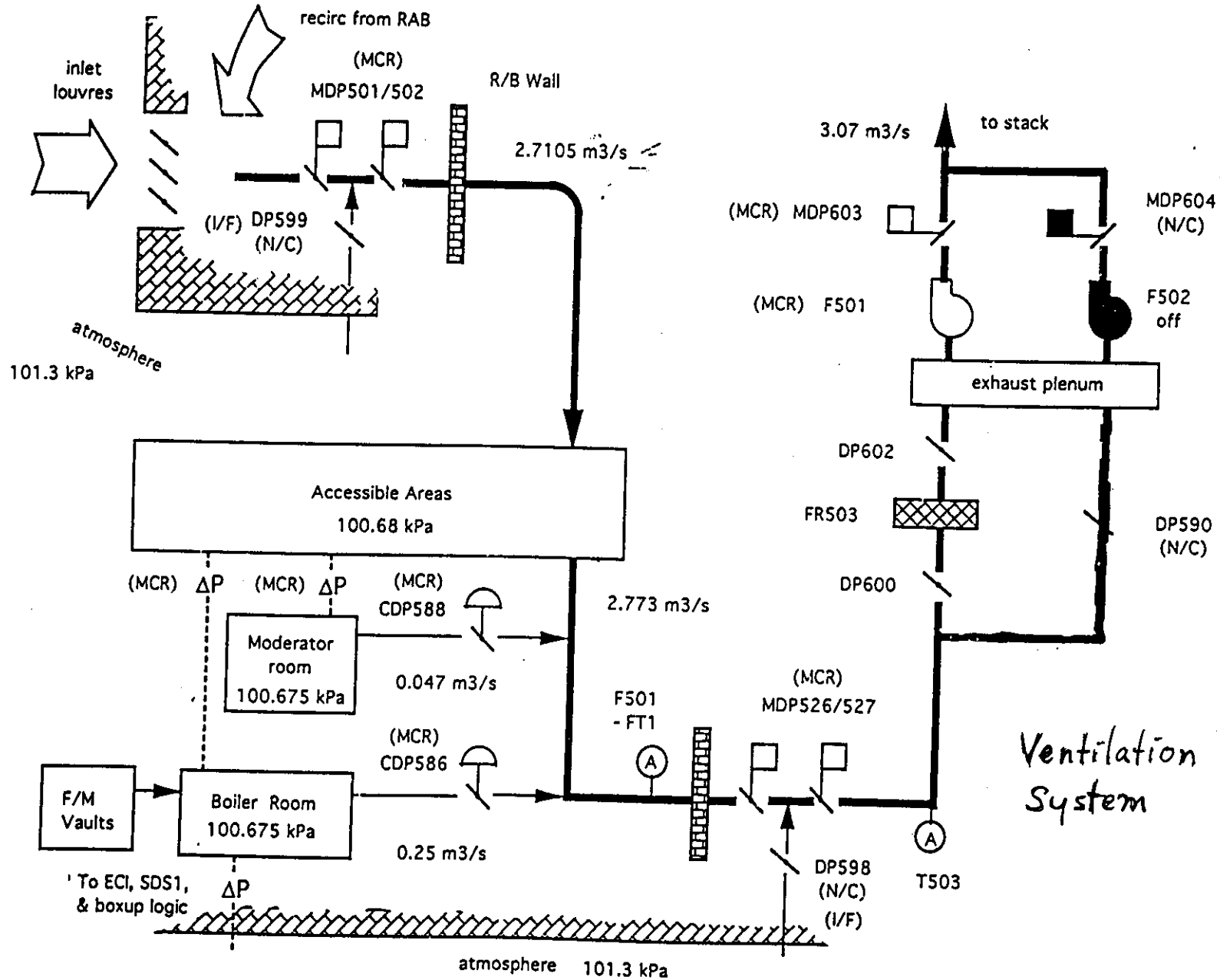
Annunciates in control room as message on computer screen, or message window on panel illuminates

Tritium monitoring system isolated

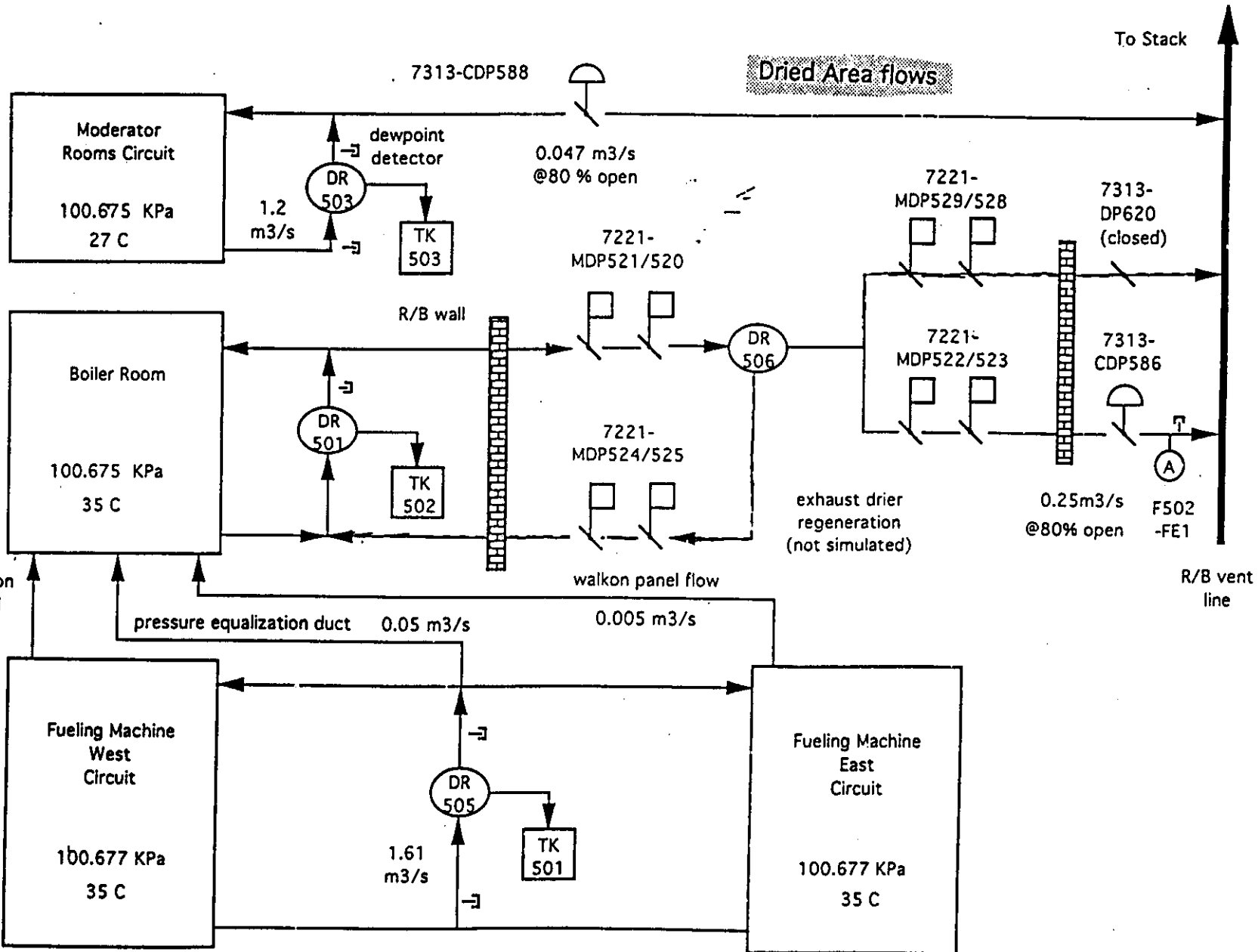
Interunit D2O transfer lines isolated

Drier fans stop

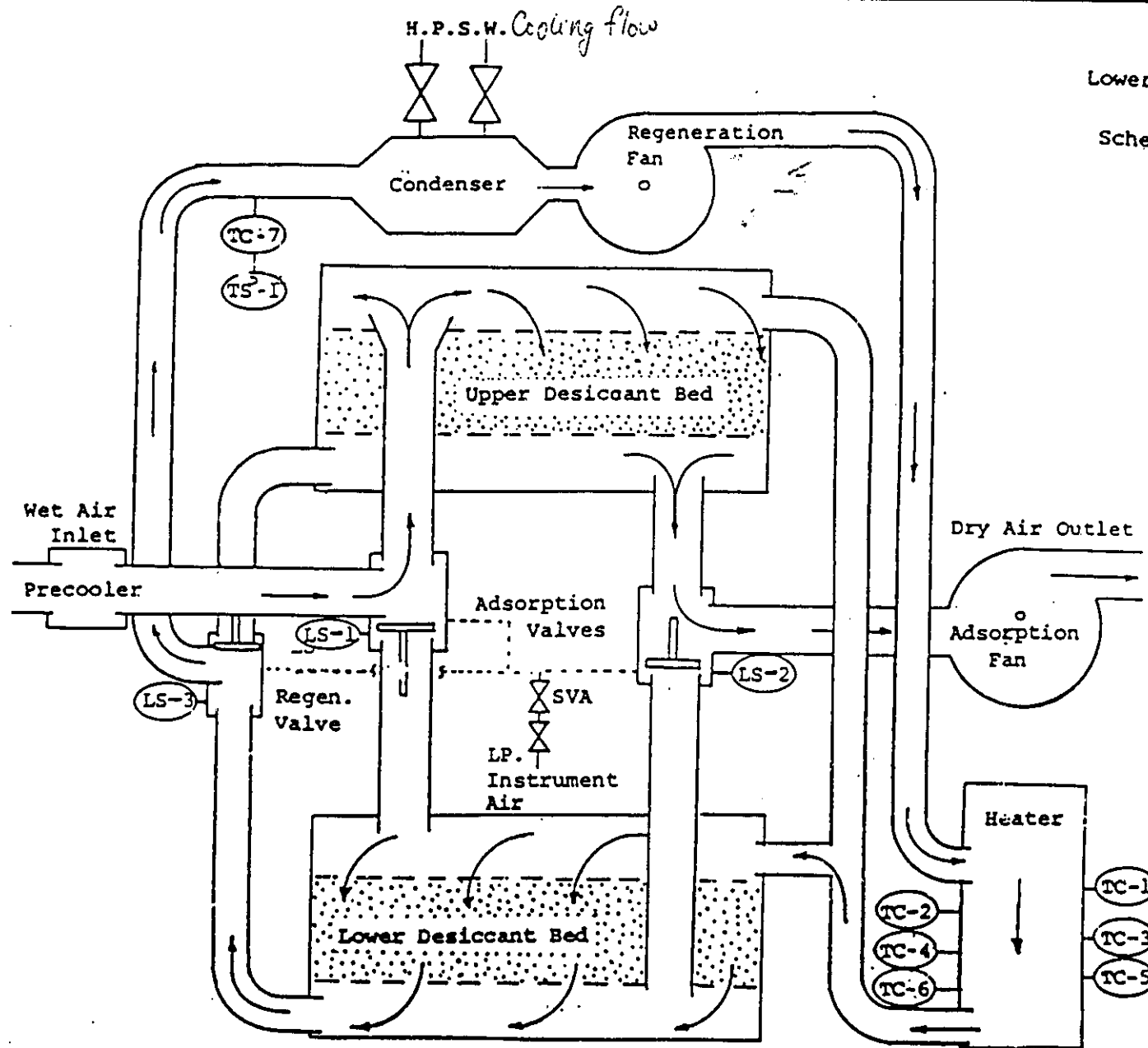
Condensate drain lines isolated

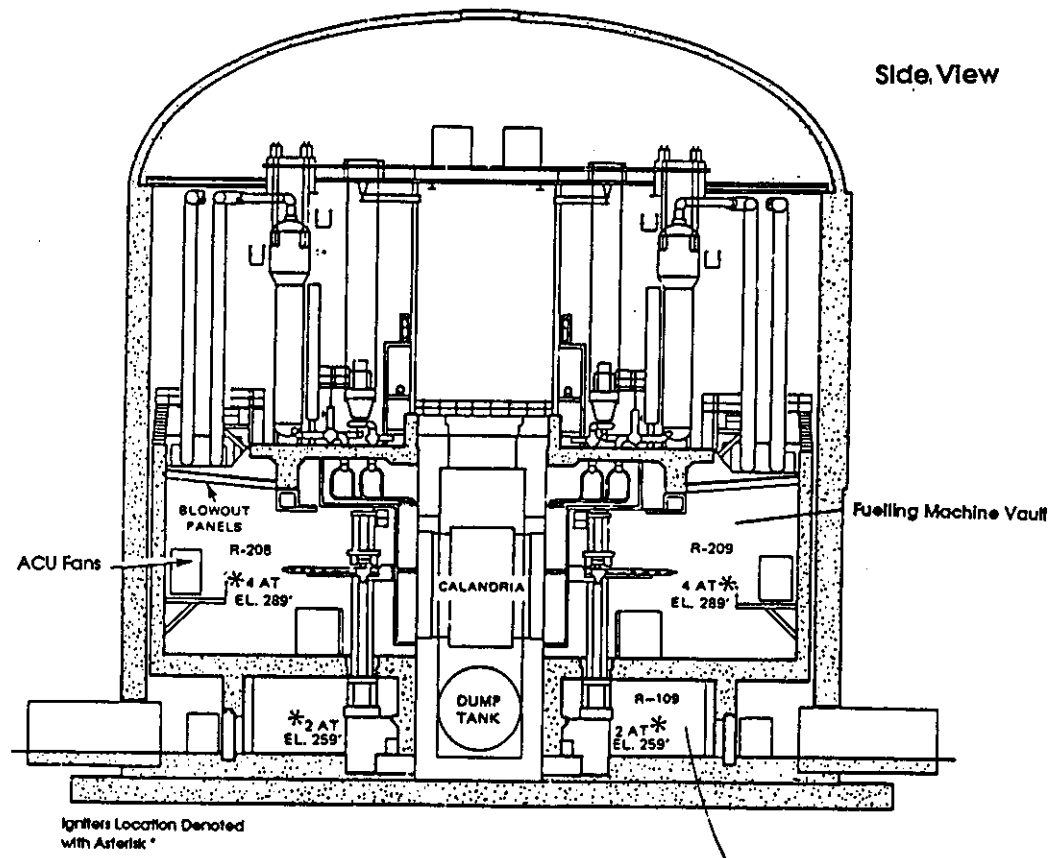
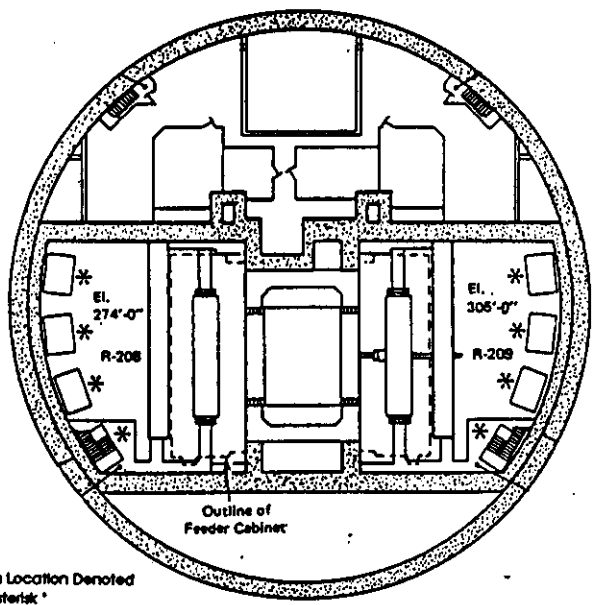


Ventilation System



Lower Bed Regenerating.
Schematic of Driers -





* Igniter Locations In CANDU Reactor Containment (Pickering)

CHAPTER 3: CANDU CONTAINMENT DESIGN AND OPERATION

MODULE D: EFADS AND CONNECTIONS BETWEEN CONTAINMENT VOLUMES

MODULE OBJECTIVES:

At the end of this module, you will be able to describe:

- 1. The panels and rupture disks for the reactor building**
- 2. The design and operation of the valves controlling flow into the vacuum building**
- 3. The purpose of the bypass valves connecting the reactor building to the relief duct**
- 4. The design and operation of the emergency filtered air discharge system**

1.0 Blowin panels, blowout panels, walkon panels, rupture panels

{ TC "1.0 Introduction" \ 1 } Panels within reactor building closed to separate air in different rooms, ensure most contaminated rooms are at lowest pressure during normal operation.

Designed to open on slight pressure differences to equalize pressure within the entire building, regardless of break location.

Most important to relieve pressure from the fuelling machine vaults, small rooms where very large breaks could occur.

Fuelling machine rooms have pressure relief to two large volumes, the accessible areas and the boiler rooms.

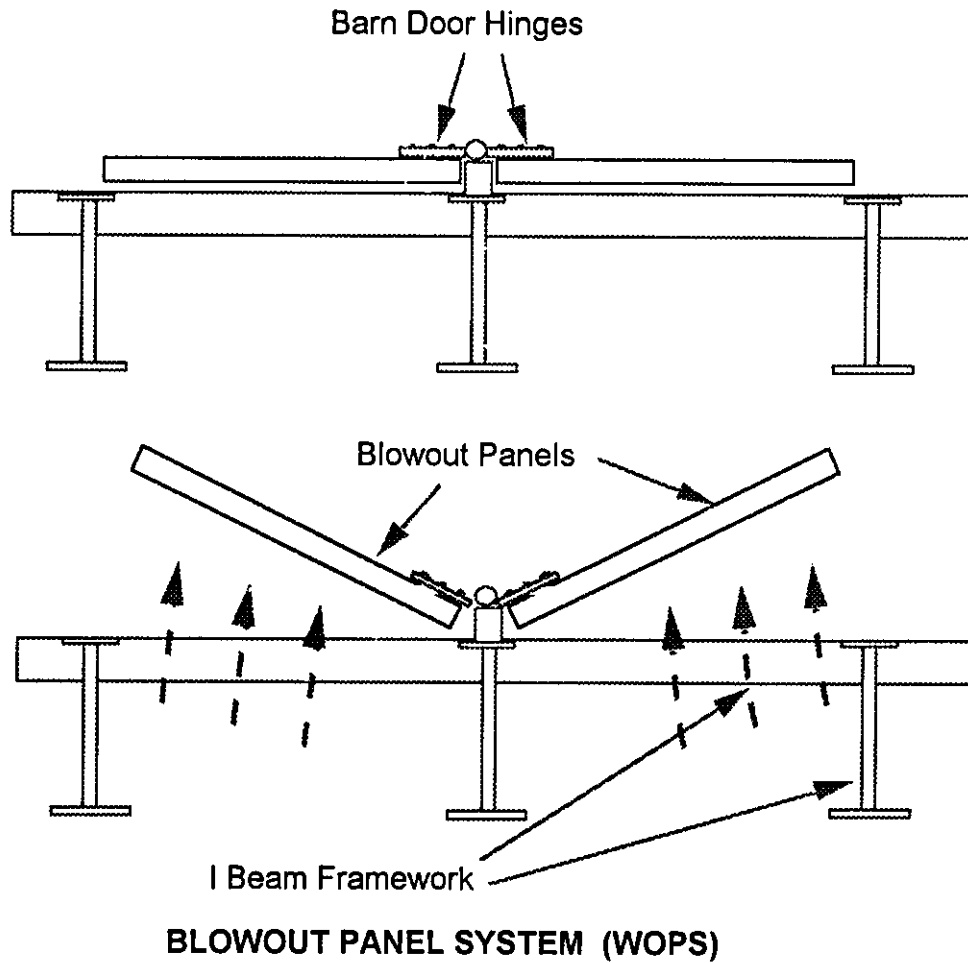
In addition, high pressure in the boiler room due to a steam line break must be relieved to the accessible area and vaults.

Some of the original panels have been permanently removed to facilitate natural circulation of hydrogen.

Except the walk-on panels, all panels are foil that bursts with a pressure difference of 5-15 kPa. The panels consist of aluminum angle frames with aluminum foil coverings which will rupture at a specified pressure differential.

Most are designed to burst in one direction but not the other (blowin or blowout)

The 38 horizontal walk-on panels separate the boiler room from the fuelling machine vaults below and lift at a very small pressure difference, only .14 kPa. They reclose.



2.0 Connection between reactor building and pressure relief duct

Only the boiler room is connected to the pressure relief duct.

The pressure increase in the boiler room is relieved to the duct through two bypass valves and the twenty-nine rupture panels in a bulkhead.

Rupture panels properties:

Burst at a pressure differential of +15 kPa(d) from boiler room to pressure relief duct, or -40 kPa(d) if pressure relief duct pressure exceeds boiler room pressure.

Provide maximum flow area for pressure relief of 18.4 m² per unit.

The bypass valves have AUTO logic to open when the boiler pressure is +3.5 kPa(g).

Two identical pneumatically operated butterfly valves (area = 0.30 m²) for each PNGSA unit

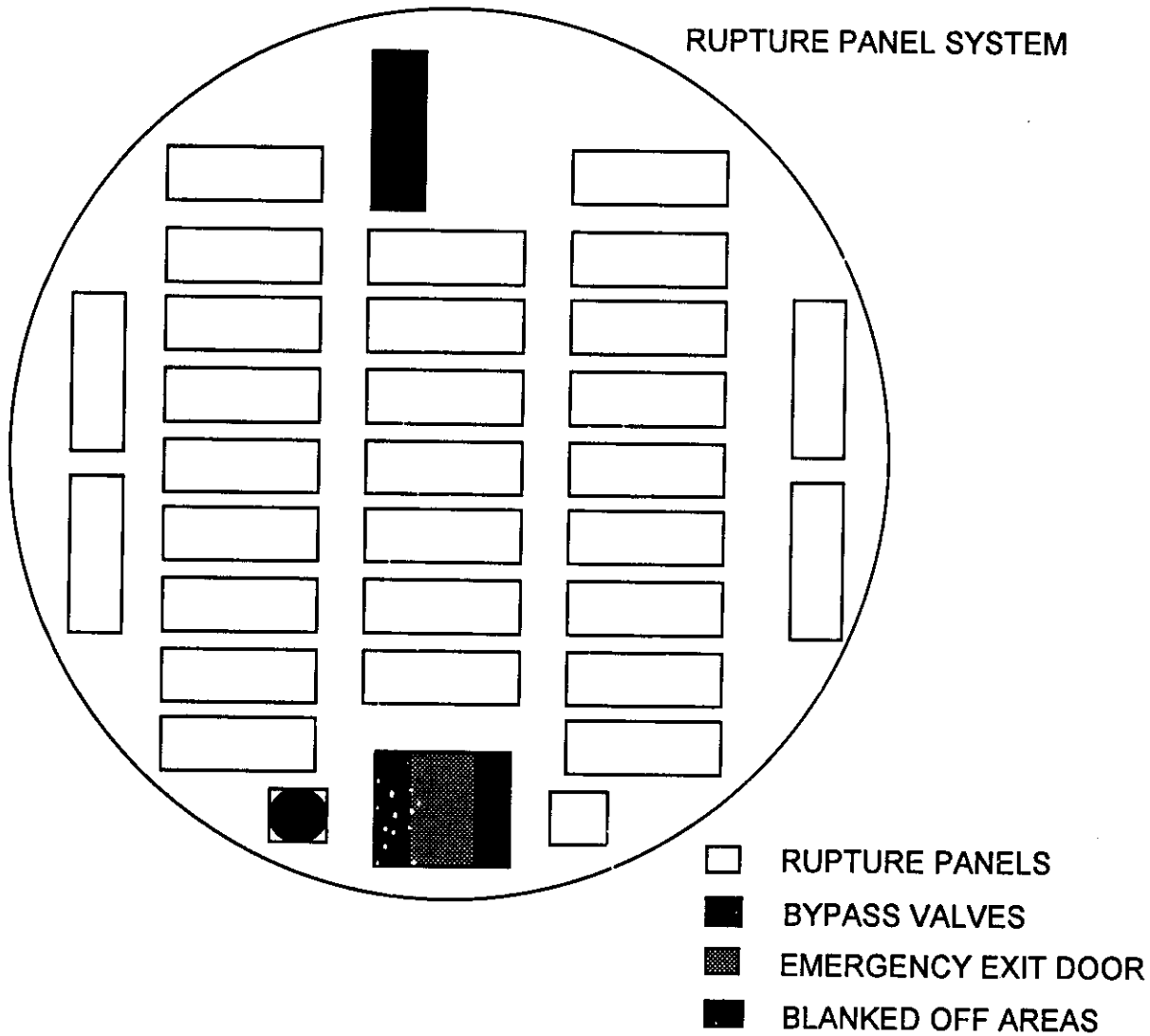
Each valve is supplied from a different instrument air station and has a compressed air tank with sufficient capacity for at least 2 valve cycles in case of an instrument air supply failure.

Remote control from main control room and secondary control area.

Automatic opening for the unit with the LOCA;

Operator opens valves for non-accident units to supply air to the accident units through the pressure relief duct during post-LOCA underpressure.

Also used when unit is isolated and pressure builds up at .3 kPa/hr due to instrument air



3. Connections between the pressure relief duct and the main vacuum building chamber

Two types of valves: instrumented pressure relief valves (IPRVs) and uninstrumented pressure relief valves (PRVs)

PRVs are passive devices activated by rising pressure in the duct

IPRVs have controllers to maintain duct pressure near atmospheric pressure

Instrumented pressure relief valves

Not standard pneumatic valves. A complicated set of valves for removing or admitting air to the chamber above the piston is used to adjust the valve position

Three separate controllers for three valves, one is set at approximately -0.70 kPa(g), one at -1.40 kPa(g), and one at -2.10 kPa(g)

Thus when the last IPRV closes at the end of the high pressure phase of the accident, the pressure relief duct and boiler room will be at -2.1 kPa(g).

Non-instrumented pressure relief valves

Passive devices

Start to open when the pressure difference between the relief duct and the chamber above the piston is sufficient to overcome the weight of the piston, approximately 4.8 kPa(d).

Initially, the air in the chamber above the piston will be at atmospheric pressure.

As the piston starts to rise the air in this chamber will be compressed and so forced through the locked open flapper valve.

After the initial acceleration upwards the piston will eventually be decelerated by the pressure build up, i.e., after a short period the pressure in the upper chamber will exceed that in the relief duct.

The air in the upper chamber is vented to atmosphere through the flapper valve.

The flapper valve is sized to provide considerable flow resistance when the piston is near the top of its travel, so that the pistons open up quickly and slow rapidly near the top of their travel, to prevent damage when the piston hits the stop.

Expect the PRVs to open briefly during the initial overpressure for a very large break, then control by IPRVs until the break stops steaming.

4. Emergency filtered air discharge system (EFADS)

Used only for long-term control of containment pressure after an accident, system is normally dormant.

The normal ventilation exhaust system is not qualified for this function

Emergency system is controlled and monitored from seismically qualified secondary control area

Power is from the most reliable source, the emergency power supply, another backup power supply in addition to the diesel generators mentioned earlier.

Operation:

Immediately after the break stops steaming, condensation makes the reactor building and duct subatmospheric; recall the vacuum building is subatmospheric too.

After 2 days (assuming no containment intact), instrument air inflow and inleakage raise pressure to atmospheric.

Must then discharge air through filters to make containment stay subatmospheric by ~ 1kPa

Designed for intermittent operation, according to weather conditions and pressure buildup

Exhausts 1-2 m³/s

Consists of ducts, dampers, fans, stack, charcoal and HEPA filters with associated preheaters, prefilters, moisture separators, personnel shielding.

Charcoal filter for iodine requires 64% humidity and T<100, hence preheaters, moisture separators

Two modes of operation:

Reactor building→pressure relief duct→EFADS→stack

Reactor building→pressure relief duct→IPRVs→vacuum building→EFADS→stack

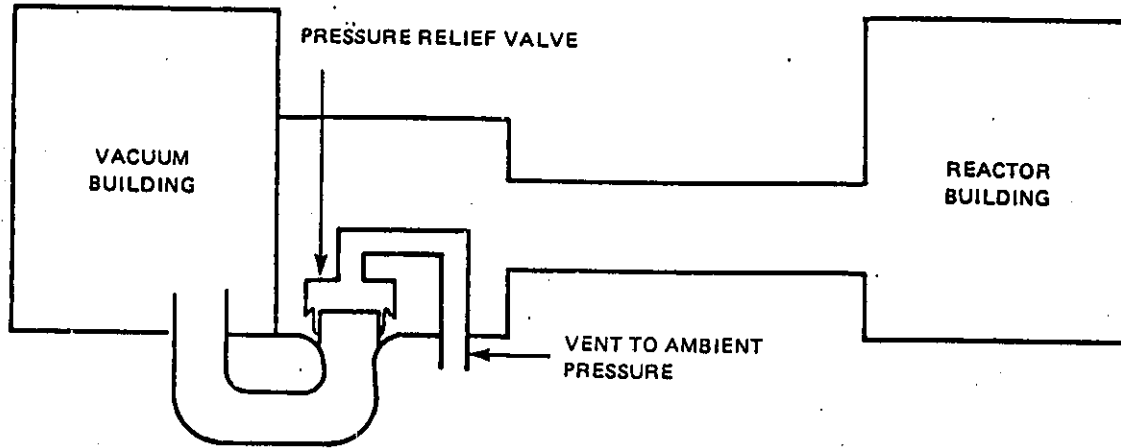
Instrumentation (display only in secondary control area):

Filter delta-pressure: high pressure indicates blockage, low pressure a hole in the filter

Effluent monitoring for gaseous fission products

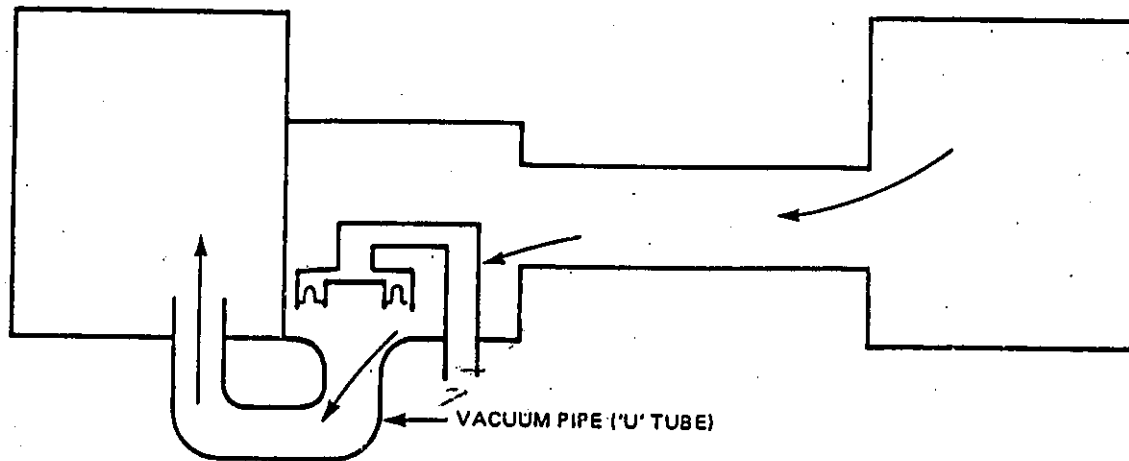
Temperature, flow

Damper status

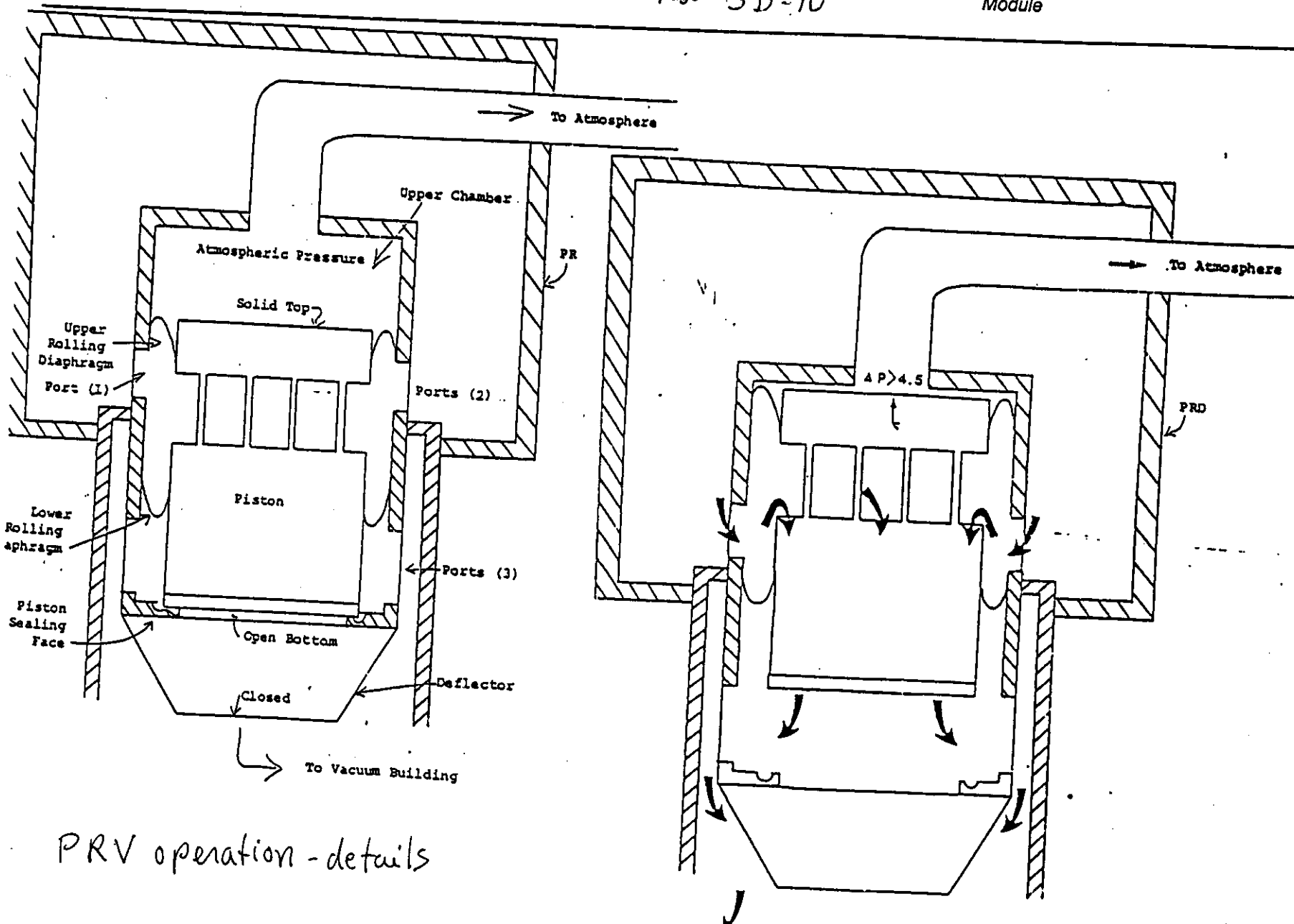


PRV operation

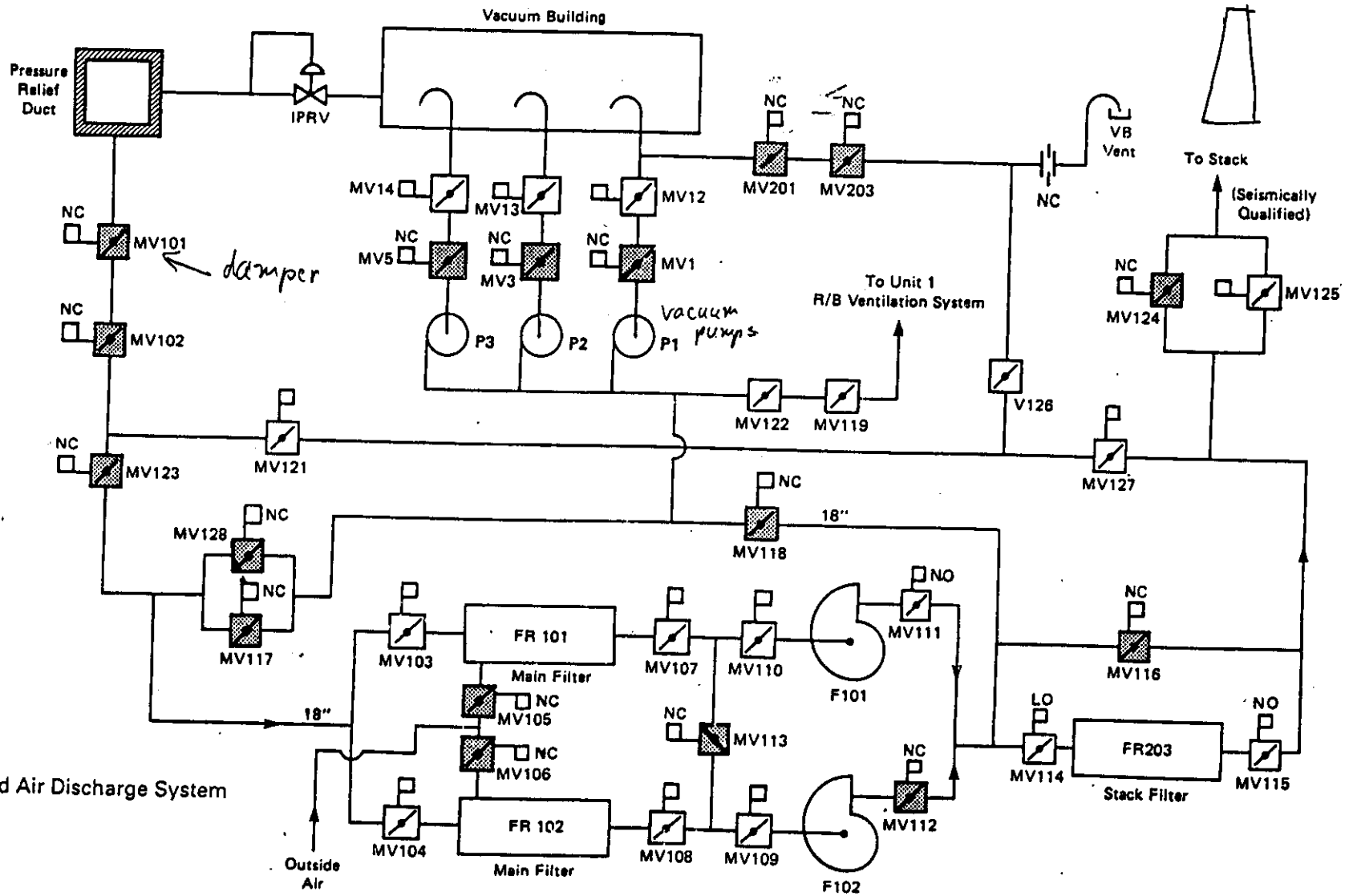
DIAGRAMATIC REPRESENTATION OF NORMAL OPERATION



FLOW PATH WITH VALVES OPEN



PRV operation - details



CHAPTER 3: CANDU CONTAINMENT DESIGN AND OPERATION

MODULE E: OPERATIONAL PERSPECTIVE

MODULE OBJECTIVES:

At the end of this module, you will be able to describe:

- 1. Information available to the operator**
- 2. Routine testing of containment functions**
- 3. Containment impairment and operational implications**
- 4. Operator actions during accidents involving containment**

1. INSTRUMENTATION FOR CONTAINMENT STATUS

1.1 Types of information available to operators:

Main control room:

On panels: meters, chart recorders (moving strip of paper with pen), status lamps, annunciation windows, pushbuttons, handswitches, controllers

Monitoring computers: schematic displays, trend plots of analogue computer inputs, annunciation messages from switches (e.g. pressure switches) on instrumentation or when analogue inputs are outside specifications

Secondary control area:

Limited displays and controls for seismically qualified equipment needed for safe shutdown

Local displays:

Equipment monitoring, local alarm panels

1.2 Containment monitoring:

Main control room meters:

Boiler room pressure (3 each for each shutdown system, 4 for ECC initiation, 3 for containment isolation, 2 for bypass valves)

Vacuum building pressure (3 chambers)

Pressure relief duct pressure

Sump levels within fuelling machine service rooms

Dousing tank level, vacuum building floor level

Pressure differences (in pascals) between rooms dried by vapour recovery

Stack exhaust flow

Chart recorders for drier dewpoints, radioactivity

Beetle ammeters (moisture indication)

Test relay status (pushbutton lamps)

Status lamps

Containment isolation status (red lamps)

Valve status for containment penetration lines

Level switches for moderator room

~30 air cooler lamps

Isolation damper lamps

Exhaust fans lamps

Bypass valve status for all 8 units

Message windows for high boiler room pressure, high activity

Monitoring computer alarms:

Several temperatures in the boiler room and each fuelling machine vault are analogue inputs, alarm if >36C

High activity at any monitor, or zero activity (indicates failed monitor)

Pressure in vault >3 kPa(d), (should open cooling valves for coolers fully)

Any IPRV open at the same time that any reactor building isolation damper not closed

Bypass valve open (delays action by safety systems on rising reactor building pressure)

Boiler room pressure >1 kPad or <-1 kPad (imminent buttonup)

Boiler room pressure >1.72, or <-1.72 kPad (buttonup signal)

Any alarm received in the secondary control area

Any IPRV controlled from secondary control area (overrides main control room handswitches)

Any IPRV controlled from the other control room (IPRVs are shared between PNGSA and PNGSB)

Any beetle indicating moisture

Dousing tank level high, low, or too cold (must not freeze)

Dousing seal lost (can't douse)

High floor level in vacuum building

High pressure in any vacuum building chamber (can't douse)

Vacuum pump electrical problem

Pressure relief duct abnormal pressure (indicates IPRV control problem, or severe underpressure)

2. ROUTINE TESTS

Purpose is to confirm that containment unavailability $< 10^{-3}$ years per year.

At every shift change (personnel goes home and is replaced) confirm key parameters within limits, no alarms

Some tests can be done remotely from the main control room with pushbuttons and test selection handswitches

These check calibration of instrumentation, relay logic, remote operation of relays and valves

Others call for inspection of equipment

High activity containment isolation (every 2 weeks):

using remote controlled motor, bring a barium source close to monitors, raise shutter

check annunciation messages and windows, buttonup relay logic, confirm dampers and valves close

High/low boiler room pressure containment isolation (2 weeks)

isolate pressure transmitter from boiler room by closing solenoid valve

open another solenoid valve connected to a test pressure

confirm 2/3 voting by relay logic is correct

check annunciation messages and windows, confirm dampers and valves close

check 4-second damper closing time

Bypass valve stroke test (2 weeks)

confirm valve operates

Unit overpressure test while at power (3 months)

isolate unit, compare dP/dt when $P=0$ kPa(g) to dP/dt when $P = +.75$ kPa(g)

estimate area of containment hole

Damper interspace test (3 months)

pressurize interspace between a pair of closed dampers, check for leakage through closed dampers

Vacuum building isolation (once per year)

confirm vacuum pumps go off and dampers close on high boiler room pressure

Blowin/blowout panel functional test (during outage)

destructive test of a subset of the panels

Boiler room pressure transmitter calibration test (6 months)

Activity monitor calibration (12 months)

Airlock seals test (3 months), airlock inspection (8 hours)

Vacuum building inspection (8 hours), instrument test (monthly)

Backup air supplies (bottles) for containment dampers and valves (yearly)

Igniters and igniter annunciators (monthly)

Inspection of penetrations (when station is shut down for maintenance)

Soap solution applied around seal, check for bubbles

Tracer gas

3. CONTAINMENT IMPAIRMENTS

If containment cannot function, unit must be shut down.

Issue is not black and white, there are levels of impairment, there is redundant equipment

Level 1: Potential dose to public >10 times allowed limit if an accident occurs

Immediate repair, controlled unit shutdown within 4 hrs unless estimated repair time < 8 hrs

Level 2: Potential dose to public > allowed limit if accident

Highest priority repair, shutdown within 8 hrs unless estimated repair time < 24 hrs

Level 3: Potential dose to public < allowed limit if accident

High priority repair, no shutdown required, increase test frequencies

Some examples:

Boxup logic error	level 1	No boxup on either high pressure or high activity
	2	No boxup on high activity
	3	One boxup channel fails the test
Reactor building leak	level 1	Area > 300 cm ²
	2	300 cm ² > Area > 24 cm ²
	3	24 cm ² > Area > 10 cm ²
Dousing tank level	level 1	<90% full
	2	< 95% full, or temperature > 25
Dousing seal lost	level 1	Shut down all 8 units

4. OPERATOR ACTIONS DURING ACCIDENT CONDITIONS

4.1 Large LOCA

CANDU design principle: any scenario that takes less than 15-20 minutes to develop into a hazardous situation is taken care of automatically without operator intervention.

Initial operator response in this case consists of confirming safety systems respond as designed.

e.g. operator verifies reactor power is falling, ECC pumps start and injection valves open, containment isolating dampers close, annunciation indicates igniters are on.

Large LOCA causes immediate reactor shutdown by both safety systems, on high reactor power or high rate of increase of reactor power or low coolant pressure.

Reactor power rises to $< 130\%$ (conservative estimate) because of steam voids in core that decrease neutron absorption

Second shutdown system with gadolinium injection into moderator guarantees sufficient negative reactivity, although first system's shutoff rods should suffice.

Coolant depressurizes in seconds to 4 MPa, the saturation pressure corresponding to initial coolant temperature. Further decrease to < 1 MPa.

Low coolant pressure and high boiler room pressure together activate the ECC system

ECC injection of cold water begins in ~ 30 s

ECC logic also causes large boiler relief to open to atmosphere, cool and depressurize boilers until emergency boiler injection system injects them with cold water

Coolant reaches 100°C in < 10 m, then no more steam flow from break

Half of the unit's electrical loads, the ones that were supplied from the unit's own generator, are switched over to the external grid. Remainder were already supplied from grid.

If power from the grid is lost, standby generators are started up (takes several minutes), and power is restored to the essential loads, e.g. air coolers, some service water pumps.

Other units in same station can also supply power to accident unit.

Instrumentation, igniters, relay logic, monitoring computers can be supplied from batteries for a while.

The most essential loads (e.g. EFADS) have backup from the emergency power supply, another set of diesel generators.

Very large initial break flow >1000 kg/s, about 1/3 vapour, in first few seconds blasts into the fuelling machine vaults

ruptures all connections between rooms inside the reactor building

causes immediate containment isolation.

vault pressure peaks at ~140 kPa(a) in seconds but falls to ~105 kPa(a), temperature jumps to 100C

blowout panels between boiler room and pressure relief duct burst, PRVs to vacuum building open within seconds

vacuum building temperature rises to 120C due to rising pressure, until dousing starts at 60kPa(a) after ~30s, falls to dousing tank temperature during dousing

Break flow rapidly decreases due to RCS pressure falling from 9 to 1 MPa, and vapour flow from break almost stops once RCS reaches 100C in 10 minutes.

PRVs close, and IPRVs control duct and thus reactor building pressure \sim -2 kPa(g)

IPRVs close as break stops steaming, vacuum building now isolated

Underpressure in reactor building and duct begins within 10 minutes of break as coolers and walls condense vapour.

Much of the air was purged from the reactor building by steam, so condensation could lower pressure dangerously.

Air from the pressure relief duct is sucked back into the boiler room.

Operators in non-accident units open their bypass valves to let more air into the pressure relief duct.

Boiler room pressure should stay $>$ \sim -10 kPa(g)

Sump level has risen after about 20 minutes of ECC injection to \sim 1.5 m, stabilizes once recovery begins automatically

Sump temperature initially \sim 90C, cools to 60C in 2.5 hrs and then cools very slowly

Boiler room temperature also starts \sim 90C, cools to 45C in 2.5 hrs and then cools very slowly

Sump and walls are now a containment heat source

Operator switches RCS heat sink from boilers to residual heat removal system.

After about two days, boiler room pressure rises above atmospheric, and operator must run EFADS

4.2 Main steam line break inside containment

Sequence of events very similar, but no power increase, only transient ECC injection

Initial blast of superheated steam into boiler room may be >7000 kg/s for 2 s

Break energy inflow soon falls as steam becomes saturated when boiler pressure drops and boiler emergency injection starts

Boiler room pressure peaks at 140 kPa(a) in seconds before relief flow into vacuum building begins

This event is what determines the flow capacity of the rupture disks and PRVs

Full douse cannot prevent vacuum building pressure from approaching atmospheric pressure together with boiler room.

No radionuclides in steam, so overpressure is not of great concern