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ITER SAFETY TASK NID-5a: ITER TRITIUM ENVIRONMENTAL SOURCE TERMS - SAFETY ANALYSIS BASIS

CFFTP G-9443
September, 1994

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CFFTP GENERAL

The Canadian Fusion Fuels Technology Project represents part of Canada's overall effort in fusion energy research. The focus for CFFTP is tritium technology and remote handling. The Project is funded by the Government of Canada and Ontario Hydro Technologies. Ontario Hydro Technologies administers the Project.

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1.0 INTRODUCTION

The following is part of the Canadian Fusion Fuels Technology Project's (CFFTP) contribution to ITER Task NID-5a, "Initial Tritium Source Term". This safety analysis basis constitues the first part of the work for establishing tritium source terms and is intented to solicit comments and obtain agreement. The second part will be the actual analysis, which will be documented in a separate analysis report. Hence, the objective of this document is to ensure that ITER - JCT has an opportunity to review and confirm the assumptions and methods that will be used in the analyses.

The analysis will be done in three steps: preliminary, interim and final. The main difference between the preliminary and the final will be the level of design information on some of the systems. At the moment, there is little design information on fuelling and vacuum pumping. As more information becomes available it will be reflected in the interim and final reports.

Also, some work will be done on tritium sorption to estimate the potential impact on the key environmental source terms. This should be reflected in the analysis for the interim report.

2.0 ANALYSIS OBJECTIVE

The analysis objective is to provide an early estimate of tritium environmental source terms for the events listed below.

3.0 EVENTS TO BE ANALYZED

Events that would result in the release of tritium are as follows:

(a) Cooling System Pipe Break (ex-vessel LOCA);

(b) First Wall, or Divertor Tube Rupture (In-Vessel LOCA);

(c) Vacuum Vessel Boundary Breach (LOVA);

(d) Torus Exhaust Line Failure;

(e) Fueling Machine Process Boundary Failure;

(f) Fuel Processing System Process Boundary Failure;

g) Water Detritiation System Process Boundary Failure, and

h) Isotope Separation System Process Boundary Failure.

This list covers releases in most areas of the facility, therefore, it provides a good starting point for estimating the initial environmental source terms.

4.0 DESIGN ASSUMPTIONS

4.1 Ventilation and Detritiation

4.1.1 General

It is assumed that the design intent is to prevent the uncontrolled leakage of radioactivity from the building. Therefore, non-active areas inside the building will be maintained at a slight negative pressure with respect to atmosphere. Likewise, active areas will be maintained at a slight negative pressure with respect to non-active areas. The concept is illustrated in Figure 1.

4.1.2 Non-Active Areas

As shown in Figure 1, non-active areas are assumed to be served by the building ventilation system. This is the normal heating and air conditioning system, with a large recirculating flow and a small purge flow to make up for building in-leakage. Normally the purge flow is exhausted to the stack, however, if radioactive contamination accidentally reaches the non-active areas, then the purge flow will be directed to the exhaust flow detritiation system.

4.1.3 Active Areas

As shown in Figure 1, active areas are assumed to be served by the active area detritiation system. It is further assumed that the system has a recirculating flow of 5000 m^3/h. A small purge flow is required to maintain the active areas under negative pressure relative to non-active areas. This purge flow is directed to the exhaust flow detritiation system.

Normally the system is on stand-by, but will operate intermittently on pressure balance mode to maintain the pressure within the specified range.

After a tritium release (and its detection), the system will operate in a clean-up mode and will remain operational until the tritium concentration in the room or compartment has reached the required value.

4.1.4 Cryostat Detritiation System

Current Naka thinking is to have such a system as shown in Figure 1. The recirculating flow is also assumed to be 5000 m^3/h. This system is used in the clean-up mode, only when the pressure in the cryostat is near atmospheric.

4.1.5 Exhaust Flow Detritiation System

As shown in Figure 1, this system is assumed to receive a purge air flow from the building ventilation system (under accident conditions only), the cryostat detritiation system (under accident conditions only) and the active area detritiation system under normal pressure balance mode and accident conditions. However, this system will also receive a purge flow from the glove box clean-up system, the cryostat vacuum pumps, the isotope separation cold box vacuum pumps (under accident conditions), and others. As there are a large number of users of this system, it is assumed that it will be a continuously operating system. The capacity of this system is assumed to be 500 m^3/h.

4.1.6 Recombiner Efficiency

Each detritiation system described above will have a hydrogen recombiner to ensure that elemental tritium will be converted to the oxide form so it can be captured by the molecular sieve dryers. The recombiner efficiency is assumed to be 99.95%.

4.1.7 Dryer Efficiency

Each detritiation system described above will be equipped with molecular sieve dryers to capture tritiated water vapours. The dryer efficiency is assumed to be 99.95%.

4.2 Tritium Confinement

All process components in direct contact with tritium are assumed to have a secondary confinement boundary (the first being the process boundary itself). The secondary boundary may be a glove box, a cold box, a second conduit (pipe) or vessel, or a sealed room (caisson).

4.3 Water Detritiation System

The water detritiation system is assumed to comprise a water distillation unit and a vapour phase catalytic exchange unit. All process components of the water distillation unit, which handles liquids and vapours, are assumed to be contained in a caisson. All process components of the vapour phase catalytic exchange unit, which circulates gases only, are assumed to be contained in glove boxes.

4.4 Isotope Separation System

It is assumed that the cryogenic distillation columns will be contained inside a cold box, which is held under vacuum. All other components of the system will be contained in glove boxes.

4.5 Cooling System Inventory

It is assumed that the total coolant inventory is 700 m^3 (500 for shielding blanket and 200 for divertor). Assuming pessimistically that there are 4 shielding blanket cooling loops (rather than 12, as is the current thinking), then the maximum discharge from a single loop will be 125 m^3. Hence, the amount of tritium that can be released from a single loop failure is 125,000 Ci (125,000 kg * 1 Ci/kg = 125,000 Ci). Similarly, if there are 4 divertor cooling loops, then the maximum discharge from a single loop will be 50 ^{3} or 500,000 Ci (50,000 kg * 10 Ci/kg = 500,000 Ci). For conservatism, it is assumed that the amount of tritium discharged will be at most 500,000 Ci, as HTO.

4.6 Room Volumes

When tritium is released into a room/area/zone of unknown (because the design has not progressed that far) it is arbitrarily assumed that the room volume is 1000 m^3. When design information becomes available, then the appropriate number will be inserted into the analysis. Whether the volume is 1000 or 10,000 m^3 should not significantly affect the environmental source terms. This assumption will be tested by parameter analysis.

5.0 ANALYSIS ASSUMPTIONS

5.1 Ex-Vessel LOCA

An ex-vessel LOCA can occur in the cryostat or in the cooling system equipment rooms.

5.1.1 Ex-Vessel LOCA Inside Cryostat

A cooling system pipe break inside the cryostat is not expected to cause the pressure in the cryostat to exceed the design pressure, due to the high vacuum and cold masses contained within it. However, it may not be possible to exclude the possibility that a coolant pipe break could cause damage to one or more cryostat penetrations, in which case a leakage path would be established to the active areas of the building. For this reason, it is assumed that cryostat penetrations will terminate in rooms served by the active area detritiation system. Furthermore, for leakage to occur, the pressure inside the cryostat must increase to atmospheric pressure. When this happens, the atmosphere inside the cryostat can be cleaned up using the cryostat detritiation system. Therefore, there is redundancy even if there is an impairement of the cryostat boundary. Hence, a release of tritium inside the cryostat can be:

(a) contained within the cryostat, if the pressure does not immediately or quickly rise above atmospheric pressure (most likely outcome);

(b) mitigated by the cryostat detritiation system once the pressure has reached atmospheric, or

(c) mitigated by the active area detritiation system, if there is leakage from the cryostat to an active area (failure of penetration) and the cryostat detritiation system is unavailable.

For case (a) there will be no significant environmental release, hence, no further analysis is required. Releases during the cryostat clean-up period will be bounded by case (b).

For case (b) it is assumed that the exhaust flow from the cryostat will be an upper bound of 1% of the cryostat volume (20,000 m^3) per day (ie., 200 m^3/day). This exhaust flow has to be made up by leakage into the cryostat, hence, it is considered to be a pessimistic upper bound, given that the cryostat boundary remains intact. As the cryostat detritiation system is assumed to not be designed for high vacuum operation, it can only be started once the cryostat pressure reaches close to atmospheric. The model for this case is shown in Figure 2a.

For case (c) it is assumed that the exhaust flow from the cryostat will be an upper bound of 10% of the cryostat volume per day (a hypothetical upper bound). The exhaust flow is assumed to be ten times greater than in case b) given that the cryostat boundary is assumed to be breached and inleakage from the penetration termination room would dominate (the room is not designed for high vacuum opration as is the cryostat). As noted above, either the cryostat detritiation system or the active area detritiation system could be used. For the purposes of this analysis, it does not matter which is used. The need for the cryostat detritiation system would be evident soon after the LOCA. Equally, a high tritium, and/or a high pressure, alarm in an active area would signal the need for the active area detritiation system. The model for this case is shown in Figure 2b.

5.1.2 Ex-Vessel LOCA Inside the Cooling System Equipment Rooms

Following a coolant pipe break inside the cooling system equipment rooms, the pressure will quickly rise and slow leakage from the room will result. In the long-term (hours after the break) the pressure will return to atmospheric due to condensation of the steam. For the purposes of this analysis, it is assumed that pressure equalization occurs at eight hours after the accident (a pessimistic assumption); and, at this time, the non-active area detritiation system will be used for clean-up of the room. Therefore, leakage to active areas of the building will occur only during the overpressure transient (assumed to be eight hours).

Three leakage rates will be considered in the analysis (1, 10 and 100% of the cooling system equipment room volume per day). These leakage rates correspond to 10, 100, and 1000 m^3/day, on the asssumption that the cooling system equipment room has a volume of 1000 m^3. To keep accident pressures to reasonable levels, it is more likely that the volume would be closer to 10,000 m^3. The sensitivity of room volume on the environmental source terms will be established, by also considering a volume of 10,000 m^3. The above leakage rates set the exhaust flowrates for the building ventilation system, which directs the purge flow to the exhaust flow detritiation system, during the eight-hour overpressure period. To ensure that even the largest leakage rate can be accommodated, a purge flow of 50 m^3/h is assumed for the building ventilation system.

After eight hours, the active area detritiation system is started and a purge flow of 50 m^3/h will maintain the cooling system equipment room under negative pressure, relative to its surroundings, hence, leakage from the room is reversed and inleakage will occur thereafter. The model to be used in the analysis is shown in Figure 3.

5.2 In-Vessel LOCA

There are two LOCAs to consider: a small LOCA and a large LOCA.

5.2.1 Small In-Vessel LOCA

The small in-vessel LOCA is the more severe, if it is assumed that the discharge of steam into the vacuum vessel is just at the right flow to optimise the steam/metal reaction with the first wall or divertor. The steam/metal reaction will produce heat and hydrogen, hence, the resulting vacuum vessel environment would be a mixture of mainly steam, hydrogen, tritium and dust. The heat, will cause tritium imbedded into the first wall to be released into the vacuum vessel. The scouring action of the steam jet will also cause tritium laden dust on the surface of the first wall to become airborne. The pressure inside the vacuum vessel will rise above atmospheric pressure, but will remain below the design pressure of the vacuum vessel. The pressure will eventually peak and the overpressure will diminish as heat is removed from the unbroken loops and the shield cooling system.

The amount of leakage from the vacuum vessel to the cryostat will depend on the magnitude and duration of the overpressure. But, as long as the leakage is into the cryostat there will be no significant environmental release and will not be considered further in the analysis.

However, due to the fast temperature and pressure excursion, it may not be possible to exclude the failure of a vacuum vessel optical window, which could cause tritium and tokamak dust to be transported directly to the outside of the vacuum vessel and cryostat, into the penetration termination room. If the breach is into the cryostat, as above, there will be no significant environmental release, hence, it will not be considered further.

The amount of leakage from the penetration termination room into the non-active areas of the building will depend on the magnitude and duration of the overpressure. It is assumed that the overpressure will last for eight hours. During this period, the building ventilation system exhaust will be directed to the exhaust flow detritiation system.

Three leakage rates will be considered in the analysis (1, 10 and 100% of the penetration termination room volume per day). These leakage rates correspond to 10, 100, and 1000 m^3/day, on the asssumption that the room has a volume of 1000 m^3. The last represents a hypothetical upper bound. These leakage rates set the exhaust flowrates for the building ventilation system, which directs the purge flow to the exhaust flow detritiation system, during the eight- hour overpressure period. To ensure that even the largest leakage rate can be accommodated, a purge flow of 50 m^3/h is assumed for the building ventilation system.

After eight hours, the active area detritiation system will be started with a purge flow of 50 m^3/h, which will be sufficient to maintain the penetration termination room under negative pressure. The model to be used is shown in Figure 4.

It is assumed that up to 1 kg of tritium could become airborne in the vacuum vessel following the in-vessel LOCA (a very pessimistic assumption as at most only one quarter of the torus would be exposed to the temperature excursion. The transport of tritium and tokamak dust from the vacuum vessel to the penetration termination room will be via a long cold tube, which has the potential to remove significant quantities of both. Initially, it will be assumed that all of the tritium will be in the elemental form, and there will be no attenuation mechanisms. This is the most pessimistic assumption to make. In the interim, mechanisms for tritium attenuation will be studied, and if they are considered to be significant, then they will be incorporated in the analysis for the interim report.

In addition to the tritium, it is assumed that 1 kg of hydrogen would be produced from the steam/metal reaction. Hence, in a 4,000 m^3 volume (3,000 for the torus and 1,000 for the room) there will be 1 kg of hydrogen and 1 kg of tritium. This corresponds to a combined concentration of 0.4%, which is well below the lower detonation threshold of 18%. Even if the amount of hydrogen produced from the steam/metal reaction is 10 kg, the resulting concentration is still well below the detonation threshold. Also, a detonation will not be possible if the steam content is more than 40% by volume. Hence, it appears that the possibility of a hydrogen/tritium detonation can be excluded from immediate consideration.

5.2.2 Large In-Vessel LOCA

It can be hypothesized that the largest in-vessel LOCA could discharge the entire inventory of the divertor, the first wall and shielding blanket cooling systems into the vacuum vessel. This event is expected to have a low frequency of occurrence and clearly represents an upper bound to the thermal energy release into the vacuum vessel. Such an event would very quickly fill the vacuum vessel with a water/steam mixture and would quickly quench the first wall and divertors. Because such a large discharge of steam would cause the first wall to cool, the steam/metal reaction discussed above would not likely occur. However, the peak pressure generated by this event would be considerably higher and would occur even faster. Hence, there may be an even stronger possibility of vacuum vessel failure.

As in the case of the small in-vessel LOCA, it is assumed that up to 1 kg of tritium could become airborne. Because the amount of energy discharged into the vacuum vessel is greater than in the case of the small LOCA, the leakage rate for this event would be expected to be higher. However, as a range of leakage rates up to 100% of room volume per day was already considered, the same range will be analyzed for this event. The model to be used is shown in Figure 5.

5.3 Vacuum Vessel Boundary Breach (LOVA)

There are two possible breaches: a breach which produces a direct connection between the vaccum vessel and the cryostat; and a breach which produces a direct connection between the vacuum vessel and the outside of the cryostat.

5.3.1 Vacuum Vessel Breach Into Cryostat

A breach of the vacuum vessel boundary into the cryostat is not a safety significant event, unless it is a common cause failure, which also breaches the cryostat boundary. Such a possibility is not considered credible.

5.3.2 Vacuum Vessel Breach Outside Cryostat

A breach of the vacuum vessel boundary via one of the diagnostic tubes has the potential to connect the vacuum vessel with the room where the cryostat penetration terminates. Such an event would cause a rapid depressurization of the room and the ingress of air into the vacuum vessel, unless the room contains an inert gas.

After the pressure inside the room and the vacuum vessel equalize (in-leakage from the room plus thermal expansion of the air/gas mixture), tritium can be slowly transported from the vacuum vessel to the room. However, by this time the active area detritiation system can be turned on, to maintain the room under negative pressure relative to its surroundings. An exhaust flow of 10 m^3/day (1% of room volume per day) will be used for the active area detritiation system. The model to be used is shown in Figure 6.

It is assumed that up to 1 kg of tritium could become airborne inside the vacuum vessel. As in the case of the in-vessel LOCA, it is assumed that all of the tritium will be in the elemental form, and there will be no attenuation mechanisms. This is the most pessimistic assumption to make. In the interim, mechanisms for tritium attenuation will be studied, and if they are considered to be significant, then they will be incorporated in the analysis for the interim report.

5.4 Torus Exhaust Line Failure

There are two places in the torus exhaust pumping system where a breach of the process boundary can occur: in the suction line or the discharge line of the mechanical pump.

5.4.1 Breach in Suction Line

A breach in the mechanical pump suction line would cause an ingress of air (or inert gas) into the vacuum vessel. Phenomenologically, the event sequence would be similar to a vacuum vessel breach outside of the cryostat (Section 5.3.2). For this event, the pentration termination room (Section 5.3.2) would be the mechanical vacuum pump room.

5.4.2 Breach in Discharge Line

A breach in the mechanical pump discharge line would cause tritium and deuterium to be released inside the pump room, pipe interspace, or glove box, where the break occurs. Assume the break occurs in the pump room (as shown in Figure 7). The analysis would not differ materially if the release was in the pipe interspace, or in the glove box.

Assume that the event occurs at the start of a 1000 s burn and that the fuel management system has sufficient holdup to support the burn, that is 140 g (500 g/h * 1000 s / 3600 s/h). Hence, if the pumps continue to pump, the most that could be discharged is the free inventory of 140 g. For conservatism, the maximum tritium release into the room is assumed to be 150 g. An equivalent amount of deuterium would also be discharged. The pressure rise from the discharge of this quantity of tritium and deuterium is small (<1 kPa), therefore, there won't be any significant leakage from the room.

Under normal conditions, following this event, the pump would be isolated and the release would be quickly terminated. Therefore, the above represents a bounding analysis.

Upon detection of tritium in the room, the active area detritiation system would be started and the pressure inside the room will be returned and maintained below that of the surrounding rooms. Two exhaust flowrates will be considered: 1% and 10% of the room volume per day (ie., 10 and 100 m^3/day, respectively). The latter is a pessimistic upperbound. The model to be used is shown in Figure 7.

5.5 Fuelling Machine Process Boundary Failure

Fuelling will consist of pellet injectors and gas puffers, which will be located in the fuelling rooms around the torus. Hence, failure of the process boundary would cause a release of tritium inside the fuelling room. Phenomenologically, this event will be similar to that described in Section 5.4.2. The mechanical vacuum pump room in Section 5.4.2 becomes the fuelling room. Clearly, there will be several fuelling machines, hence, failure of one would not necessarily cause the shutdown of the reactor. Equally, the failed fuelling machine can be easily isolated thus terminating the tritium release. To a first approximation, however, the environmental source terms for this event will be the same as those for the event in Section 5.4.2.

It is assumed that the pellet injector propellant gas is helium. If it is hydrogen, then the possibility of a hydrogen detonation has to be assessed, unless the pellet injector room is filled with an inert gas.

5.6 Fuel Processing System Process Boundary Failure

The fuel processing system equipment will be located inside glove boxes rather than inside a room. The event is a breach of the process boundary inside the glove box. Phenomenologically, this event will be similar to that described in Section 5.4.2. The environmental source terms will be bounded by those of Section 5.4.2.

5.7 Water Detritiation System process boundary failure

Only the water distillation unit of the water detritiation system is considered here, as it has the largest tritium inventory. The tritium inventory in the vapour phase catalytic exchange unit is small, even if the tritium concentration is higher. Therefore, the environmental source terms for the vapour phase catalytic exchange unit are bounded by those of the water distillation unit.

There are two places where a breach of the water distillation process boundary can be significant (other than the column itself): in the liquid line of the reboiler circuit (upstream of the boiler), or in the vapour line of the reboiler circuit (downstream of the boiler).

5.7.1 Breach in Liquid Line

A breach in the liquid line of the reboiler circuit will cause a spill of hot water in the water distillation room. The water in the column is between 50 and 70°C, therefore, there will not be any significant flashing of water to steam. Hence, the airborne tritium concentration will not be high. The TRITSPIL code will be used to determine airborne concentrations for this event. The spilled water will be collected in drain tanks for future processing.

Following the water spill, a high tritium alarm will cause the active area detritiation system to be started, hence, the water distillation room will be maintained under negative pressure, relative to its surroundings. The exhaust flowrate is assumed to be 50 m^3/h. The model to be used for this event is shown in Figure 8.

5.7.2 Breach in Vapour Line

A breach in the reboiler circuit vapour line will cause tritiated steam to be discharged into the room.

If the reboiler pump continues to operate, which is unlikely, as it would trip on column high pressure/low level, then it is possible to discharge the complete column inventory into the room. Assuming a column inventory of 6000 kg and an average tritium concentration of 10 Ci/kg, then, the total amount of tritium that could become airborne is 60,000 Ci. Most of this tritium

(HTO) will condense on the walls of the room. However, as there is no significant overpressure associated with this event, leakage will be negligible. As discussed in Section 5.7.1, above, and as shown in Figure 8, the active area detritiation system would be turned on to maintain the room under negative pressure.

5.8 Isotope Separation System Process Boundary Failure

The tritium inventory is held mostly in the cryogenic distillation columns, therefore, a process boundary failure inside the cold box will give rise to the largest possible release of tritium from the system. The inventory of tritium in the columns is at most 400,000 Ci. Assuming another 100,000 Ci is held up in the rest of the system, the total that can be released inside the cold box is 500,000 Ci.

The cold box is kept under vacuum, hence there is no leakage from it. However, as the pressure and tritium level inside the cold box increase, the vacuum pumps will turn on. As shown in Figure 9, the discharge from the vacuum pumps is sent to the exhaust flow detritiation system. If there is a significant amount of tritium in the pump flow, the the flow can be directed to a buffer tank for later tritium recovery. The discharge rate of the vacuum pumps is assumed to be 10 l/s and the volume of the cold box is assumed to be 30 m^3.

The isotope separation room is also served by the active area detritiation system, but it is not required for this event.

6.0 METHODOLOGY

In this past year, CFFTP has developed a user interface for the TMAP code, which is the official ITER code to be used for tritium source term work. Included in the interface is a tritium enclosure model (TEM), which can simulate accidental, or chronic, tritium releases in a room that is directly connected to an air detritiation system, or connected to another room that is. This model is therefore ideal for the analysis work in hand. CFFTP is proceeding with additional development work on TEM. The next upgrade will contain data from experiments conducted at CRL on various architectural/structural surfaces. This will allow the interaction between airborne tritium and surfaces (the sorption/desorption process) to be modelled in TEM. However, this version of TEM will not be available for this task. It is expected that it will be available source term analysis in 1995 and beyond.

The TRITSPIL code predicts the tritium release rates into the room air following a spill of tritiated water. The model considers mechanisms such as evaporation and condensation from wetted surfaces, and isotopic exchange.

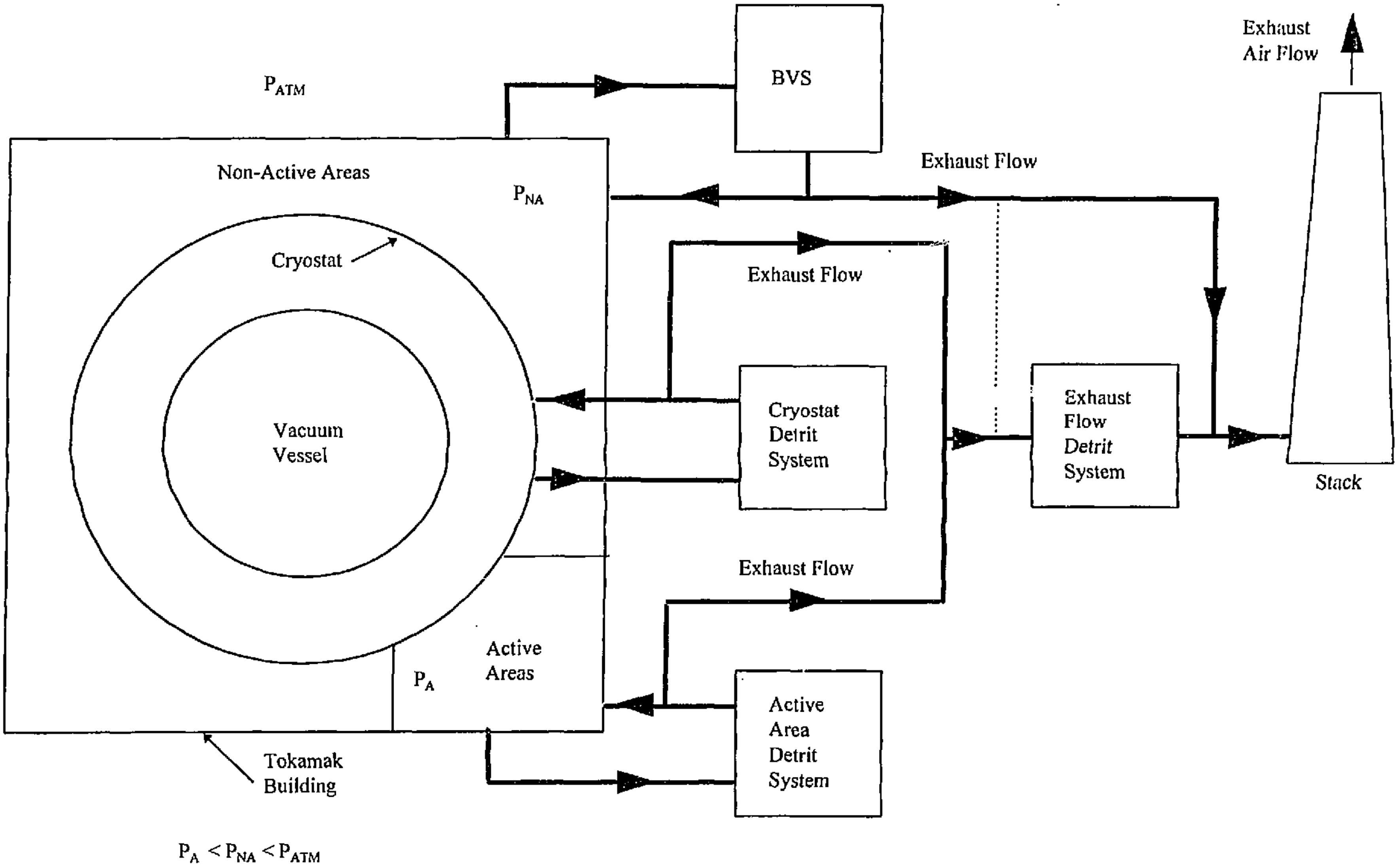

Figure 1
GENERAL VENTILATION AND DETRITIATION SCHEME

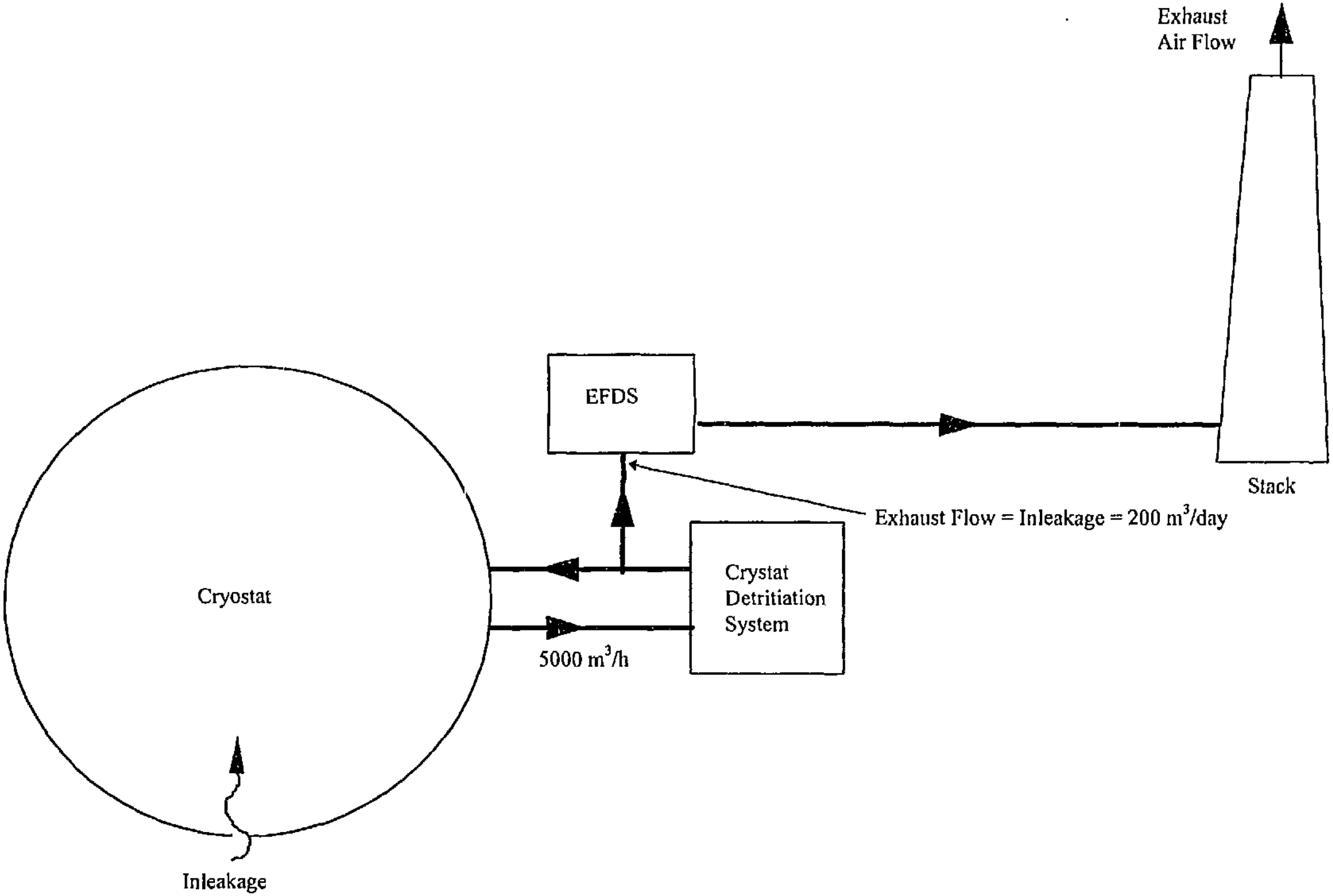

Figure 2a
EX-VESSEL LOCA INSIDE CRYOSTAT Case (b)

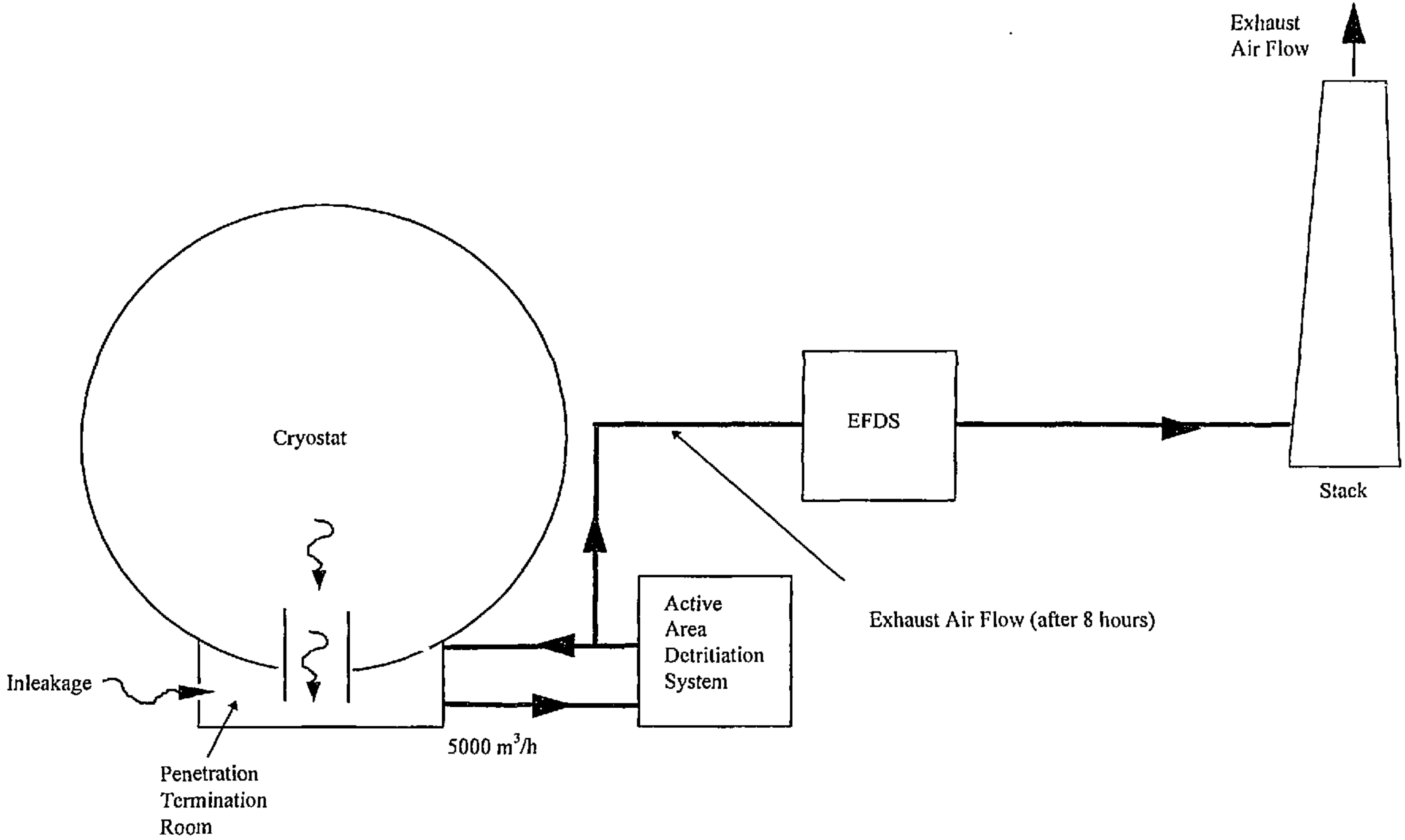

Figure 2B
EX-VESSEL LOCA INSIDE CRYOSTAT WITH CONSEQUENTIAL FAILURE OF PENETRATION Case (c)

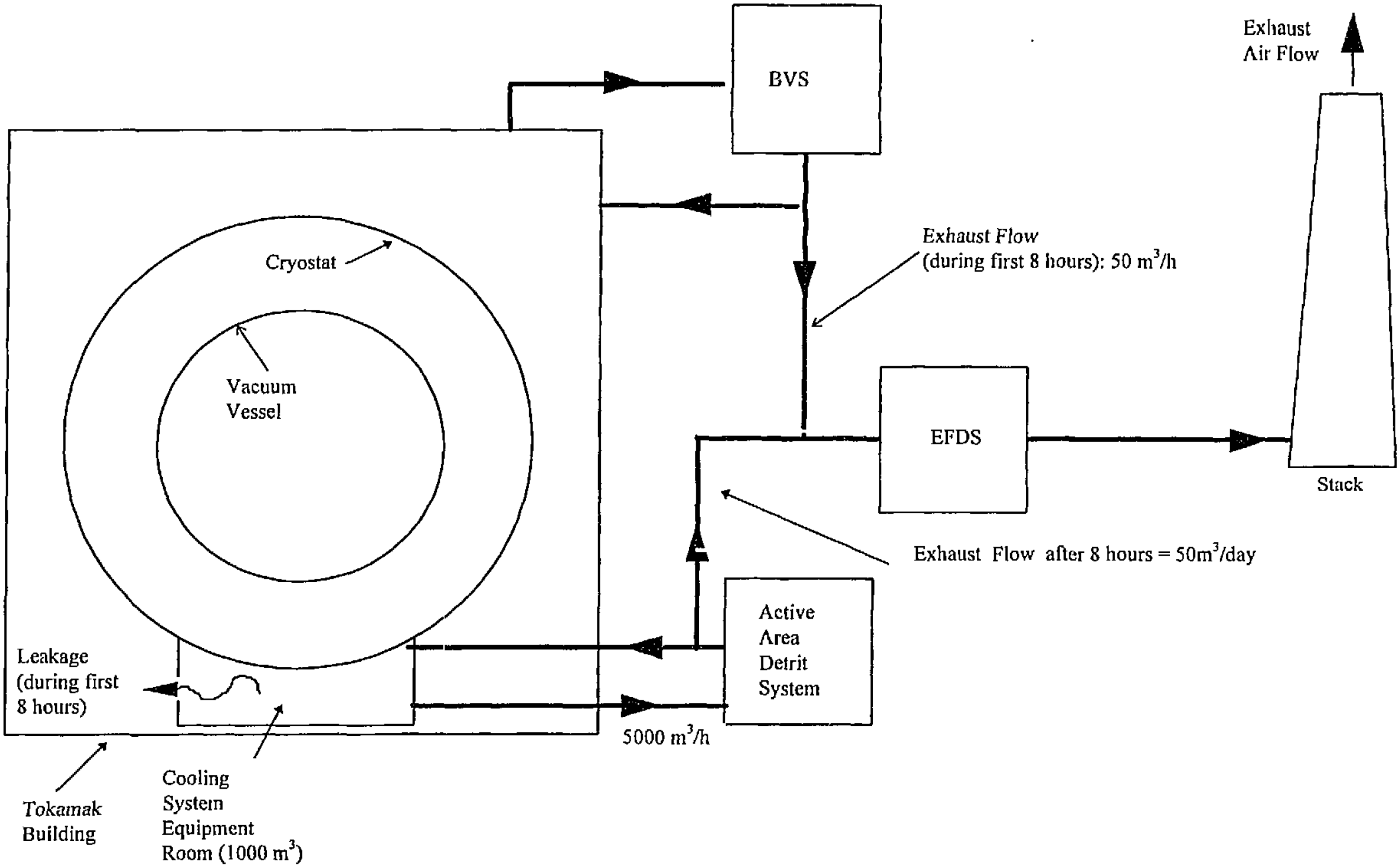

Figure 3
EX-VESSEL LOCA INSIDE COOLING SYSTEM EQUIPMENT ROOM

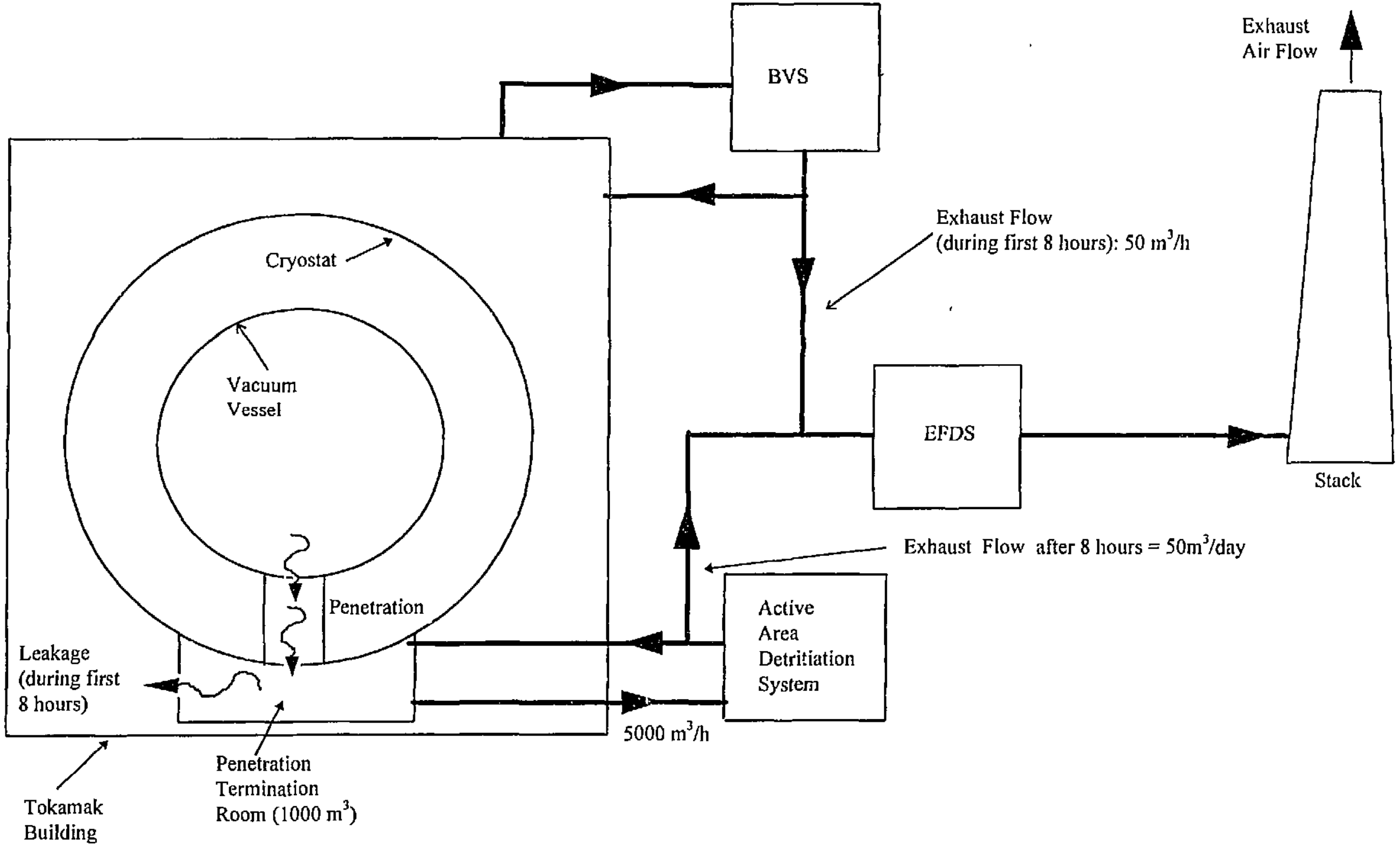

Figure 4
SMALL IN-VESSEL LOCA

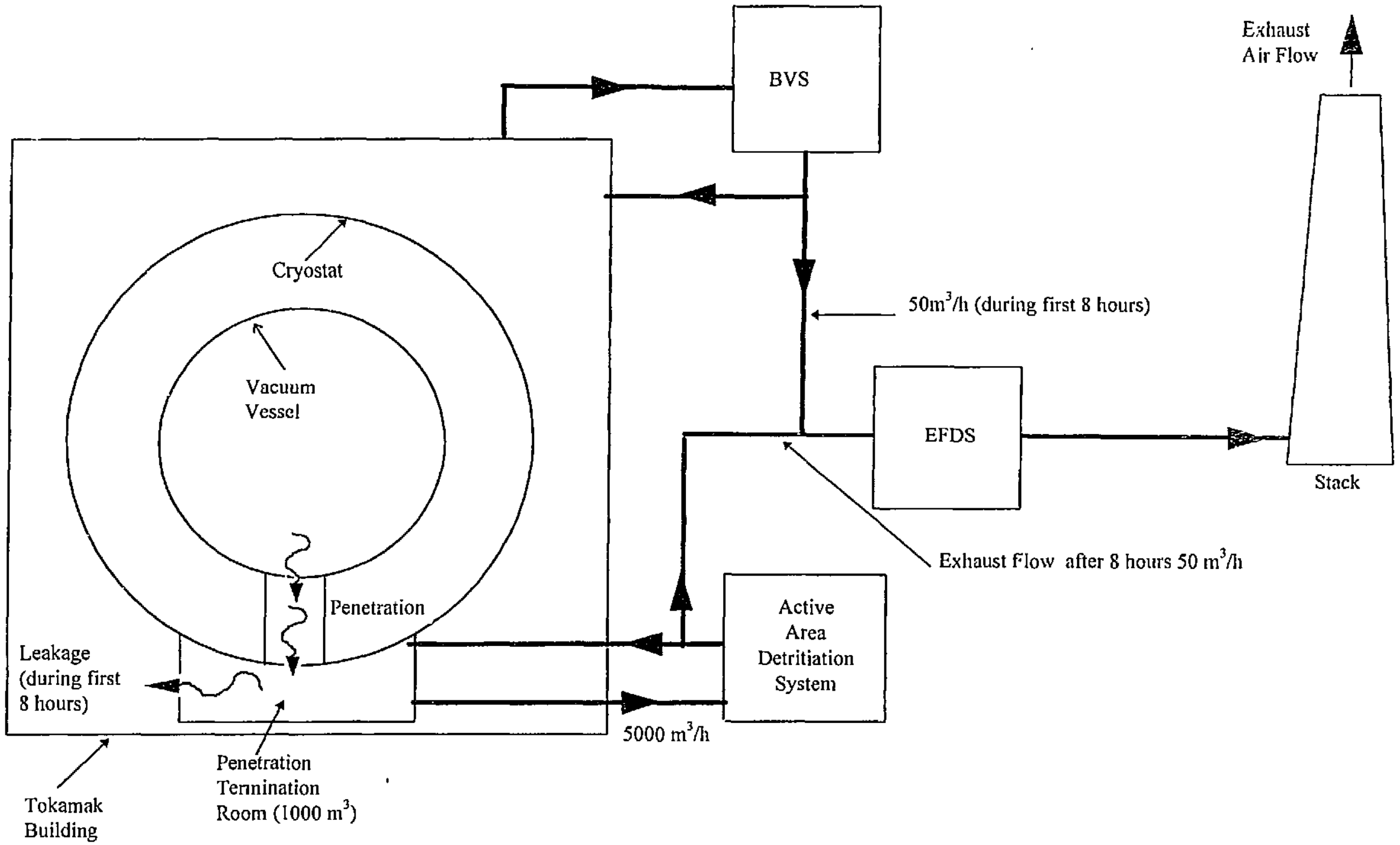

Figure 5

Large

IN-VESSEL LOCA WITH CONSEQUENTIAL FAILURE OF PENETRATION

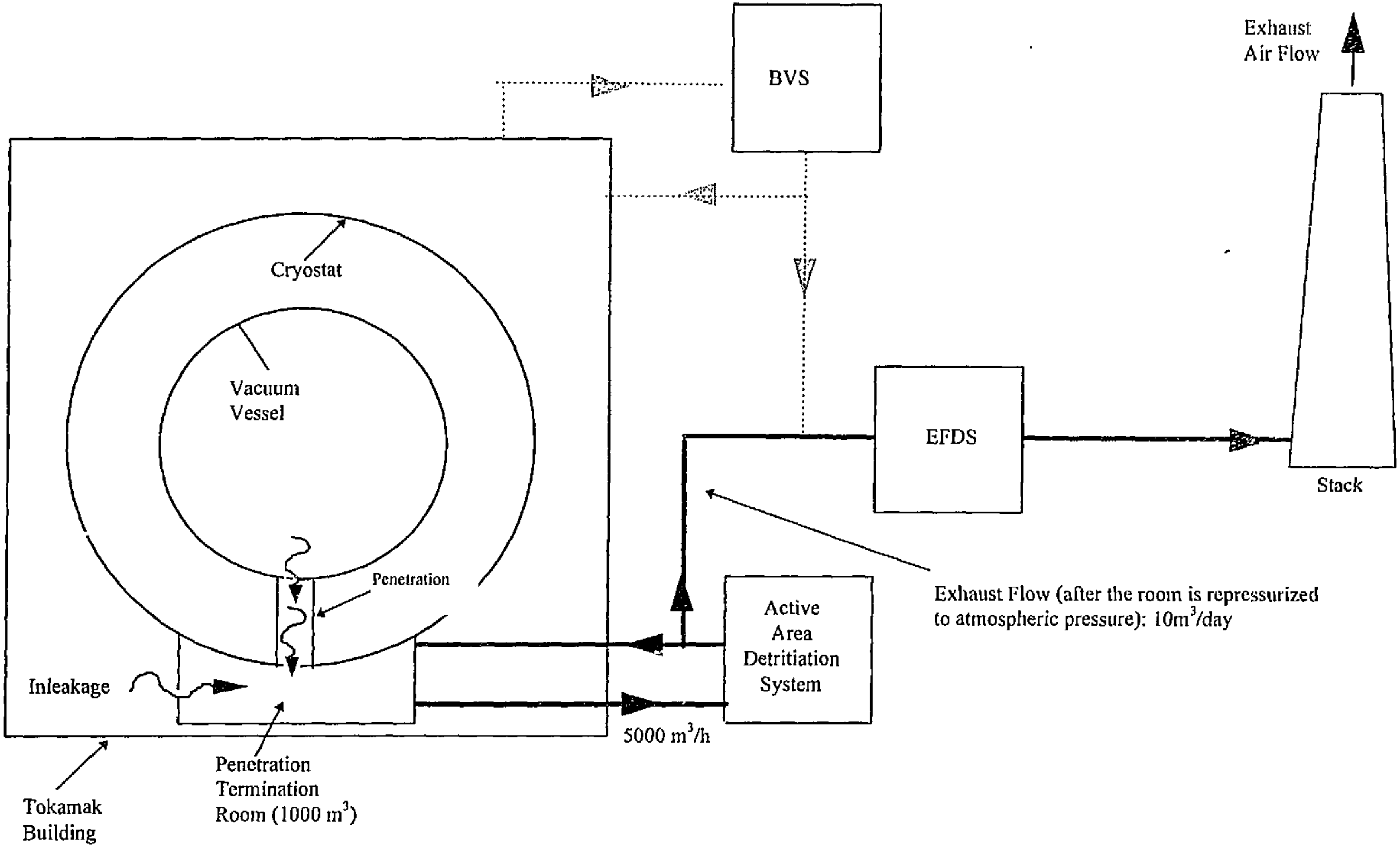

Figure 6
VACUUM VESSEL BREACH OUTSIDE CRYOSTAT (LOVA)

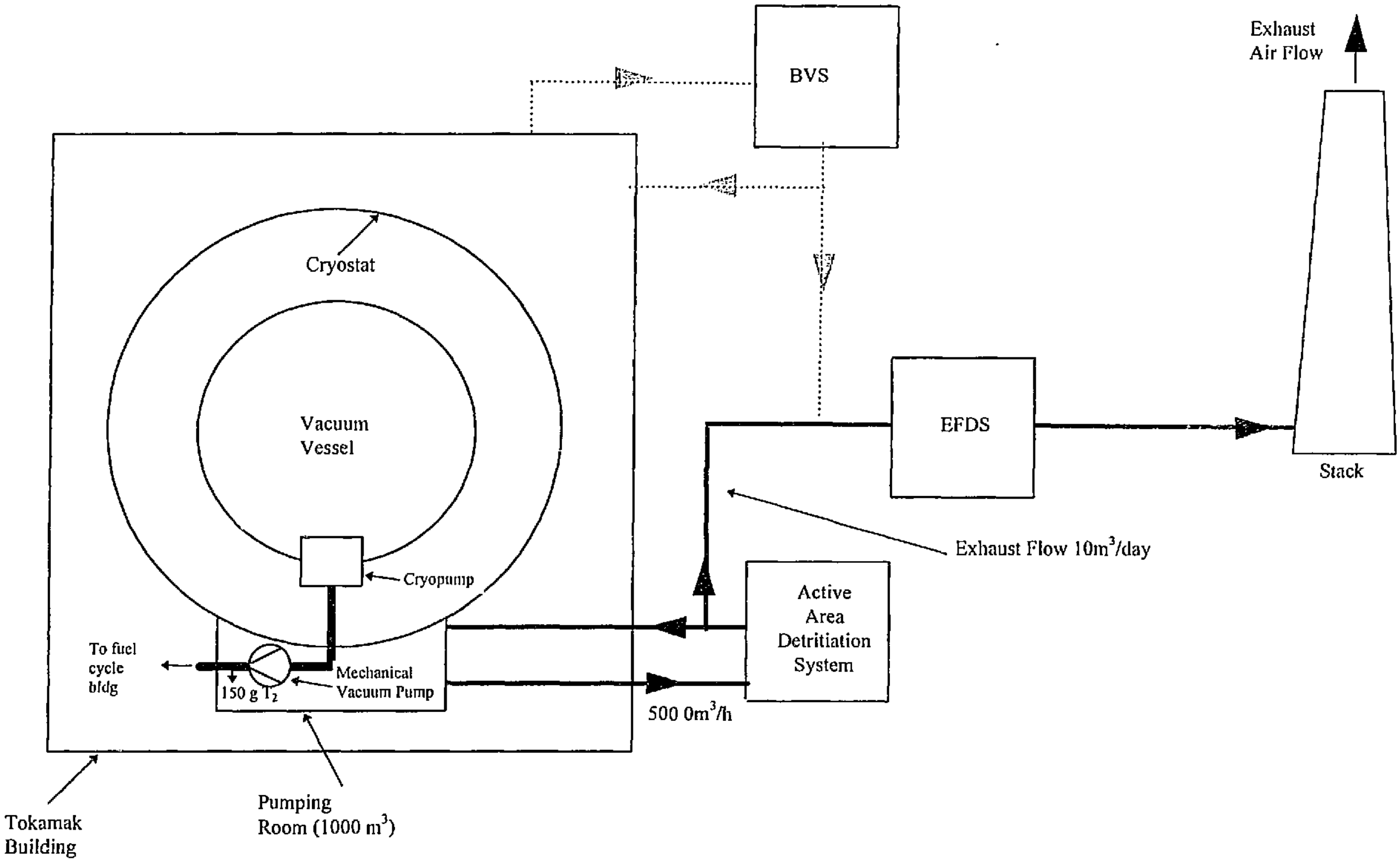

Figure 7
TORUS EXHAUST LINE FAILURE

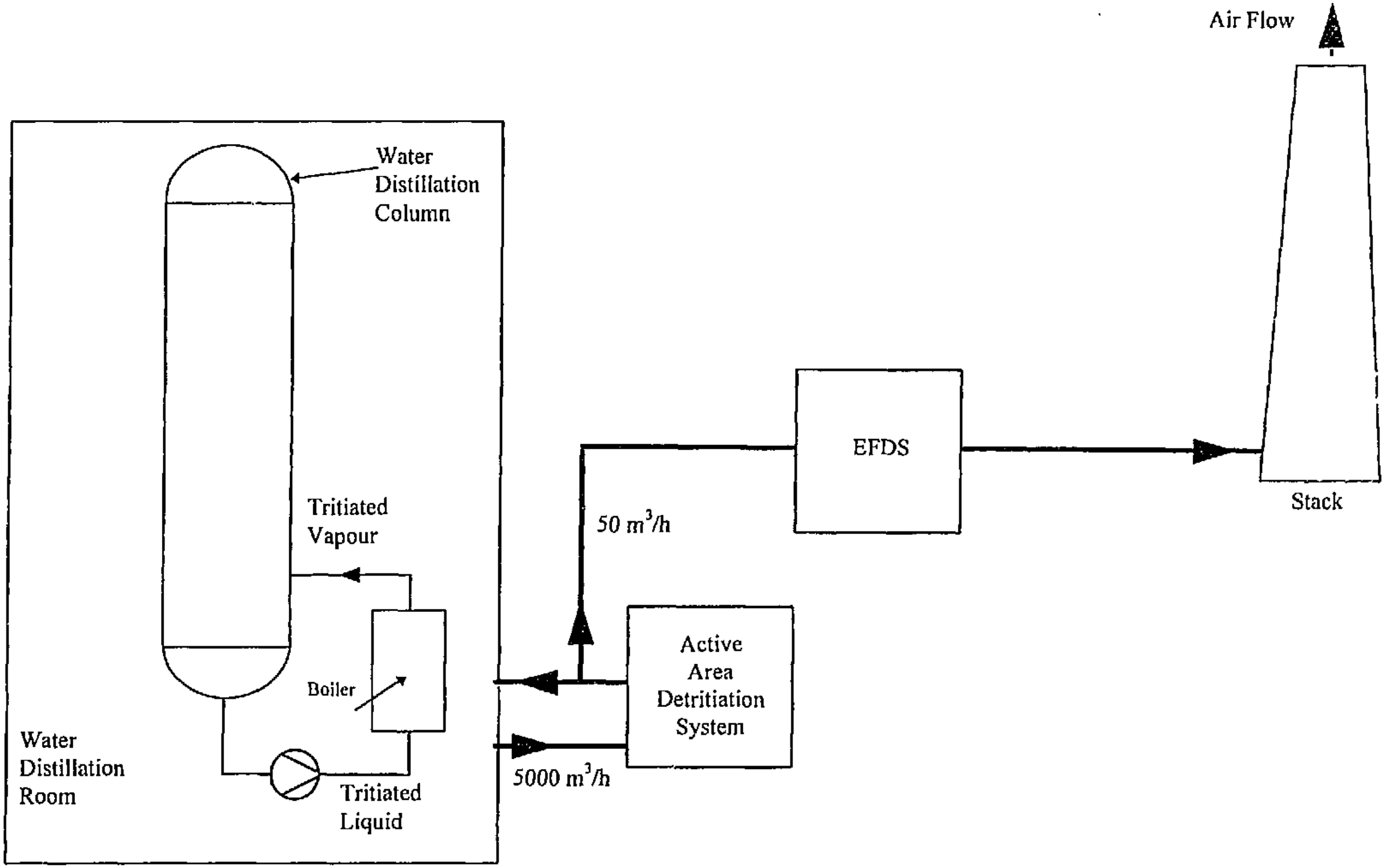

Figure 8
PROCESS BOUNDARY FAILURE IN WATER DISTILLATION SYSTEM

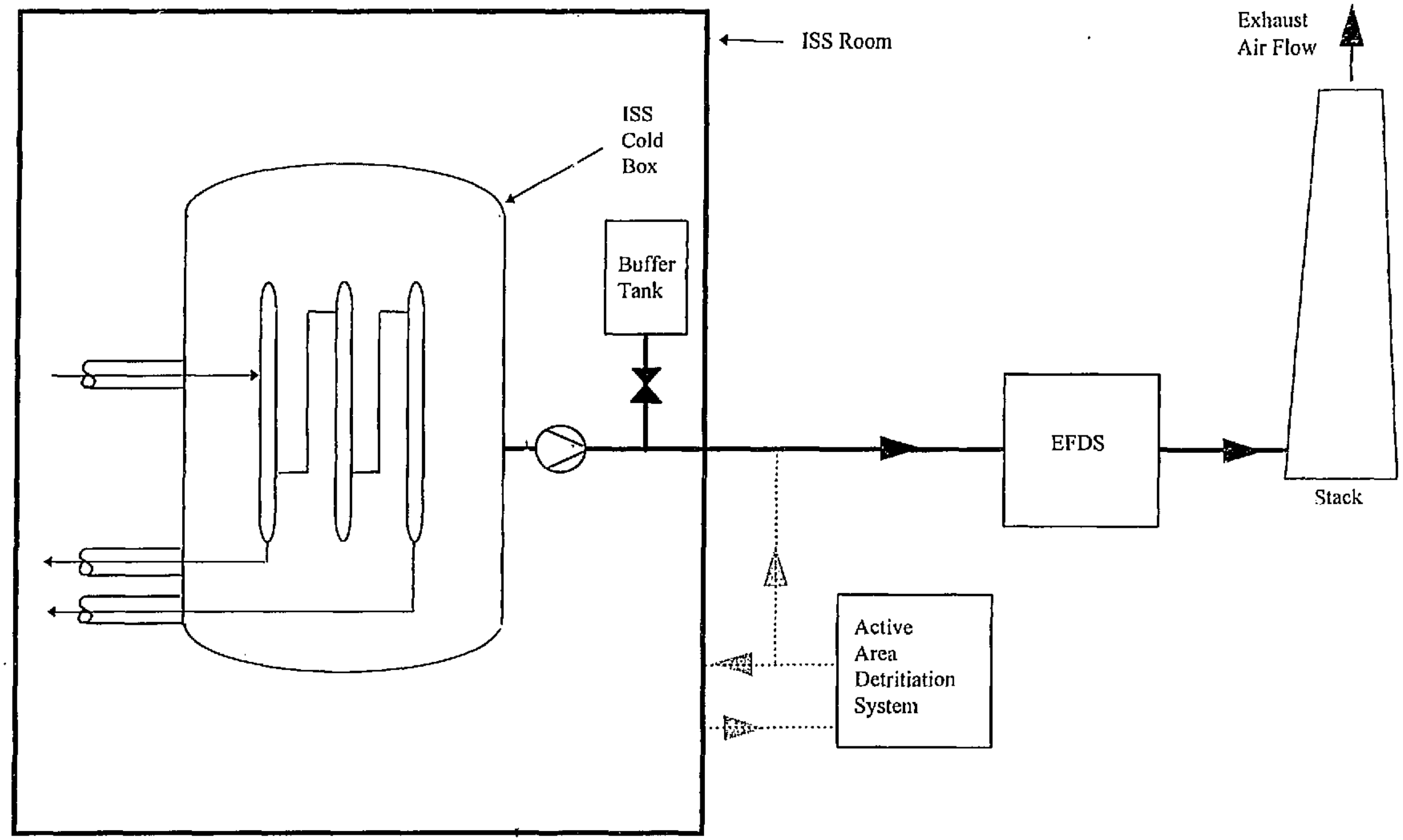

Figure 9
ISOTOPE SEPARATION SYSTEM (ISS) PROCESS BOUNDARY FAILURE