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ROLES OF ENGINEERED SAFETY FEATURES IN SEVERE ACCIDENT

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OECD/CSNI organized a special task force group to evaluate current technology for estimating LWR source term. One of the tasks of the task force group was to review and evaluate roles of engineered safety features (ESFs) of LWR in severe accidents. Among ESFs, containment sprays, icecondensers, filter system including SGTS and fan cooler were discussed by JAERI. In addition to the ESFs, the filtered-vented containment was also included in the discussion. The following comments were made through the discussions.

1) ESFs are in general effective to reduce fission products.
2) ESFs will be important when operator action is considered.
3) In that case, vulnerability of ESFs components must be evaluated.
4) A filtered-vented containment seems effective in reducing fission products.

KEYWORDS: Severe Accident, Source Term, FP, ESF, Containment,
Icecondenser, Filtered-Vented Containment, Fan Cooler,
Containment Spray, OECD/CSNI

シビアアクシデント時の工学的安全施設の役割

日本原子力研究所東海研究所燃料安全工学部
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OECD／CSNIは，軽水炉ソースターム評価の最近の技術基盤を評価するため，特別タスクフォースを組織した。このタスクの1つは，シビアアクシデント時の工学的安全施設（ESF）の役割を検討し，評価することであった。原研では，ESFのうち，格納容器スプレイ，アイスコンデンサ，SGTSを含む，フィルタ系，ファンクーラについて検討した。ESFに加えて，フィルタ付ベント型格納容器についても検討した。その結果，ソースターム評価に及ぼすESFの効果について次のような結果を得た。1）ESFは一般的にいってFPを減少するのに効果がある。2）運転員の介入を考慮する場合には，ESFは重要な役割を果たす。3）その場合，ESFが作動できるか否かが問題である。4）フィルタ付ベント型格納容器はFPを減少させるのに有効と思われる。

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付　録

1. INTRODUCTION

A light water reactor is equipped with engineered safety features (ESFs) to prevent and/or mitigate a reactor accident. Those ESFs include an emergency core cooling system (ECCS), containment, pressure suppression system such as containment sprays, icecondensers and suppression pools, and emergency air cleaning system. Figures 10.1 and 10.2 schematically show those ESFs for PWR and BWR, respectively.

Among the ESFs, ECCS is designed to prevent core degradation in the case of a loss of coolant accident (LOCA) by injecting additional water into the reactor core and maintaining its coolable geometry. It implies that if ECCS functions and no multiple failure exists, the loss of coolant accident would be mitigated and there would be little concern on source terms. This is the design basis of ECCS. Therefore in source term evaluation of severe accident, ECCS is assumed to fail in most of risk dominant sequences.

Containment as the third physical barrier for fission product release from the nuclear fuel is defined as ESFs and its role is to contain fission products within the containment and not to release fission products to the environment. Containment is designed and constructed to withstand pressure and temperature which are anticipated in the design basis LOCA. Therefore containment may lose its integrity when temperature and pressure exceeds the design basis in severe accident. As the result, radioactive materials would be released to outside of the containment. Containment integrity is subject of discussion in TASK XVII.

Pressure suppression system is designed to reduce containment pressure and temperature loading by condensing steam in the containment. PWR and BWR are equipped with containment sprays. BWR is equipped with suppression pool. There are three types of BWR suppression pools, namely Mark I, Mark II and Mark III. Some of PWR has icebeds in the containment to reduce pressure during accident and consequently the design pressure of the containment is also reduced. Pressure suppression system is also capable of removing fission products during accident. TASK X discusses the pressure suppression systems other than suppression pools which is to be discussed separately in TASK IX.

Emergency air cleaning system consists of filter systems to reduce fission products release outside of the containment. Fan coolers are expected to remove heat generated in the containment. In addition to the emergency air cleaning system within the containment, a standby gas treatment system (SGTS) is provided as a safety system in a reactor building of BWR for removal of fission products in a reactor building.

In addition to the existing ESFs, some of a reactor is equipped with a filtered-vented containment for reducing fission product release specifically in severe accident conditions. The concept and its effect of fission product release is also discussed in TASK X.

Even though a role of non ESFs in reducing fission product release was not discussed in this task, it is worth considering a possible use of non ESFs, e.g. a chemical volume control system (CVCS) and startup feed water pumps for PWRs, and HPCS, control rod drive pumps and pool overflow beyond weir wall (Mark III) for BWRs. Those non ESFs as additional accident mitigation measures could supply coolant to the reactor system and to prevent or delay core degradation during a severe accident.

2. ENGINEERED SAFETY FEATURES

2.1 Containment Spray

2.1.1 Technical Background

Containment spray system is provided to suppress pressure in the containment by condensing steam released from the primary system to the containment in the event of a loss of coolant accident. The spray system is also used to remove fission products from the containment atmosphere to prevent release of radioactive materials to the environment.

Steam condensation is the key mechanism of pressure suppression by the spray. Therefore parameters affecting steam condensation rate should be taken into account for thermohydraulic analysis. The following parameters are thought to be important in determining steam condensation rate during LOCA and the spray operation.

- noncondensible gas content
- natural convection in a containment
- size and distribution of spray droplets
- spray flow rate
- spray header height
- coagulation of spray droplets

For fission product removal, the mechanism is different depending on physical state of fission products, namely gaseous state or particulates. It is common practice in many countries for safety analysis of siting evaluation that elemental iodine is the form of inorganic iodine. Therefore gaseous iodine must be absorbed by water such as the spray droplet and the condensate on the containment wall. The following parameters must be considered in the analysis in addition to the above thermohydraulic parameters.

- partition coefficient
- iodine concentration in liquid phase and gas phase
- composition of environment gas
- spray additives and pH value
- chemical state of spray water

Recent source term assessments have shown that chemical form of inorganic iodine is likely to be CsI which would exist as aerosol in a containment. Therefore an injection of spray is equivalent to an addition of larger sized aerosol to a containment and the following natural mechanisms must be considered for particulate removal by spray droplets.

- interception
- impaction
- Brownian diffusion
- diffusiophoresis

2.1.2 What is known.

Fairly large amount of experimental data are available for iodine removal by containment spray especially for gaseous iodine such as elemental iodine and organic iodide(12). Table 10.1 summarizes test conditions of large scale containment spray experiments conducted by several organizations and Table 10.2 shows results of the tests for fresh spray mode and recirculation spray mode.

These experiment results showed that containment spray is very effective for removal of inorganic iodine. For this case, reduction rate depends on pH of spray water and initial iodine concentration in gas phase. Spray is more effective in the case of high pH and low initial concentration of iodine. From JAERI's test for BWR simulation, half life of initial iodine reduction rate was found to be less than 10 min and partition coefficient was larger than 100. For PWR simulation, half life of initial iodine reduction rate was approximately 37s and partition coefficient was 4300.

For organic iodide removal, containment spray was not effective as inorganic iodine. The CSE (Containment Systems Experiment) at the Hanford Engineering Demonstration Laboratory showed that 2 hour dose reduction factor (DSF) was 1.5 for large PWR containment. From the test results of the NSPP (Nuclear Safety Pilot Plant) at the Oak Ridge National Laboratory, it was found that methyl iodide was more effectively removed by spray when the spray flow rate was larger and the spray droplet was smaller.

It was found from the CSE experiments that containment spray was very effective to remove aerosol particles as shown in Figure 10.3 (7).

2.1.3 Areas where studies agree and disagree.

Among the reports presented at the first source term task force meeting, ANS, APS and IDCOR reports mentioned ESFs to some extent. The ANS report describes ESFs most in detail since the charter of the ANS report among others is to take ESFs into consideration for source term evaluation as more realistic estimation. The APS report does not discuss much about containment spray by saying that electric power is necessary to activate containment spray and by assumption, it is lost during severe accident such as TMLB'(3). However the APS report mentioned that estimation of fission product removal by containment spray can be made with relatively high confidence because existence of large amount of experimental data(2). The IDCOR report also acknowledged the effectiveness of containment spray in a very short sentence in that if spray is available, consequence will be much less significant(8).

Other reports did not mention specifically of containment spray effectiveness mainly because it is agreed implicitly that containment spray is effective and a lot of information is available for iodine removal, especially for elemental iodine and organic iodide.

Among the source term reports, a consensus seems to exist such that containment spray is effective to reduce fission products in a containment.

2.1.4 Areas where information is sufficient or not sufficient.

Sufficient information exists on containment spray effectiveness for elemental iodine and methyl iodide. However experiment data on removal of high density aerosol by containment spray is not sufficient mainly because the TID-14844 type source term assumes 1 % particulates among the released fission products.

Vulnerability of containment spray components should be evaluated for a long term cooling and also for an activation of containment spray system during severe accident. There is a possibility of the pump suction being blocked by debris and other foreign material during the recovery process and the containment spray may not be available even though an external power is restored.

With a spray system, any aerosol will tend to be washed down into the pump and thus a check must be made that the pump suction offtakes do not get blocked up, particularly relevant if large amounts of aerosols have been generated. If the aerosol particles do not agglomerate, the smaller sizes may be swept into the pumps and heat exchangers. Depending on whether there are volumes with low velocity flow, deposition may occur eventually causing blockage of, for example, parts of the heat exchanger. Alternatively, the pump bearings may suffer from excessive wear due to particulate. Provided the system keeps working, it is unlikely to suffer from overheating problems due to fission product decay heat in the aerosol, but failure of a pump might then lead to local overheating if particulate has deposited preferentially in a part of the circuit. Additional problems might arise due to the radiation field produced by active particles which would make maintenance difficult.

There is a possibility of generating a large amount of steam or dispersal of debris if spray or ECCS is initiated later in the transient and water is sprayed onto debris bed at the bottom of containment.

2.1.5 Application to different plants.

Basis physics should be applicable to any kinds of plants as long as spray system is used and the spray parameters are specified.

2.1.6 Conclusion and recommendations.

Effectiveness of containment spray to remove fission products is fairly well understood for elemental iodine and methyliodide at representative accident conditions used for the siting evaluation. Less data is available for high density aerosol which represents more realistic severe accident conditions. Studies agree that aerosol removal by containment spray is very effective even if density is not high enough to represent severe accident conditions (7).

Further research area may be in the area of vulnerability of the spray components and effect of the late spray initiation on debris dispersal.

Possible implication to regulations would be a consideration of physical form of iodine for spray calculation since spray removal is evaluated by assuming elemental iodine rather than particulates.

2.2 Icecondenser

2.2.1 Technical background

Icecondenser is used in a certain type of PWR in order to reduce pressure by condensing steam by icebeds. Typical configuration is shown in Figures 10.4 and 10.5 (2). The benefit of having icecondenser is that the design pressure of the containment can be lowered as compared with a large dry containment. It is also expected that fission products can be trapped in icecondenser by large amount of melting ice as well as large structural surface area in the ice compartment.

Similar to spray removal of fission products in a containment, mechanisms of fission products removal are different depending on physical form of fission products. For gaseous fission products such as elemental iodine, absorption and adsorption are the primary mechanisms of removing fission products by icebeds. Water produced from the melting of ice and the condensation of steam will absorb gaseous fission products. Adsorption onto large solid surface may be effective in the ice compartment even after all of ice melts.

Parameters affecting absorption are largely dependent on thermohydraulic conditions in icebeds. Thermohydraulic phenomena occurring in icebeds is complex and detailed analysis may be difficult. For example, amount of melting of ice depends on flow rate, temperature of gas, heat transfer between ice and flowing gas, direction of flow, local flow obstruction, changing shape of ice while melting, and others. Once amount of melting of ice is known with respect to time, absorption of gaseous fission products will be predicted if partition coefficient, water chemistry, concentration of gaseous fission product in gas and liquid, and other physical states are known similar to spray removal analysis.

When fission products are aerosol in containment, those aerosol will be removed in icebeds by the natural removal mechanisms of aerosol. Since ice baskets and ice beds itself form complicated physical form, important mechanisms of aerosol removal are a flow induced removal such as impaction, interception and fluid turbulence diffusiophoresis and thermophoresis due to large temperature gradient and condensation rate.

Therefore estimation of flow pattern and condensation rate onto the wall and ice itself is important.

2.2.2 What is known.

Theoretical treatment of fission products removal in icebeds has been developed in the ICEDF code (13). The following removal mechanisms were considered in the code for particle retention: sedimentation, Brownian diffusion, inertial impaction, particle interception, thermophoresis, diffusiophoresis, and turbulent deposition. Thermohydraulic conditions in the ice compartment are not well analyzed and the code assumes well mixed condition of the gas phase in the icebeds. The assumption tends to predicting the low limit of particle removal efficiency.

The sensitivity calculation showed that removal efficiency depends on size distribution of aerosol. The minimum removal efficiency occurred at a particle diameter of 0.4 micron as shown in Table 10.3 (13). Particles smaller than 0.01 micron were efficiently removed by diffusion, and particles larger than 2 micron were effectively removed by sedimentation and inertial impaction.

The model predictions were in reasonable agreement with experimental data on the removal of elemental iodine as shown in Figure 10.6. However little data is available for particle removal and flow pattern of gas flow.

2.2.3 Areas where studies agree and disagree.

The APS report recognizes the lack of experimental data and the uncertainty associated with availability of ice and estimation of ice area to which iodine is deposited. The ANS report also describes the size dependance of aerosol removal and the uncertainty of ice surface area. Both reports is essentially based on the same reference. The IDCOR report has gone a little bit further by saying that structural area in the icecondensers is fairly large and it increases deposition rate of aerosol even after ice melts.

Agreement exists among the reports that icecondensers will remove fission products if ice is still there. Quantitative estimate of fission product removal in the icecondensers is uncertain because an estimate of available ice surface area has the largest uncertainty.

2.2.4 Areas where information is sufficient or not sufficient.

Experimental data base on aerosol removal in the icecondenser are scarce while information is available for elemental iodine removal in the icecondenser. Theoretical models have been developed and important physical process related to aerosol removal are incorporated into the modelling.

Thermohydraulic data in the icecondenser are also insufficient and flow pattern in the icebeds is not well predicted at present.

2.2.5 Application to different plants.

All of a PWR with icecondensers are designed by the Westinghouse Electric Company and the configuration is nearly the same so that the result should be applicable to all of the icecondenser type PWR.

2.2.6 Conclusions and recommendations.

Icecondensers are unique feature to some of PWRs. Effectiveness of icecondensers on fission products removal depends both on size distribution of particles and also on to what extent ice is available during severe accident. In addition, thermohydraulic conditions such as flow pattern and steam condensation rate are important to better predict scrubbing fission products in the icecondenser.

Due to lack of experiment data on aerosol removal in the icecondensers, predicted value of fission product removal may be conservative estimate. However quantitative verification of the computer code requires an experiment representing reactor situation.

2.3 Filter System

2.3.1 Technical background

Filter system is ESFs and forms a part of an emergency air cleaning system and its purpose is to remove fission products from containment air. Filter, adsorber and HEPA filter as shown in Figure 10.7(11). Normally two such trains are provided for redundancy.

In the filter train, demister is to protect prefilters, HEPA filters and adsorbers from water droplets and is made of wave plate for larger droplet and of wire mesh for smaller particles. Prefilters are installed to collect coarce particles to extend life of HEPA filters.

HEPA filters are used to remove the rest of particles with high efficiency. Adsorbers are made of charcoal and iodine removal depends on the charcoal adsorber beds.

Those components are designed for thermal hydraulic conditions corresponding to the design basis accident and therefore if those conditions are exceeded, efficiency of the filter systems might be lower or the filter system might be deteriorated. For severe accident, the filter system efficiency must be evaluated in terms of the following items;

- thermohydraulic conditions (pressure, temperature)
- chemical forms
- radiation effect
- high humidity
- loading capacity

2.3.2 What is known.

The USNRC Regulatory Guide 1.52 requires air clean-up system as ESFs in the design of light water reactor to mitigate the consequences of postulated accident for filter systems. The postulated design basis accident conditions are shown in Table 10.4. Therefore filter system should be intact under the conditions specified in the table.

However in the case when the design basis conditions are exceeded as anticipated in severe accident, the capability of the filter systems is not certain. Therefore experimental data about the behavior of the components of the filter systems are needed to ;establish the limits of fission product confinement at the extreme conditions. The state of knowledge is summarized in Tables 10.4 and 10.5, respectively for HEPA filter and iodine adsorbent(11).

2.3.3 Area where studies agree and disagree.

The APS report takes a credit of the filter system for fission product removal and so does the ANS report. However the ANS report describes the possible inefficiency of the filter if severe accident conditions persist prolonged time and the filter lose its integrity due to high density fission product aerosol.

2.3.4 Areas where information is sufficient/not sufficient.

Filter performance at the extreme conditions beyond the design limit may need further investigation. Especially informations on the filter performance under the following circumstances are not sufficient.

- high temperature and high humidity
- radiation doses
- mechanical loads due to high differential pressure
- combination of the above items

2.3.5 Application to different plants

All of nuclear reactor has filter systems to remove fission products from an exhaust gas from the plant. If the design criteria of the filter systems and the postulated accident conditions are the same, conclusions in the present sections should be applicable to all plants.

2.3.6 Conclusions and recommendations:

The existing filter system is designed for the postulated design basis accident and there exists uncertainty in the filter system efficiency at high temperature and high humidity beyond the design limit in severe accident. Therefore experimental data is needed to confirm filter efficiency under those extreme conditions to quantify the bounding capability of the filter system.

2.4 Fan Coolers

2.4.1 Technical background

Many reactors are provided with fan coolers consisting of banks of finned tubes with cold water flowing through them. Air is drawn past these banks of tubes by a large diameter fan, which throws the air back across the containment volume to ensure well mixed atmosphere. For design basis accidents, these coolers will condense large quantities of steam out of the containment atmosphere and so reduce the internal pressure. Some of the condensate will drain back down to the containment sump, while some may be entrained into the air flow induced by the fan.

Fan cooler may be effective to remove fission product since cold surface exists in the heat exchanger so that steam condenses onto the cold surface. Fission products will be absorbed by the water. If fission products are aerosol, then aerosol will tend to move towards the coolers and due to the lower temperatures may easily be entrained and trapped in the condensate. Potential problem areas could be blockage of protective screens, if used; deposition on the finned cooler tubes and to introduce a thermal resistance and hence degrade the cooler performance; or to be deposited on the fan blocks or motor housing, again degrading performance.

However fan cooler is an active system which requires electricity to operate. If it is operable, an appropriate credit should be taken in severe accident analysis.

2.4.2 What is known.

Components performance under the design conditions is well understood. However component performance is relatively unknown under an extreme conditions exceeding the design conditions.

2.4.3 Areas where studies agree and disagree.

The ANS report describes containment fan cooler as a heat removal and fission product removal system. It is noted in the ANS report that no credit for fission product removal is taken in severe accident analysis.

2.4.4 Areas where information is sufficient/not sufficient

Integrity of a pump to circulate water in the heat exchanger must be evaluated. Vulnerability of the fan cooler components must be investigated.

2.4.5 Application to different plant.

Information should be applicable to all plants.

2.4.6 Conclusions and recommendations.

Fan cooler is used to remove an excess heat out of the containment. Fan cooler is also possible to remove fission products. An appropriate consideration in severe accident analysis is necessary.

2.5 Filtered-Vented Containment

2.5.1 Technical background

In order to relieve excessive pressure and to reduce radioactive materials release to the environment, the concept of a filtered-vented containment has been developed and adopted to the Barseback BWR in Sweden and to the French PWRs.

The filtered-vented containment is unique to the plant. The Swedish filtered-vented containment is schematically shown in Figure 10.8. The filtered-vent system consists of a cylindrical vessel of 10,000 m^3 volume, 20 m diameter and 40 m height. The vessel is a cylindrical reinforced concrete structure built above ground. The vessel is filled with 1 inch size crushed quartzite rock gravel.

The gravel bed filter acts as a heat sink for condensation of the steam from the containment and it removes aerosols and iodine from effluent gas from the containment after the rupture disk is broken at 650 kPa.

The removal mechanisms of aerosols by the gravel bed are similar to those by icecondensers; sedimentaion, Brownian diffusion, impaction, interception, diffusiophoresis and thermophoresis. Thermohydraulic conditions must be specified in order to reliably predict fission product removal by the gravel bed. There is a difference between the gravel beds and the ice beds in that the configuration of the gravel beds stays the same while that of the icebeds changes due to melting of ice.

The efficiency of aerosol removal by the gravel bed depends on the grain size, bed depth, gas velocity, residence time and steam fraction of the gas flow. Large scale experiments were conducted to determine the removal efficiency of aerosols and iodine. Analytical models were developed to characterize a full scale gravel bed.

The French filtering system, which is to be used when the U5 emergency procedure for consequence mitigation is implemented, is based on a moderately expensive sandbed filter placed between the containment and the stack, the gases being monitored by the stack radioactivity control system before release.

Specifications for the design of the venting system are the followings:

- maximum gas flow rate : 3.5 kg/s ;
- typical gas composition : air (33%), CO_2 (33%), CO (5%), steam(29%);
- gas density : 4 kg/m^3 ;
- inlet gas temperature : 140 C ;
- inlet pressure (before decompression in the pipes) : 0.5 MPa
- pressure drop through the filter : 0.01 MPa ;
- pressure at filter outlet : nearly atmospheric ;
- maximum airborne aerosol concentration : 0.1 g/m^3 ; total amount: 5 kg ;
- aerosol mean diameter : 1 micron ;
- filtration efficiency : 10 (objective).

The filtering system - about 40 m^2 in surface area and 0.8 m of sand height - is not expected to constitute a heat sink large enough, for the bulk of the steam passing though to be condensed.

2.5.2 What is known.

Experiment was conducted to obtain thermohydraulic data base in terms of heat removal and gas flow in the gravel bed. It showed that a gravel bed with a volume of 4,000 to 10,000 m^3 filled with a gravel fraction of 25 to 35 mm can condense all expected flows from the containment postulated in the safety analysis of the Barseback reactor. The condensate did not clog the gravel bed and most of the condensate flowed downward.

In order to determine amount of fission products removal by the gravel bed, experiments were conducted with aerosol particles and iodine. The experiment was performed at 100 C with condensing steam. Results showed that elemental iodine was removed by physical adsorption to the gravel and trapped chemically in the bed through chemisorption.

The sandbed filter to be used in French PWRs has been specified according to the results of the "PITEAS - filtration" experimental study, in which the best combination of filtration efficiency/pressure drop parameters has been established.

2.5.3 Areas where studies agree and disagree.

The filtered vented containment is adopted only in Sweden and France, and no other detailed study is available. Therefore no comparison is possible.

2.5.4 Areas where information is sufficient/not sufficient.

Sufficient data seem to exist for the filter efficiency of the gravel bed of the Swedish reactor and of the sandbed of the French PWRs. Since the filter system is plant specific, new data would be needed if the different type of filter is selected.

2.5.5 Application to different plant.

Effectiveness of the filtered vented containment depends on plant and/or the design of the filter of the system. Therefore evaluation must be plant specific.

2.5.6 Conclusion and recommendation

The filtered-vented containment is employed in the Swedish reactor and the French PWRs to mitigate severe accident by relieving the containment pressure. The filtered vent consists of the gravel bed or of a sandbed in which fission products are removed. Choice, size and configuration of materials, gas composition and temperature are important parameters for designing the filter. Several experiments were conducted to determine the design criteria. It was found that the gravel bed and the sandbed are efficient in reducing fission product release to the environment.

3. SUMMARY

The following ESFs were discussed.

* Containment sprays
* Icecondensers
* Filter systems including SGTS
* Fan coolers

In addition to the ESFs, the filtered-vented containment was also included in the discussion. The following comments can be made on the impact of ESFs on source term estimate.

* ESFs are in general effective to reduce fission product.
* ESFs will be important when operator action is considered.
* In that case, vulnerability of ESFs components must be evaluated.
* A filtered-vented containment seems effective in reducing fission products.

2.5.6 Conclusion and recommendation

The filtered-vented containment is employed in the Swedish reactor and the French PWRs to mitigate severe accident by relieving the containment pressure. The filtered vent consists of the gravel bed or of a sandbed in which fission products are removed. Choice, size and configuration of materials, gas composition and temperature are important parameters for designing the filter. Several experiments were conducted to determine the design criteria. It was found that the gravel bed and the sandbed are efficient in reducing fission product release to the environment.

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Table 10.1 Comparison of tests conditions

Item	NSPP	CSE	JAERI Model C.V.
Test vessel			
Material	Stainless Steel	Carbon steel(paint)	Stainless Steel
Size	3.0m(dia.)x4.6mH	7.6m(dia.)x20mH	7m(dia.)x20mH
Volume	38 m^3	750 m^3	708 m^3
Volume of spray tank	0.38 m^3	7.6 m^3	80 m^3
Spray nozzle			
Type of nozzle	1713	3/4 7G3, 3/8 A20, 3/8 A50	1EX-554L-1C
Number of nozzle	1	3 or 12	6
Heating of test vessel	Steam injection	Steam injection	Steam injection
Iodine injection	I_2+^{131}I (Sweeped by carrier air)	$I^{‡}$+$Cs^{‡}$+UO_2 mixed aerosol(sweeped by steam) ‡: labeled by radio nuclide	I_2 or I_2+^{131}I (sweeped by N_2 gas)
Sampling of iodine			
Gas phase	Maypack sampler (2ch)	Maypack sampler (14ch)	Maypack sampler (4ch)
Liquid phase	Water sampler	Water sampler	Water sampler (+Water concentration vessel)
Iodine measurement method	Radioactivity measurement	Radioactivity measurement	X-ray fluorescence analysis or radioactivity measurement
Number of tests	17	7	2

Table 10.1 Comparison of tests conditions (continued)

Item	NSPP	CSE	JAERI Model C.V.
Free gas phase volume : V	38 m^3	594 m^3	708 m^3
Spray nozzle height : H	4.5 m	11.7 m (average)	15 m
Spray flow rate : F	3.4 m^3/hr	2.9 32 m^3/hr	21 m^3/hr
Spray flux : FH/V	0.40 m/hr	0.057 0.59 m/hr	0.44 m/hr
Initial gas phase temperature	130°C	120°C	125°C
Temperature of spray	Room temperature	32°C or room temperature	70°C
Initial pressure	4.2 kgf/cm^2 (Air at 1atm + saturated steam)	same as left	same as left
Spray period Fresh spray Recirculation spray	6 min for 5 0 tests 6 min for 12 4 8hr tests	3 60 min for 6 0 60 min tests 40 min for 1 20 hr test	50 min for 2 25 hr tests
Quality of spray water	Borax : boric acid(B=3000ppm) +NaOH,PH=7.2 9.4 or water	Borax : boric acid (B=525 3000ppm) +NaOH,PH=9.5 or boric acid (B=3000ppm,PH=5.0)	Borax : boric acid (B=2450ppm)+NaOH PH=9.5 or boric acid (B=2500ppm)
Initial iodine concentration in gas phase	100 mg/m^3	160 mg/m^3	41 mg/m^3

Table 10.2 Tests results : Removal of inorganic iodine by borax spray

(a) Fresh Spray

Item	NSPP	CSE	JAERI Model C.V.
Partition coefficient	>100,000	>10,000	(not measured)
Ratio of iodine reduction rate ($\lambda s(E)/\lambda s(C)$)	2	1	0.66 (half life of iodine reduction = 37 sec)
General tendency		Iodine reduction rate is very high until the iodine concentration in gas phase reduces 1/100 of initial state.	same as left

(b) Recirculation Spray

Item	NSPP	CSE	JAERI Model C.V.
Partition coefficient	>10,000	>10,000	4,300
Ratio of iodine reduction rate ($\lambda s(E)/\lambda s(C)$)	2	1	
General tendency	Overall dose reduction factor is smaller in recirculation spray mode than in fresh spray mode.	Iodine concentration reduces to 0.1 % of initial value after 1 day of recirculation spray.	Iodine concentration reduces to 0.5 % of initial value after 1 day of recirculation spray.

Note: Partition coefficient is defined as the ratio of iodine concentration in liquid phase to that in gas phase .

Table 10.3 Predicted Decontamination Factors (DFs) for Particles in an Ice Compartment[a]

Aerodynamic Particle Diameter, μm	Predicted DF Case A $\varepsilon F = 0$[b] $X_i = X_o = 0$[c]	 Case B $\varepsilon F = 0.3$ $X_i = X_o = 0$	 Case C $\varepsilon F = 0.3$ $X_i = 0.5;\ X_o = 0.05$
0.001	8.9	202.3	203.1
0.01	1.4	10.4	11.2
0.10	1.0	1.5	2.3
0.40	1.0	1.3	2.1
1.0	1.0	1.8	2.6
2.0	1.1	3.7	4.5
4.0	1.1	11.2	12.0
8.0	1.4	40.7	41.5
10.0	1.6	62.6	63.5
20.0	6.1	248.1	248.9
50.0	24.2	1528.7	1529.5
100.0	55.8	6063.2	6064.0

(a) gas flow rate = 18.9 m^3/s, T = 293 K; P = 1 atm; $\mu = 1.8 \times 10^{-4}$ poise.

(b) ε = fraction of bed filled with ice; F = fraction of ice surface available for sedimentation.

(c) X = mole fraction of gas that is steam; i refers to inlet, o refers to outlet.

Table 10.4 Typical Accident Conditions for ESF Atmosphere Cleanup Systems in Light-Water Cooled Nuclear Power Plants

Environmental Condition	Atmosphere Clean-up System Primary	 Secondary
Pressure surge	Result of initial blowdown	Generally less than primary
Maximum pressure	60 psig (410 kPa)	Atmospheric
Maximum temperature of influent	280°F (138°C)	180°F (82°C)
Relative humidity of influent	100 % plus condensing moisture	100 %
Average radiation level		
For airborne radioactive materials	10^6 rads/hr	10^5 rads/hr
For iodine buildup on adsorber	10^9 rads	10^9 rads
Average airborne iodine concentration		
For elemental iodine	100 mg/m^3	10 mg/m^3
For methyl iodide and particulate iodine	10 mg/m^3	1 mg/m^3

Table 10.5 Current Knowledge for HEPA Filters

Operational Parameters	Extent of Knowledge*			
	New		Aged	
	Normal	Accident	Normal	Accident
Pressure Differential	VG	F	F	NE
Vibration	G	G	NE	NE
High Humidity) Free Water)	F	F	NE	NE
Chemicals	P	P	NE	NE
Radiation	G	F	P	NE
Temperature	G	P	NE	NE
Loading Capacity	G	F	P	NE

* VG = Very Good.
G = Good
F = Fair
P = Poor
NE = Non-Existent.

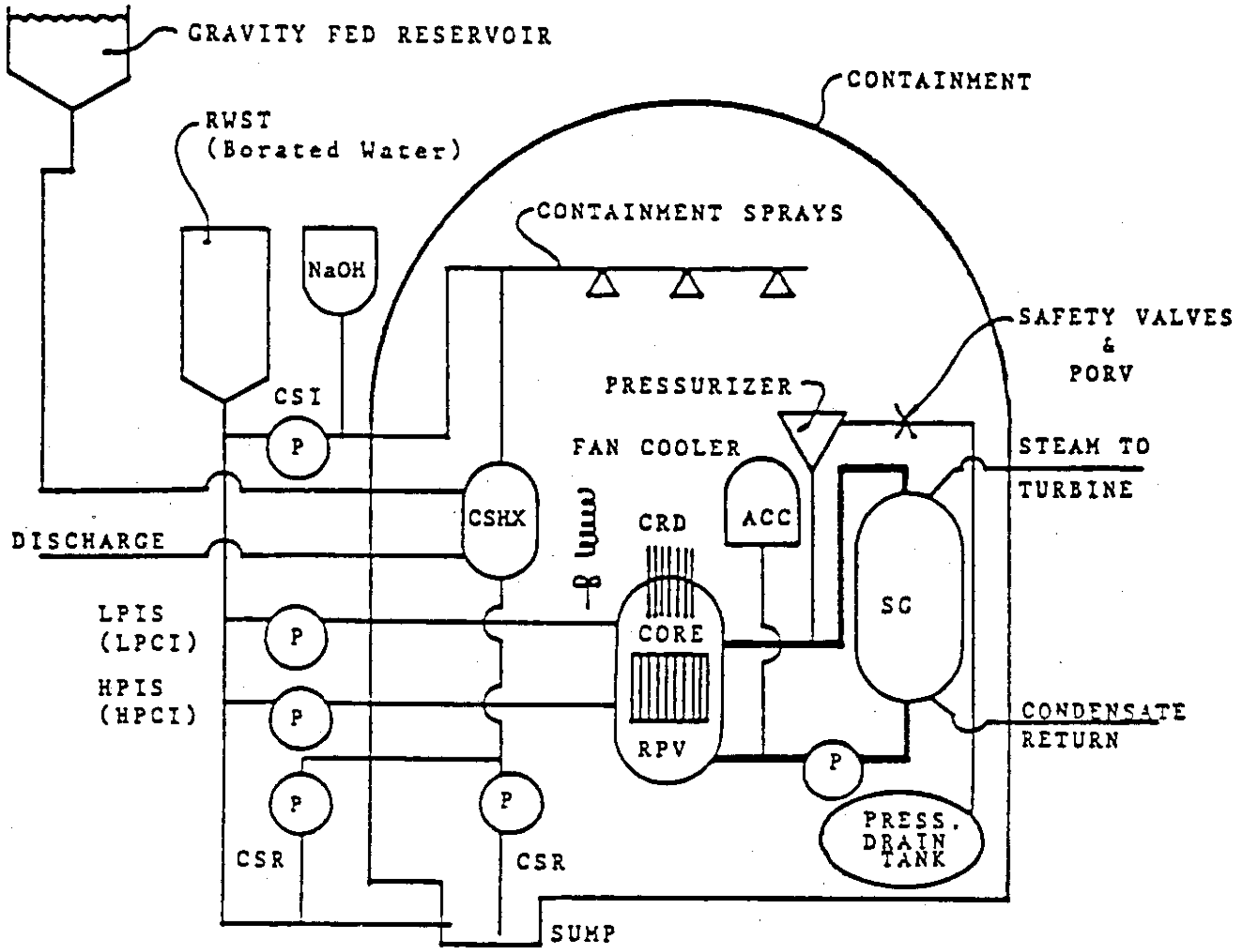
Little is known on any combination of extreme values of these parameters.

Table 10.6 Current Knowledge Regarding Carbon-based Iodine Adsorbers

Operational Parameters	Extent of Knowledge*			
	New		Aged	
	Normal	Accident	Normal	Accident
Pressure Differential	VG	G	G	G
Vibration	VG (USA) P (Others)	VG (USA) P (Others)	NE	NE
High Humidity/Free Water	VG	VG	F	P
Chemicals (Poisoning)	P	P	P	P
Radiation	VG	VG	VG	F
Temperature	VG	G	F	P
Loading Capacity	VG	F	F	P

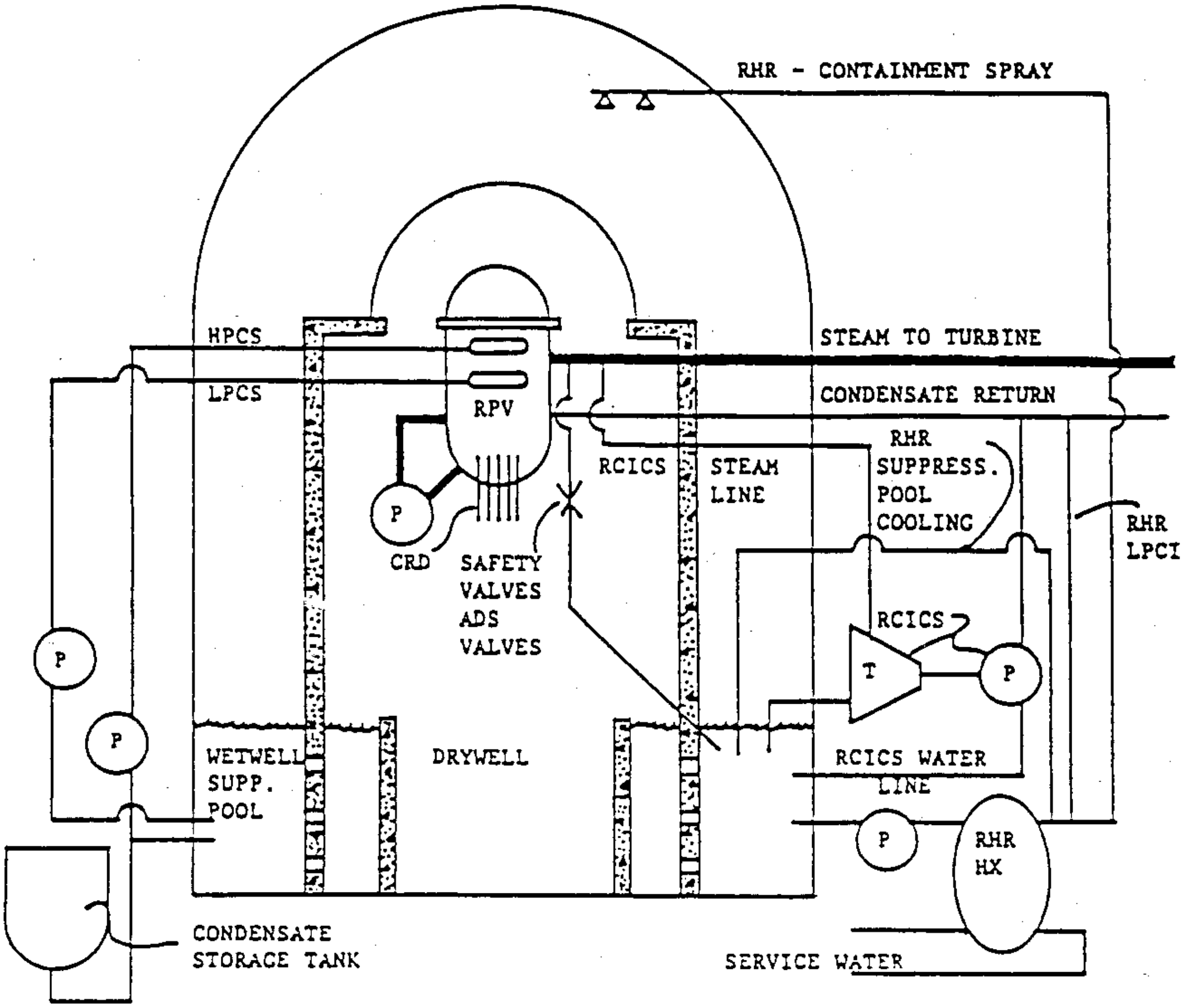
* VG = Very Good
G = Good
F = Fair
P = Poor
NE = Non-Existant.

Little is known about combinations of extreme values of these parameters.



CSI - Containment Spray Injection
LPIS - Low Pressure Injection System
HPIS - High Pressure Injection System
CSR - Containment Spray Recirculation
RWST - Refueling Water Storage Tank
CSHX - Containment Spray Heat Exchanger
RPV - Reactor Pressure Vessel
ACC - Accumulator
PORV - Power Operated Relief Valve
p - Pump
CRD - Control Rod Drives

Fig. 10.1 PWR-ESFs (Reference (2))



HPCS - High Pressure Core Spray
LPCS - Low Pressure Core Spray
P - Pump
RHR - Residual Heat Removal System
HX - Heat Exchanger
LPCI - Low Pressure Coolant Injection
RCICS- Reactor Core Isolation Cooling System
T - Turbine
RPV - Reactor Pressure Vessel
CRD - Control Rod Drives
ADS - Automatic Depressurization System

Fig. 10.2 BWR (Mark-III) ESFs (Reference (2))

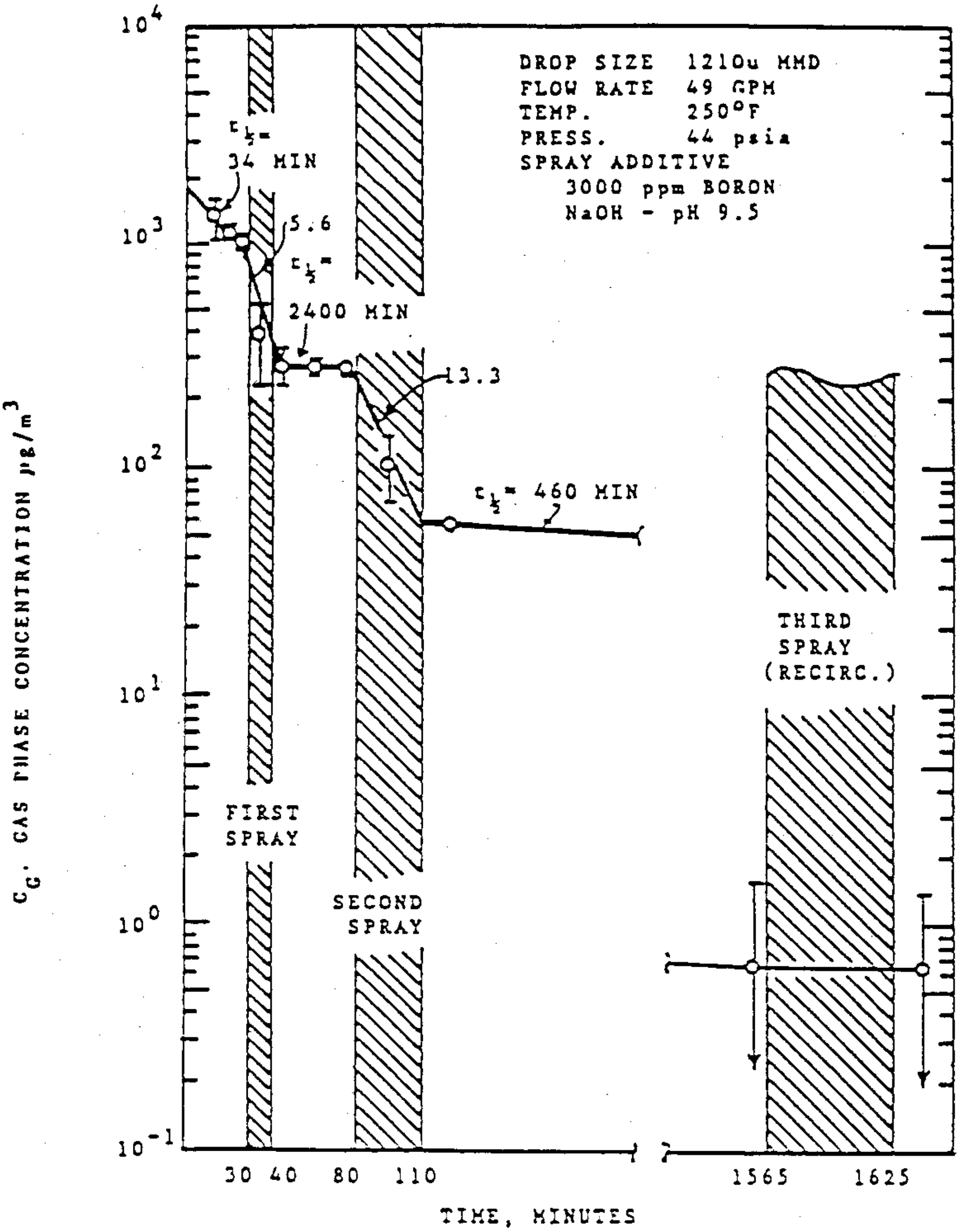


Fig. 10.3 Cesium Removal by Sprays in Containment Systems Experiment (Reference (2))

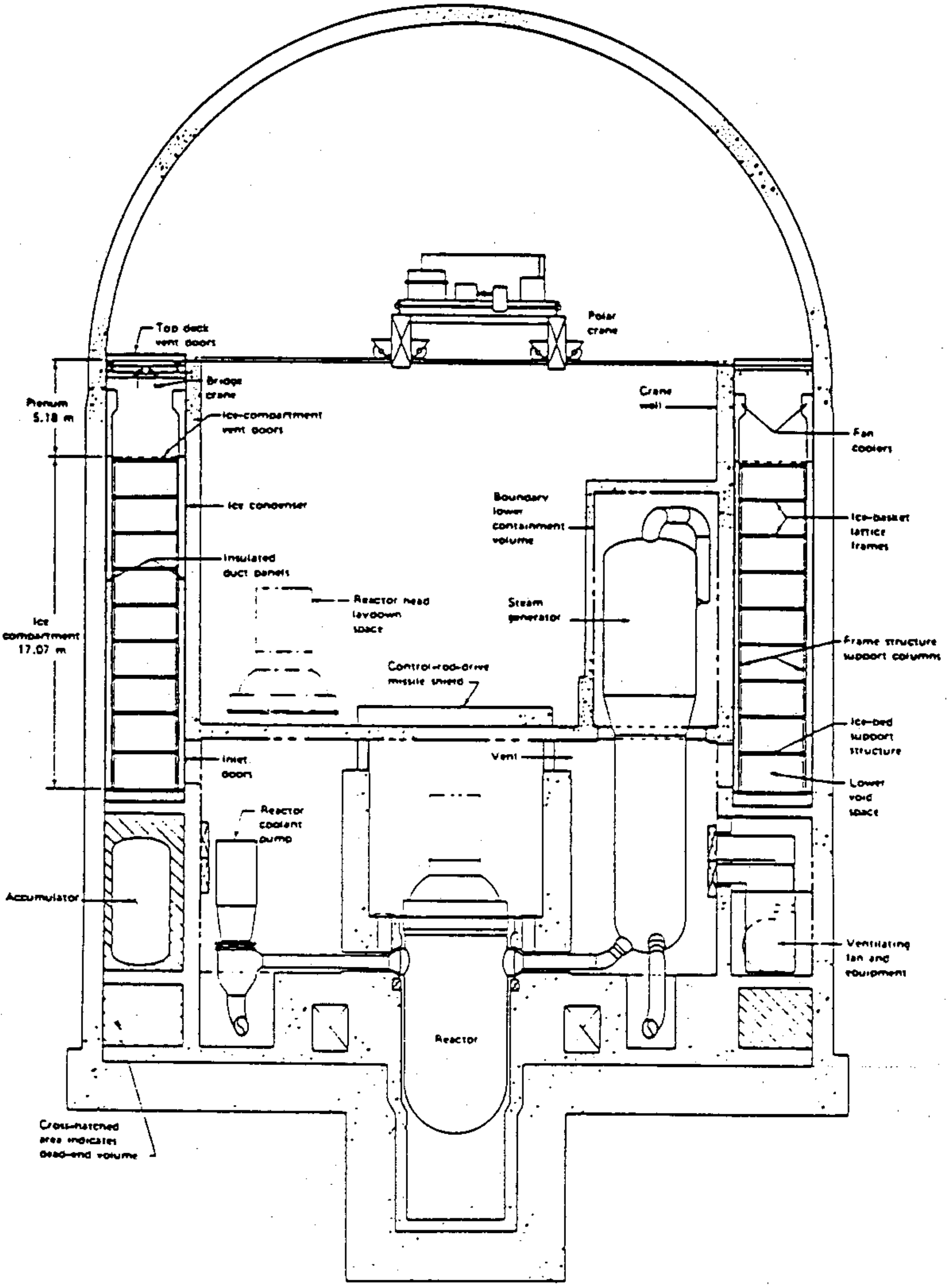


Fig. 10.4 Sectional Elevation View Showing the Ice Compartment and Containment Region Boundaries (Reference (13))

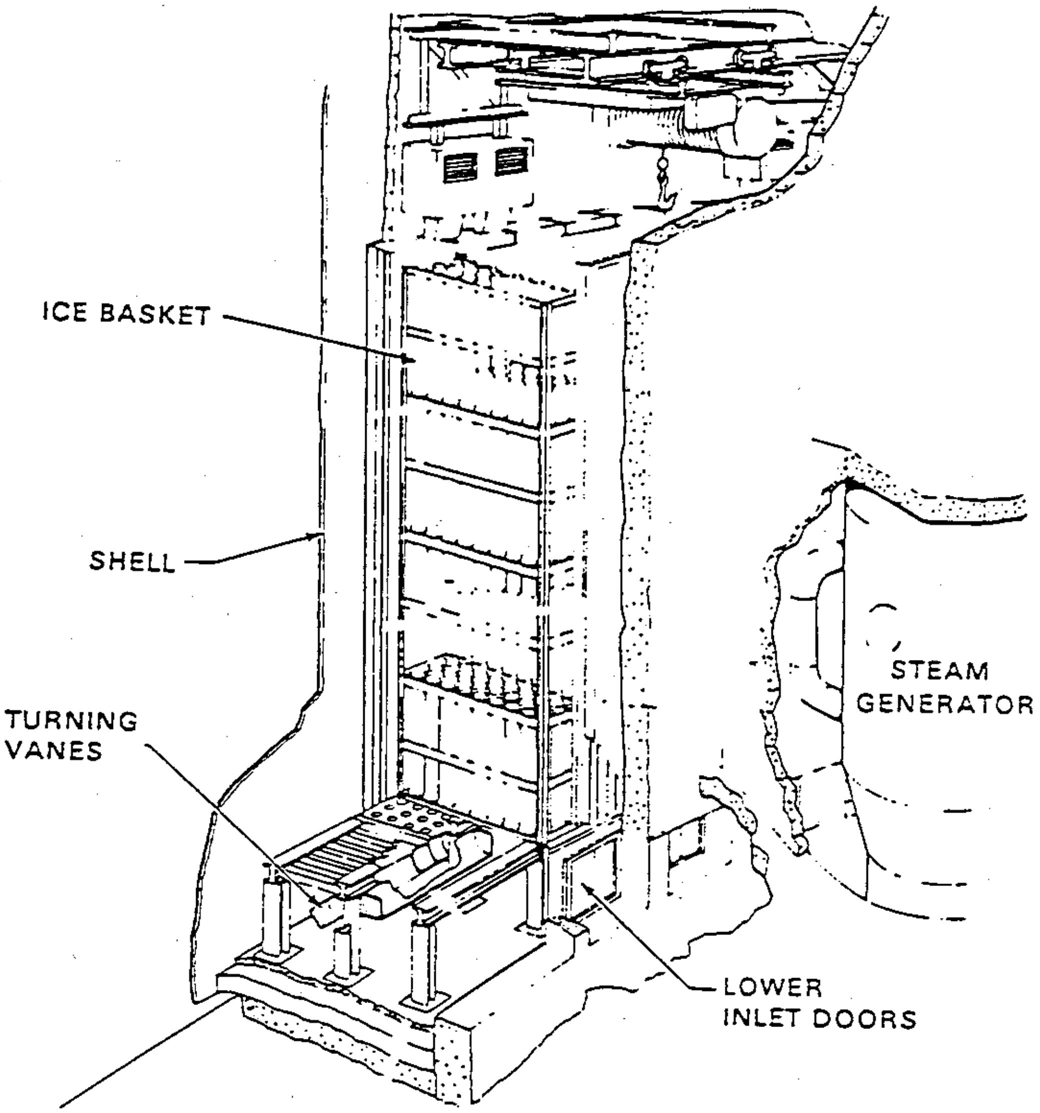


Fig. 10.5 Isometric View of Ice Basket Arrangement (Reference (13))

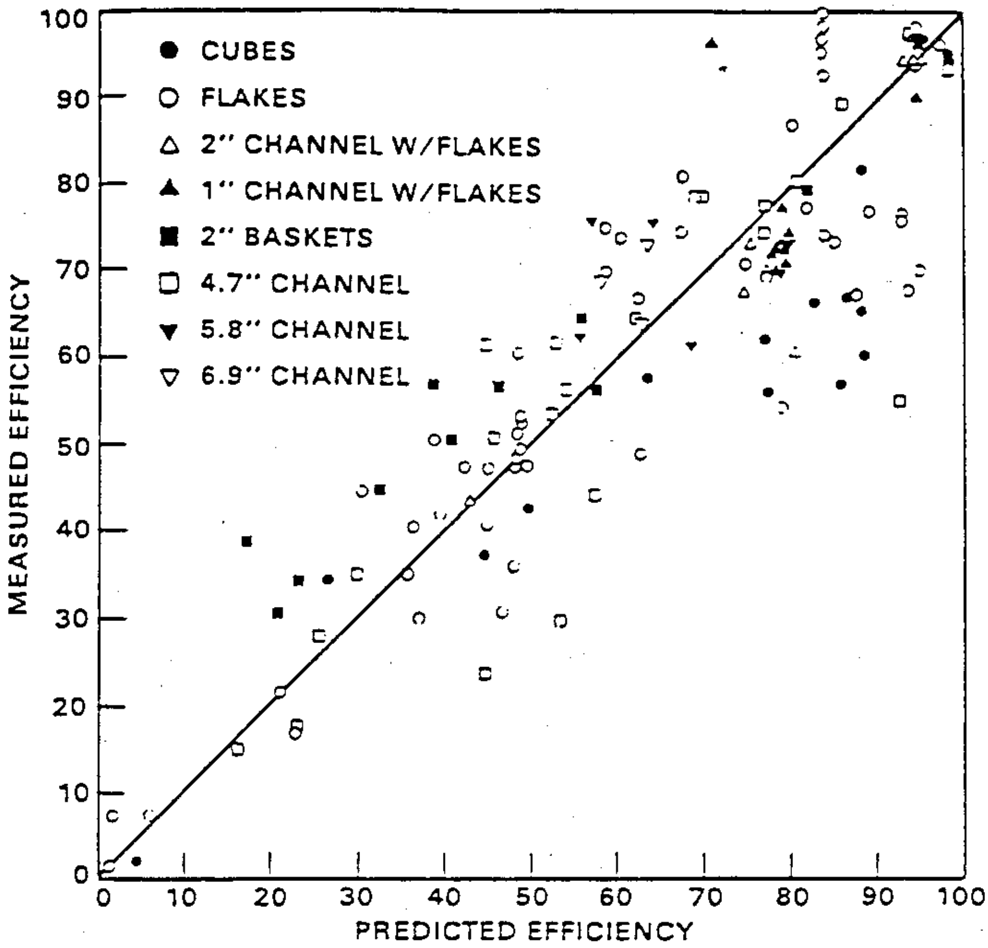


Fig. 10.6 Comparison of Predictions With Measurements of I_2 Removal Reported by Malinowski (Reference (10))

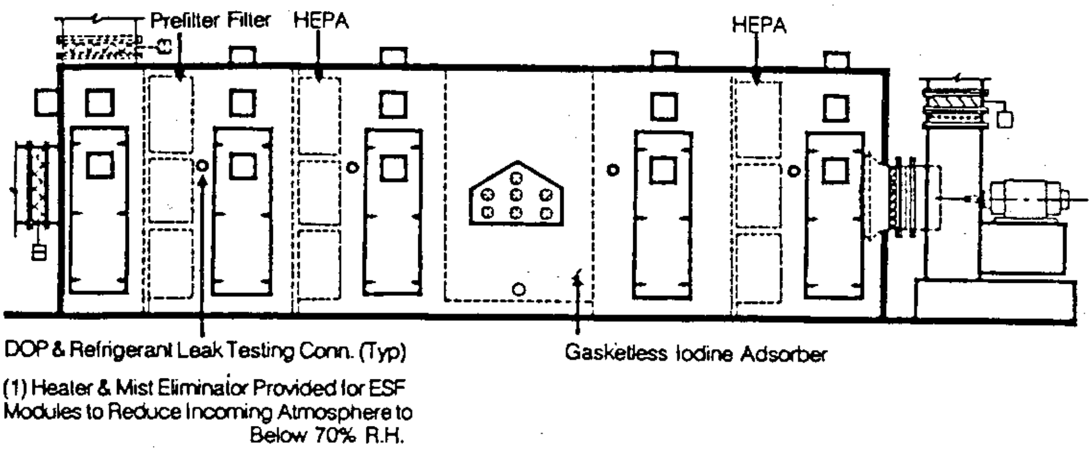


Fig. 10.7 Air Cleanup Unit (Reference (11))

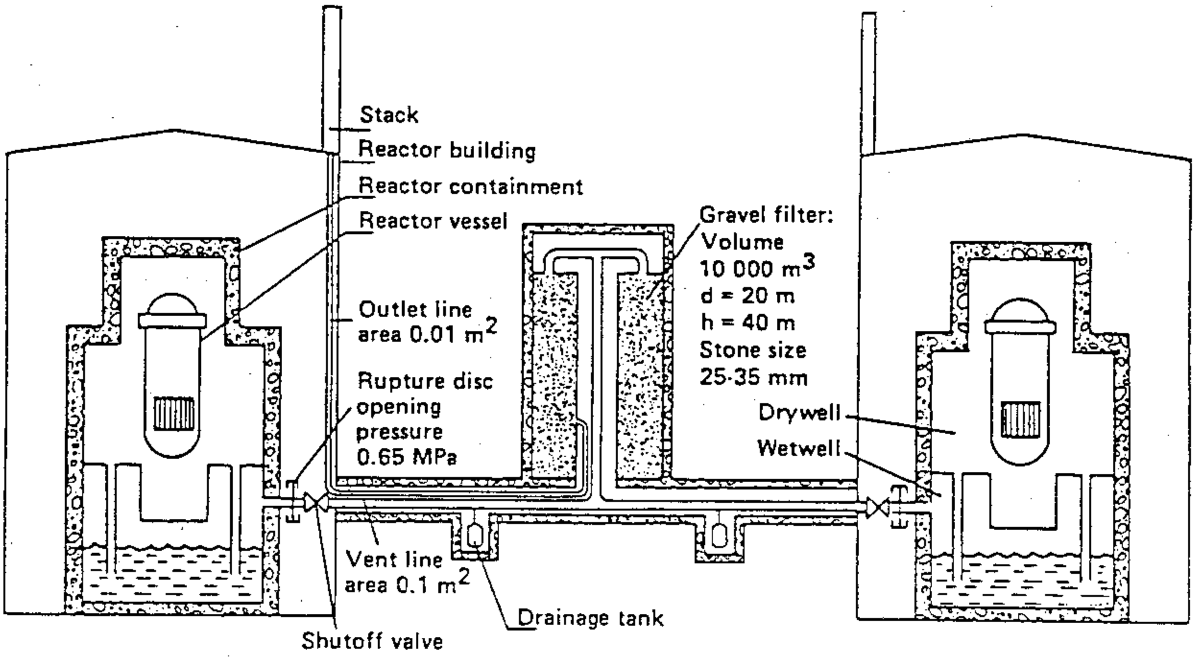


Fig. 10.8 Schematic Drawing Filtered Venting of Reactor Containment (Reference (1))

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付録A　特別タスクフォース構成メンバ

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	R.C. Vogel	(EPRI)	
	M. Silberberg	(NRC)	

付録B　タスクフォース分担一覧

(i)	fission product inventory	H.G. Friederichs
(ii)	fission product release from fuel/aerosols	H.G. Friederichs
(iii)	(a) in-vessel thermal-hydraulics/reactor coolant system thermal-hydraulics	E.F. Hicken
	(b) RCS thermal-hydraulics (relating to fission product transport), core behaviour/RCS failure	B.R. Sehgal
(iv)	RCS fission product transport and chemistry	R.L. Ritzman
(v)	core/concrete interactions and other ex-vessel sources	T.S. Kress
(vi)	ex-vessel thermal-hydraulics	E.F. Hicken
(vii)	fission product/aerosol transport in containment	F. Abbey
(viii)	fission product behaviour in water and long-term effects	D.J. Wren
(ix)	retention in suppression pools	B.R. Sehgal
(x)	engineered safety features	K. Soda
(xi)	steam generator tube failure: included in sub-task (iii) (a)	
(xii)	hydrogen combustion, including equipment survivability and containment integrity	D. Torgerson
(xiii)	steam explosions: included in sub-task (iii) (a)	
(xiv)	regulatory implications, including consequence analysis	G. Petrangeli
(xv)	operator actions	J. Duco
(xvi)	containment performance/leakage	K.O. Johansson
(xvii)	accident sequences and source term ranges	G. Petrangeli