Journal of
NUCLEAR
Technology in Applied Science
ISSN 2314-8209 e-ISSN 2314-8217

J. Nucl. Tech. Appl. Sci., Vol. 6, No. 1, PP. 59 : 69 (2018)

Assessment of Ventilation and Air Cleaning System Design Approaches for Nuclear Safety Requirement during Accidental Conditions in Nuclear Fuel Cycle Facilities

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Received: 19/03/2018
Accepted: 22/04/2018

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ABSTRACT

Safe operation of the nuclear and radiological facilities requires confinement of radioactive and toxic materials involved behind suitable barriers which provide sufficient shielding. This is to minimize the internal and external radiation hazards at prescribed limits to protect plant workers and the environment according to ALARA principle. Most nuclear facilities can expect to have at least one fire accident during its operating life. Such fire events are energized with the potential to damage confinement barriers and transport radioactive materials out of the building. This paper provides and evaluates four different design concepts or safety performance approaches of the ventilation and air cleaning system (VACS) that can be used to achieve safety and adequate protection in nuclear fuel cycle facilities during fire and accidental criticality conditions. The work presents a summary of the recent international requirements for ventilation and air cleaning system protection and a discussion of selected fire protection considerations in designing nuclear facilities. Also, it describes the possible fire protection approaches with their functional classifications and their engineered and administrative safety features. Finally a conclusion of the selection of the best design concept is recommended.

KEYWORDS

Ventilation and Air Cleaning System, HEPA Filters/Sand filters, Fire and Accidental Criticality Conditions, Nuclear Fuel Cycle Facilities.

1. Egyptian Nuclear and Radiological Regulatory Authority (ENRRA).

INTRODUCTION

In nuclear and radiological facilities, there have been numerous events of accidental releases and the spilling of radioactive materials due to mishandling of radioactive materials. This can reduce or eliminate the effectiveness of safety measures. And consequently health hazards for workers and facility operation staff. At least, one of these involved the backward installed of the ventilation and air cleaning systems (VACS) filters which results in the release of radioactive materials to the atmosphere **(Husdal *et al.*, 2009).**

On the other hand, there are two important safety features common to all VACS systems. These are:

a) the requirements to maintain the pressure of the ventilated volume below that of surrounding, relatively non-active areas, in order to inhibit the spread of contamination during normal and abnormal conditions, and b) the need to treat the ventilated gas so as to minimize the release of any radioactive or toxic materials. The goals of the fire protection scenarios are to minimize the potential for:

The occurrence of a fire or related events; A fire that causes an unacceptable on - site or off - site rule of hazardous or radiological material that will threaten the health and safety of employees, the public or the environment; Unacceptable interruptions as a result of fire and related hazards; Property losses from a fire and related events exceeding the prescribed limits ; and Critical process controls and safety class systems being damaged as a result of a fire and related events.

One of the most important tasks of the VACS is to limit the undesirable movement of radioactive material (i.e., contamination) inside and outside the nuclear facility. The normal flow movement is from areas of least, contamination of highest contamination. Filtration systems are used to prevent the contamination from entering exhaust plenums and exiting the building. A schematic diagram for VACS of a nuclear fuel cycle facility is shown in Fig.1. It consists of supply and exhaust systems and the filters are intended to prevent the contamination spread out of the building in the event accidental reverse flow. The High Efficiency Particulate Air (HEPA) filters on the inlet to the exhaust plenum are expected to reduce the contamination entering the exhaust ducts, thus minimizing the buildup of contamination in the exhaust system.

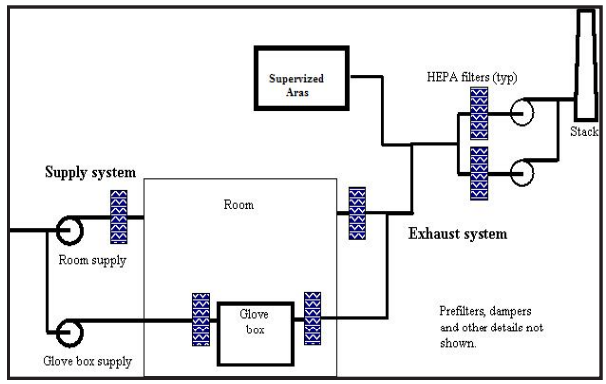

Fig. (1): A Simplified Schematic for VACS in Nuclear Fuel Cycle Facility.

In the nuclear facilities, the supply and exhaust air handling units are selected and balanced to maintain the required air movement to prevent undesired contamination migration. Also, the exhaust system will handle slightly more air than the supply system to account for leakage through doors and building joints. During accident conditions the ventilation systems usually automatically respond to, maintain the required negative pressure differential. If an exhaust fan fails to run, a standby fan will automatically start or supply fans will shut down as necessary. While this is often discussed as maintaining negative pressure differential, it is positive in-flow that is critical. This differentiation becomes very important during a fire where bi-directional flow can occur in doors and openings.

Scope and Importance of the Study

For the VACS system to successfully mitigate radioactive contamination spread during accidental conditions, it will require the following engineering safety requirements:

a) Air handling equipment to maintain the building at a negative pressure during and following the fire

b) Filtration media that allows ventilation flow during and following the fire (i.e., does not plug)

c) Control of the air temperatures approaching the filtration media, to avoid filter media failure by excessive temperature

d) Filtration media that do not collapse as a result of smoke loading during a severe fire.

e) Screens or water sprays that prevent hot brands from damaging the filters

To accomplish the above five requirements efficiently, different design concepts or approaches for the VACS system are proposed as shown in Table 1. One or more approach could be implemented. In the following sections, different engineered and administrative safety design concepts or approaches for the VACS as well as its design requirements have been discussed and evaluated. These concepts can be used to provide adequate protection during a fire and accidental criticality conditions in nuclear fuel cycle facilities e.g. nuclear fuel fabrication plants and radwaste storage facilities.

This work presents, discusses and evaluates different design concepts or approaches for the ventilation and air cleaning system that can be used to provide safety and adequate protection in nuclear fuel cycle facilities e.g. nuclear fuel fabrication plants and radwaste storage facilities, during fire and accidental criticality conditions. This Paper provides a summary of the recent international requirements for ventilation and air cleaning system protection, a discussion of selected fire protection considerations in designing nuclear facilities, and a description of the possible protection concepts with functional classifications, and conclusions on selection of the best design concept. It is the intent of this Paper to provide the regulatory body experts and inspectors of the ventilation system with the background necessary to fully evaluate the ventilation and air cleaning system fire protection design concepts in a nuclear facility. However the Paper is not intended to provide all of the design requirements, but to allow the filter media selection to be based on a comprehensive understanding of the different design concepts.

VACS Design Concept Approaches

In the design of VACS in nuclear and radiological facilities, several automatic responses to fire events are considered. The earliest approach is to shut off the supply air and close inlet dampers when a fire is detected. This has the effect of reducing the airflow through the facility, thus reducing the oxygen supply to the fire and limiting the fire size. If a significant fire size reduction is achieved the temperatures in the fire compartment will drop. The more recent approach is to maintain or increase flow during a fire event. This has the effect of reducing room temperatures and pressure by diluting the heated combustion gases as shown in Figs. (2 and 3). As shown in these figures, it is possible, although undesirable, to optimize the air movement or flow through the building to control the fire compartment temperature and pressure. Table 1, summarizes different VACS concepts and their design features approaches which are proposed and discussed in this paper.

The first concept, in which full dependence on the HEPA filter spray system is considered; reliance on active components could be successful. As mentioned above, the difference between the specified detector temperature range and the filter failure temperature is minimal, thus the system may not activate on demand. This shortcoming is considered a potentially irreconcilable issue representing a very high potential risk. This high risk merits exclusion of this design concept from further consideration. In addition, there are limited test data demonstrating the reliability of this design approach. However, this concept has been approved by the DNFSB **(Zavadoski *et al.,* 2000).**

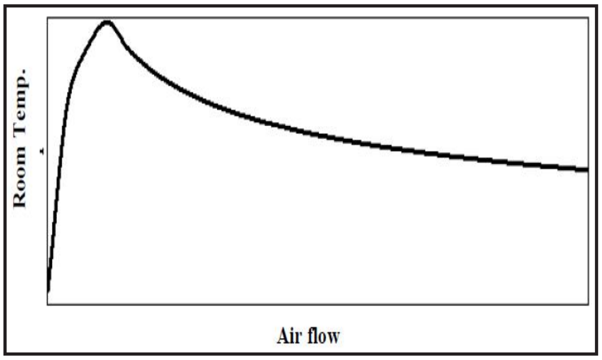

Fig. (2): Ventilation effect on room temperature.

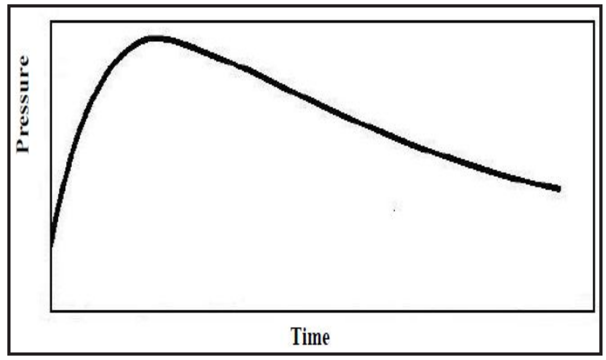

Fig. (3): Ventilation Effect on Room Pressure.

Table (1) : *Proposed VACS Concepts and Their Design Features.*

VACS Concept	Design Features
I	• Full HEPA filters protection and demonstrate that the automatic water spray system reduces the effect of plugging.
II	• Adequate face area to preclude unacceptable plugging during a fire and adequate dilution to preclude excessive temperatures at the filters.
III	• Using safety class building suppression system for preventing fire propagation to more than 3 rooms. Demonstrate that a fire in 2 rooms will not result in excessive temperatures at the HEPA filters, or unacceptable plugging.
IV	• Combined HEPA and sand filter with an exhaust system that is sized to accommodate the design basis fire
V	• Charcoal filter for Radioiodine absorbing combined with the full HEPA filter approach.

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The second concept can be readily constructed. While there is some uncertainty in the smoke plugging data, excess capacity can compensate for this shortcoming. In addition, it is expected that active safety class components may be needed to switch the flow prior to filter plugging. The flexibility of this design is limited and the costs for this concept have not been developed. The major issues that must be addressed by the designers to successfully implement an all-HEPA filter design are Design Data: There is little empirical design data on the performance of HEPA filters during fires. The data available are based on HEPA filters that were fabricated prior to the pricing pressure for clean rooms and DOE budget cuts.

- Life Expectancy: There has been an issue raised on the life expectancy of HEPA filters **(Zavad, 2015).** Resolution of this issue may affect the final design and operating approach for a design based solely on HEPA filtration.
- Active Components: The integrity of the filtration system is dependent on active components to shift airflow between filter sets. The design of these components is expected to require additional effort by the design team.
- Housing Protection: No acceptable method to adequate, reliable fire protection of the HEPA filter housings from direct fire effects has been identified.
- Pre filter Credit: It is possible to credit the pre filters to mitigate the smoke loading on the HEPA filters. If so, the pre filters are expected to be safety class and additional design data would need to be developed.
- Administrative Controls: The reliability of the filtration system is sensitive to the administrative controls that limit transient combustible loading and concept configuration controls to maintain the planned fixed combustible loading. This requirement will require special efforts by the design team and the facility operator.

There are no nuclear fuel cycle facilities that rely on concept 3 (Safety class building suppression system) so the concept has not been reviewed by RB authorities. However, this concept was never fully developed into a final design. Thus, it is uncertain if RB authorities would accept this concept. Based on the lack of demonstrated success using concept 3, the risk is considered very high and further consideration of this Concept is not recommended.

Regarding **concept 4**, it is a successful design concept that is used at multiple nuclear fuel cycle facilities **(Zavad, 2015 and Zavadoski *et al*., 2000).**

The major issues that must be addressed by the designer to successfully implement a combined HEPA filter and Sand filter design are:

- Design Standard: No formal design standard has been published, so it will be necessary for the RB to generate a design basis
- Seismic Qualification: There is limited information on how sand filters perform during earthquakes. The RB will need to generate empirical data and analysis to demonstrate that sand filters will perform adequately during seismic events.

The restricted supply air approach (i.e., ventilation controlled) has several disadvantages. If the flow is not restricted adequately, it is possible that the flow reduction could increase, rather than decrease the fire temperatures. In addition, this approach seldom will extinguish the fire, thus significant smoldering combustion is expected. This type of combustion produces carbon monoxide, rather than carbon dioxide, that has the potential to explosively ignite (i.e., back draft). Thus, while restricting the supply air will often result in a less severe fire, the approach has an inherent instability (i.e., explosion potential) that can cause significant consequences.

The high air supply approach reduces the air temperature, as shown in Fig. 2, in smaller and less severe fires. Thus, the likelihood of these fires growing until they cause measurable contamination releases is reduced. Since such fires are generally anticipated (frequency > 1E-2/yr) **(Wilhelm, 1982),** this is very desirable. This approach is possible because the combustion rate of most fuels is limited by the evolution of combustible gases (i.e., fuel surface controlled). The ventilation has other advantages, these include: removal of smoke allows fire fighters to be more effective, and removal of heat reduces compartment pressure as shown in Fig. 3, and minimizes damage of equipment and containers.

Nuclear fuel processing or reprocessing plants, **concept 5** is a matter of safety concerns, where radioiodine removal either during normal operation or criticality, is performed throughout a combined unit of charcoal and HEPA filter assemblies. Since the aim is to collect all the iodine in one off-gas stream so as not to have to set up numerous iodine removal devices, as much iodine as possible should be removed from the feed solution to the dissolved off-gas. In order to do this, the iodine must be maintained in or converted into the highly volatile elemental form. Radioiodine releases during normal or accidental conditions could be reduced by using of modular and mobile filter units as shown in Fig. 4, which are particularly useful for localized extraction and air cleaning operation.

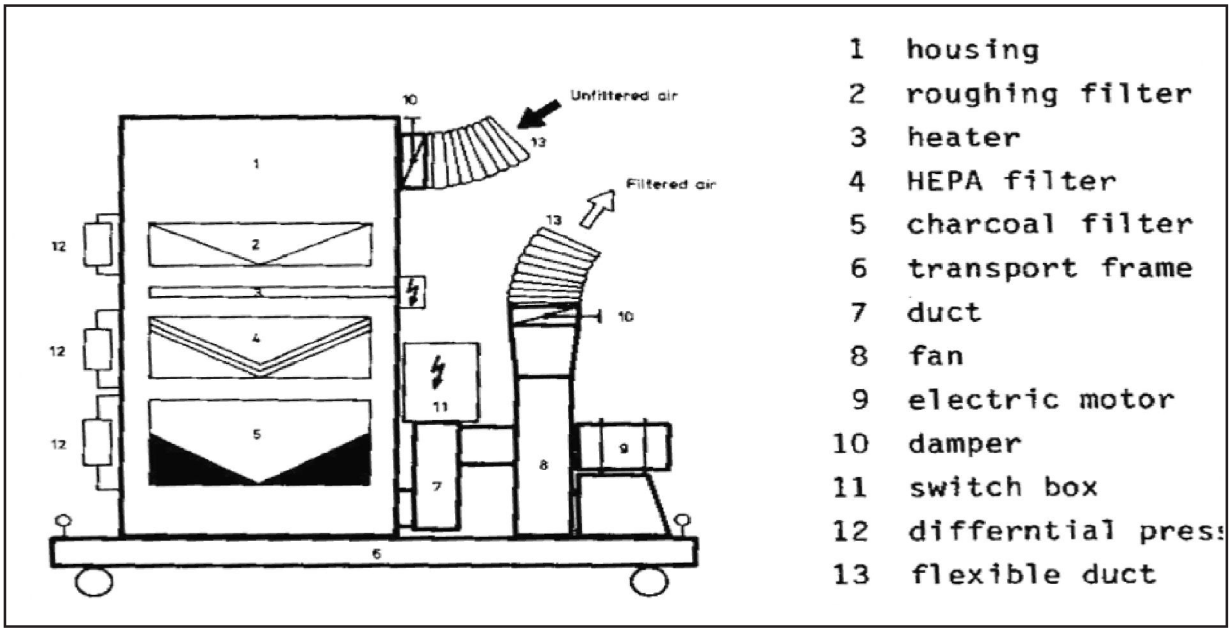

Fig. (4): A Modular and Mobile Filter Unit›s Schematic.

Table (2) : *Summary of Potential Risks for VACS Design Concepts.*

VACS Design parameters	Concept 1: ALL-HEPA	Concept 4: HEPA & Sand Filter	Concept 5: Charcoal & HEPA
State of the art for design concept	-	+	+
Reliableness of the design approach	-	+	+
Extent of design data available	-	+	+
Flexibility of the design	-	+	+
Acceptance by reviewers	-	+	+
Complexity	-	+	+
Extent of passive features	-	+	+
Design standard at component level	+	-	+
System design standard	-	-	-
Seismic integrity fully demonstrated	-	-	+

Table (3) : *Ranking of design features for proposed VACS protective concepts.*

Function	SSC	Item Description	HEPA			Concept 4	Concept 5
			Concept 1	Concept 2	Concept 3	HEPA & sand filter	Charcoal & HEPA
Containment	Building structure	Exterior	SC	SC	SC	SC	SC
		Fire barriers	IS	SC	SC	O-F	O-F
		Fire partitions	O-F	O-F	SC	O-F	O-F
Fire protection	Ventilation	Supply fans	O-F	O-F	O-F	O-F	O-F
		Exhaust fans	SC	SC	SC	SC	SC
		Fire dampers	O-F	O-F	SC	O-F	O-F
		Supply	O-F	SC	OF	O-F	O-F
	Control dampers	Exhaust	SC	SC	O-F	SC	SC
	Ductwork	Internal to building	SC	SC	IS	IS	IS
		External to building	SC	SC	IS	SC	SC
	Filtration	Supply HEPA	SC	SC	SC	SC	SC
		Exhaust	SC	SC	SC	O-F	O-F
		HEPA	…	…	…	SC	…
		Sand filter	SC	IS	IS	…	…
	HEPA	Automatic spray	O-F	O-F	O-F	O-F	O-F
		Manual spray	SC	SC	SC	…	…
		Fire screen	SC	SC	SC	…	…
	Building wide	Demister	O-F	O-F	SC	O-F	O-F
		Sprinkler	O-F	O-F	SC	O-F	O-F
		Detection					
Iodine retention			…	…	…	…	SC
Number of safety class SSCs			10		11	6	6

DISCUSSION AND EVALUATION

Regarding concept 1, this approach provides the utilization of a full HEPA filter protection system as well as the automatic water spray system is used to reduce the effect of plugging. There have been several studies and standards that discuss the protection of HEPA filters by active water spray components. While most demonstrate successful protection, some indicate that water sprays can also accelerate filter plugging. In addition, the seal failure temperature (122°C for urethane) is very close to the upper value of the fire detectors (121°C) **(Herbert, 2015),** so excessive exposure may occur without spray system activation. Thus, the successful protection of HEPA filters by active water spray is problematic. It is possible that these issues can be resolved, but not with high certainty.

During fire accidents, the generated smoke, soot and dust aerosols due to fire will enter the exhaust system and transfer to the filtration system where it will deposit on the filters causing filter plugging. The quantity of smoke generated during a typical multi-room fire is expected to blind most HEPA filter media **(Herbert, 2015).** The blinding can have two possible outcomes. (1) The air movement through the facility is reduced, compromising the negative pressure containment and allowing contamination to leave the building through doors and other openings; or (2) the filter collapse, allowing the contamination to bypass the filtration media and exit the building through the filter plenum. In concept 2, there is an adequate face area of HEPA filter media, to preclude unacceptable plugging during a fire and adequate dilution to preclude excessive temperatures at the filters. The two concepts are very similar and rely on the integrity of the HEPA filters. For both concept 1 and 2, the filter housings must be protected from direct (external) fire effects, since the concepts only provide for internal fire protection. This external protection might be accomplished by redundant parallel trains separated by fire rated construction, high-integrity, automatic fire suppression, or any other high reliability method. Without such protection a fire in the room containing HEPA housing has the potential to allow an unacceptable release.

The philosophy behind concept 2 is very simple. It provides enough HEPA filter face area and any possible fire can be accommodated. To make such a system works some methods or procedure is required to prevent hot brands from damaging the HEPA filters. This could be accomplished by fire screens. It is expected, but not confirmed, that the entire filter bank capacity cannot be on-line at one time, since the efficiency of the HEPA filters will drop for some particle sizes at low flow rates **(Burchsted *et al.*, 2003).** Thus, to make a large face area concept, work it may be necessary to install a switching system to transfer airflow from “plugged” to “clean” filters.

Concept 3 relies on the building safety class suppression system to prevent the fire from becoming too large for the ventilation system to handle. In this approach, fire propagation to more than 3 rooms must be prevented. Demon starting that a fire in 2 rooms will not result in excessive temperatures at the HEPA filters, or unacceptable plugging.

In concept 4, a mix of HEPA, sand filters and exhaust systems that are developed to accommodate the design basis fire accidents. It is a successful design concept that is used at many nuclear fuel cycle facilities **(Zavad, 2015).** With the exception of the exhaust fans, all of the safety class features are passive, thus the concept is very reliable and flexible. Recent cost estimates for an integrated sand filter design are not available. The cost estimates for recent VACS designs have been for standalone attachments to facilities that have multiple stages of HEPA filtration. Thus, the estimates do not show the cost savings associated with reducing the complexity of the ventilation and air cleaning system. This concept will require the fewest number of safety class components to limit the fire risk. The major safety class components would include the building structure, exhaust fans, external ventilation ducts and the filter. With the exception of the exhaust fans all of these components will be passive, thus the system can be considered very reliable.

Concerning concept 5, this concept provides the utilization of radioiodine charcoal filters combined with the full HEPA filter concept. It is demonstrated especially for radioiodine removal in fuel processing plants either in normal operation or during accidental criticality conditions.

To evaluate the above concepts, the importance of the various design features need to be ranked. Several ranking criteria for a functional classification process can be useful. Table 2 provides a ranking of the importance of the design features of the different ventilation concepts. This process identifies the following levels of protective features:

- Safety Class (SC) - controls that reduce the unmitigated public risk to below the evaluation guidelines
- Safety Significant - controls that reduce the unmitigated worker risk to an acceptable level or provide defense-in-depth to a safety class protective feature
- Design Feature - controls that provide for a significant reduction in risk, but are not required to be safety class or safety signs.

In performing this ranking the functional classification level of safety significant and design features were combined into a category considered important to safety (IS). An additional category, Operating Feature (OF) was also created. Features in this category might limit risk but are not required for facility risk to be considered acceptable. There were several features that must be safety classes for all possible concepts. These include the building structure, the exhaust fans, the supply system filtration (or backflow prevention) and the exhaust filtration. This at least five features must be safety class. In evaluating each concept the respective number of SC as shown in Table 2. Thus, the sand filter approach requires the fewest SC features.

In selecting between the different proposed designs concepts, the evaluation metrics are: construction cost, operating cost, and risks. The designers focus on the potential risk metric since cost estimates can be readily developed once the design and operating costs are understood. There are many factors or parameters that contribute to the design risk metric. There are:

- State of the art for design concept
- Reliability of the design approach
- Extent of design data available
- Flexibility of the design
- Acceptance by reviewers and
- Complexity of the design concept

Table 3 summarizes the potential risks for the proposed VACS concepts. In judging complexity of the number and type of protective controls that will be used, it is preferable to use engineered controls (i.e., structures, systems and components, SSC) rather than administrative controls. Where engineered controls are used passive is preferable, since they usually have the greatest reliability. Active controls can be further separated into two sets, those requiring a change of state following the accident initiator and those that do not. The order of preference is thus:

1. Passive SSC (e.g., building structure).
2. Active SSC not requiring a change of state (e.g., continuously operating exhaust fan).
3. Active SSC that must change state after the event initiatory occurs (e.g., emergency generator).
4. Administrative controls.

CONCLUSIONS

This Paper provides and evaluates different design concepts for the VACS system proposed to achieve adequate fire protection of the nuclear fuel cycle facilities:

1. Two approaches are considered viable: an all-HEPA filter system that relies on dilution to prevent excessive temperatures during a fire, and a system that relies on a combination of HEPA filters and a sand filter. The other concepts are relying on the HEPA filter water spray fire suppression system, and a building-wide safety class fire suppression system. Both of these latter concepts are considered to have an unacceptably high potential risk.
2. The all-HEPA filter VACS system concept will require multiple passive and active safety class components to limit fire risk. Some of these would include building structure, exhaust fans, exhaust, filtration, supply filtration (or back-

flow protection), fire screens, and active control dampers redirect flow when filter plug.

3. The sand filter VACS system concept will require the fewest number of safety class components to limit the fire risk. The major safety class components would include the building structure, exhaust fans, external ventilation ducts and the filter. With the exception of the exhaust fans all of these components will be passive, thus the system can be considered very flexible and reliable.

4. Charcoal filters in a modular, mobile and reliable units combined with the all HEPA filter concept could be used in fuel cycle facilities during normal operations and in case of accidental criticality conditions.

5. Both the all-HEPA filter and the sand filter VACS system concepts can be successfully constructed and operated to achieve the desired risk profile. Since both have advantages, the selection between these concepts is best made by balancing construction costs, operating costs and the potential risk.

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مجـلة
التقنيــات النـــوويـــة
فى العلوم التطبيقية
مجلد 6، عدد 1، ص 59 : 69، (2018)

دراسة في تقييم جوانب الأمان لعدد من التصميمات لأنظمة التهوية وتنقية الهواء اللازمة لتحقيق متطلبات الأمان النووي أثناء حوادث الحرائق والحروجية في منشأت دورة الوقود النووي

أحمد حمزة خليفه وابراهيم سليمان ابراهيم وعبد الرءوف جاد الله

تعد الحرائق من الحوادث المحتملة الحدوث في المنشآت النووية وأماكن تخزين المواد المشعة والتي من الممكن أن تؤدى إلى إتلاف أو تدمير هذه المنشآت وبالتالي انتشار المواد المشعة داخل وخارج المنشأة، لذلك فإنه عند تصميم وإقامة هذه المنشآت يتم الأخذ في الاعتبار تزويدها بالوسائل اللازمة لمنع أو تقليل أثار هذه الحرائق.

وحيث إن أنظمة التهوية وتنقية الهواء بالمنشآت النووية من الأنظمة المهمة والمنوط بها العمل على احتواء الهواء الملوث بالمواد المشعة خاصة أثناء حوادث التسرب الإشعاعي (مثل حوادث الحرائق والحروجية) وتنقيته داخل أماكن تداول هذه المواد، فان هذا البحث يقدم بالشرح والتحليل والتقويم عدة نماذج مختلفة لأنظمة تنقية ومعالجة الهواء في المنشآت النووية وأماكن تخزين المواد المشعة لكي تعمل على الوفاء بتقليل أثار الحرائق

والتسرب الإشعاعي في تلك المنشآت. حيث يعتمد النموذج التصميمي الأول كلياً على استخدام مرشحات الهواء ذات الكفاءة العالية (HEPA) مع استخدام رشاشات مياه لتقليل ترسيب أحمال ذرات الغبار على أسطح المرشحات وتقليل درجات الحرارة أثناء الحريق، ويعتمد التصميم الثاني على استخدام وحدات تنقية تتكون من مرشحات الهواء ذات الكفاءة العالية مع استخدام المرشحات الرملية، بينما يعتمد النموذج الثالث على زيادة المساحة السطحية للمرشحات المعرضة لتقليل الإنسدادات نتيجة ترسب ذرات الغبار على مادة وسط الترشيح، مع استخدام تدفق هوائي عالي لتقليل درجات العالية ويعتمد التصميم الرابع على استخدام جميع وسائل الإطفاء الآلية واليدوية المتاحة بالمنشأة وذلك لتحجيم انتشار الحريق بحيث لا تمتد لأكثر من ثلاث حجرات بالمنشأة مع التقليل قدر الإمكان من درجة الحرارة لضمان سلامة المنشأة خاصة مرشحات الهواء ذات الكفاءة.

كما ناقش البحث إمكانية إضافة وحدات متحركة من مرشحات اليود المشع (مرشحات الكربون النباتي) جنباُ إلى جنب مع مرشحات الهواء ذات الكفاءة العالية كنموذج خامس وذلك لاستخدامها عند حوادث الحروجية وخروج نواتج الإنشطار مثل اليود ومركباته حيث كثرت في السنوات الأخيرة الماضية مثل تلك الحوادث في اليابان والاتحاد السوفيتي السابق وغيرها من دول العالم. ويخلص البحث إلى إن استخدام مرشحات الهواء ذات الكفاءة العالية مع المرشحات الرملية هو النموذج الأمثل في التقليل من أثار الحرائق من وجهة نظر الأمان وكذلك من الناحية الاقتصادية حيث يحتاج إلى أقل عدد من أنظمة الأمان للحد أو تقليل مخاطر الحريق.

1. هيئة الرقابة النووية و الإشعاعية.