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Scenarios and Analytical Methods for UF_6 Releases at NRC-Licensed Fuel Cycle Facilities

M. Siman-Tov
J. Dykstra
D. D. Holt
W. P. Huxtable
R. A. Just
W. R. Williams

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U.S. Nuclear Regulatory Commission
Office of Nuclear Regulatory Research
Division of Risk Analysis
Transportation and Materials Risk Branch
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SCENARIOS AND ANALYTICAL METHODS FOR UF_6 RELEASES AT NRC-LICENSED FUEL CYCLE FACILITIES

ABSTRACT

This report identifies and discusses potential scenarios for the accidental release of UF_6 at NRC-licensed UF_6 production and fuel fabrication facilities based on a literature review, site visits, and DOE enrichment plant experience. Analytical tools needed for evaluating source terms for such releases are discussed, and the applicability of existing methods is reviewed. Accident scenarios are discussed under the broad headings of cylinder failures, UF_6 process system failures, nuclear criticality events, and operator errors and are categorized by location, release source, phase of UF_6 prior to release, release flow characteristics, release causes, initiating events, and UF_6 inventory at risk. At least three types of releases are identified for further examination: (1) a release from a liquid-filled cylinder outdoors, (2) a release from a pigtail or cylinder in a steam chest, and (3) an indoor release from either (a) a pigtail or liquid-filled cylinder or (b) other indoor source depending on facility design and operating procedures. Indoor release phenomena may be analyzed to determine input terms for a ventilation model by using a time-dependent homogeneous compartment model or a more complex hydrodynamic model if time-dependent, spatial variations in concentrations, temperature, and pressure are important. Analytical tools for modeling directed jets and explosive releases are discussed as well as some of the complex phenomena to be considered in analyzing UF_6 releases both indoors and outdoors.

1. INTRODUCTION AND SCOPE

The Nuclear Regulatory Commission (NRC), Office of Nuclear Regulatory Research, is sponsoring the Fuel Cycle Facility Safety Research Program for the purpose of developing improved methods for determining and characterizing accidental releases of radioactive materials at NRC-licensed fuel cycle facilities. As part of that program, the NRC Division of Risk Analysis is preparing the ***Fuel Cycle Facility Accident Analysis Handbook*** (AAH) to provide analytical techniques and a data base for preparing realistic accident assessments. The NRC Transportation and Materials Risk Branch has requested that the Engineering Division of Union Carbide Corporation, Nuclear Division (UCC-ND Engineering) assist in developing that handbook by considering UF_6 handling systems. The objectives of this project are (1) to identify and define the major accident scenarios in fuel cycle facilities that involve the release of UF_6, (2) to determine the important parameters and data required for UF_6 release accident assessments, (3) to evaluate available methods for determining source terms for such accident assessments, and (4) to document the above information for inclusion in Chapters 2, 3, and 4 of the AAH.

The accidental release of UF_6 results from the violation of containment of equipment containing UF_6 either by equipment failure or operator error. Once a release occurs, UF_6 and its hydrolysis products may follow one or several of a number of pathways to the outdoor environment depending on the point of release and the design and operating procedures of the facility. Possible UF_6 release pathways to the environment are illustrated in Figures 1 and 2. For example, consider a release from a cylinder that ruptures as a result of being dropped from an overhead crane. The UF_6 would be released into a room where some or all of the UF_6 could be hydrolyzed. If doors are open to the outside, then a release to the environment of at least some of the UF_6 products would occur, and UF_6 and/or its hydrolysis products might also enter the ventilation system. If the ventilation system included filters, some products of a UF_6 release could be trapped, while untrapped products would pass on to the stack and out to the environment.

The scope of this study has been limited to the initial release of UF_6 from containment into a room, steam chest, or the outdoor environment (pathways A, B, C, and D in Fig 1), with some consideration for the behavior after release. Accident scenarios were to be developed from information in the literature

ORNL-DWG-83-16697

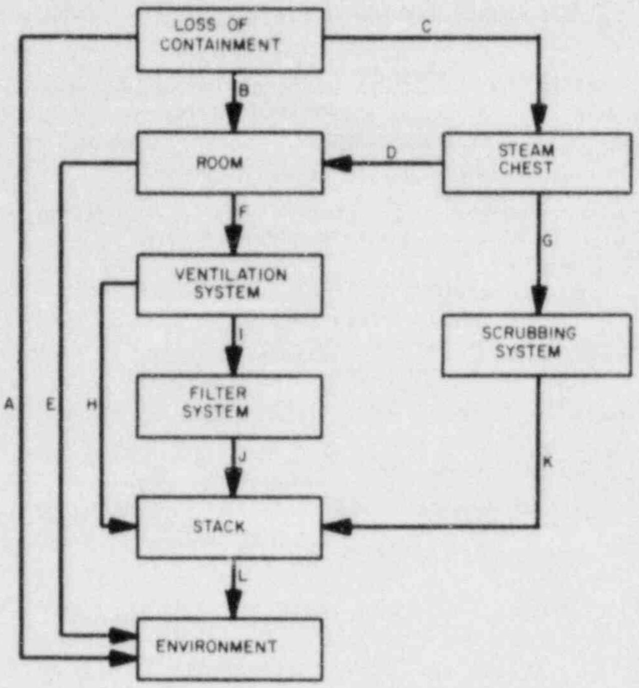

Fig. 1. Schematic diagram of some possible UF_6 release pathways to the outdoor environment.

ORNL-DWG-83-16698

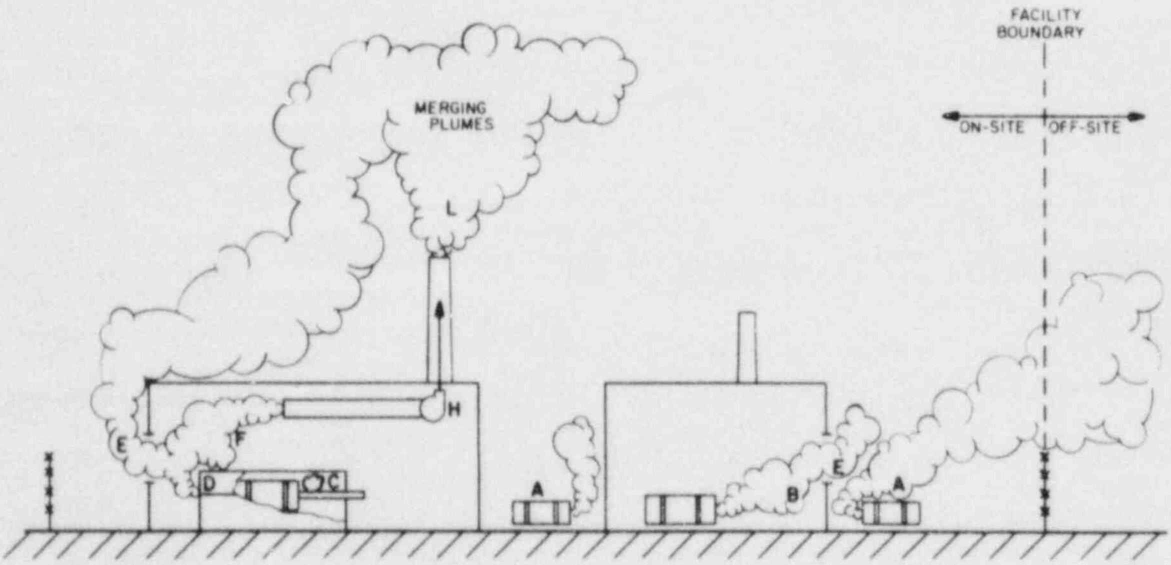

Fig. 2. Diagrammatic representation of some of the UF_6 release pathways shown in Fig. 1. Letters on this figure refer to pathways similarly lettered in Fig. 1.

(primarily documents in NRC docket files for facilities of interest), site visits to NRC-licensed facilities, and experience in DOE uranium enrichment facilities (to the extent that operations and processes are similar in nature to those in NRC-licensed UF_6 production and fuel fabrication facilities). These scenarios were to address major accidents involving UF_6 both inside and outside the buildings but within facility boundaries, exclusive of accidents involving cylinders secured for transport to other facilities. The areas of interest within facility boundaries include outdoor cylinder storage areas, transport to and from storage areas in the plant, UF_6 processing operations, and sampling and transfer operations, The primary accident analysis concern in this study was development of methods for estimating the source term itself including the amount of material released, as well as other source term information necessary to analyze a release. Quantitative analysis of release phenomena and consequences (such as atmospheric dispersion, dose commitments, structural damage, etc.) was beyond the scope of this investigation.

As a part of the Fuel Cycle Facility Safety Research Program, Los Alamos National Laboratory (LANL) and Battelle Pacific Northwest Laboratories (PNL) are developing a large ventilation system model, a compartment model, and a source term model for accidents involving fire and explosion. These areas are excluded from this present study except for a review of the models for their applicability to accidental UF_6 releases.

Several terms have been defined that are required for this study and for subsequent activities. ***Important parameters*** are quantities that must be known or estimated to appropriately analyze an accident and its consequences. An ***event controlling parameter*** is any important parameter that significantly affects the event or the source terms characterizing the event. A small error in an important parameter that is not an event controlling parameter will not significantly affect the consequences of the accident. ***Source terms*** are parameters that define and characterize the release into the affected surroundings. Source terms do not include ambient conditions.

The concept of source term is sometimes confusing because of its application. In the case of a cylinder rupture in a room, the mass, temperature, pressure, and phase of UF_6 in the cylinder at the time of release are source terms for evaluating the amount of UF_6 vapor released from the cylinder, which in turn is a source term for evaluating the mass of UF_6 hydrolysis products and hence room air concentrations. The mass of UF_6 hydrolysis products and air concentrations are source terms for a ventilation system model that calculates source terms for an atmospheric dispersion model.

This report includes the results of the literature review effort, schematic descriptions of typical UF_6 handling systems, a compilation and discussion of credible UF_6 release accident scenarios, and a review of methods for determining source terms for UF_6 release accident assessment. The information provided in this report will serve as a basis for preparing material for inclusion in the AAH.

2. SUMMARY

The objectives focused on in the initial phases of this project were (1) the identification and definition of major accident scenarios in fuel cycle facilities that involve the release of UF_6 and (2) the evaluation of available methods for determining source terms for such accidents. A review of information obtained from eight NRC dockets identified a few accident scenarios considered to be "bounding" cases in some documents. The lack of specified scenarios from NRC sources led to the development of a list of potential major accident scenarios involving the release of UF_6 based primarily on the experience of and studies performed by enrichment facility contractor personnel for the Department of Energy (DOE). Available analytical methods, including codes under development by LANL and PNL for the AAH, were reviewed for their applicability to developing source terms and analyzing accident consequences for UF_6 releases. To bring some perspective to the results of these activities, the scenarios were categorized and discussed in several different ways, which led to a discussion of some bounding considerations for UF_6 releases. Modeling tools needed for analyzing various UF_6 releases were also discussed.

Chapter 3 discusses information from NRC dockets and licensees and presents the findings based on this information. About 7000 pages of NRC documents for eight facilities were searched, including environmental impact assessments and radiological contingency plans. These documents describe only two basic scenarios and contain little useful information for developing accident scenarios involving the release of UF_6. The principal goal of the NRC documents with respect to UF_6 accidents was to consider a bounding event that invariably involved the release of UF_6 from a single cylinder containing liquid UF_6. Cylinder releases may not, however, represent the bounding event with respect to off-site consequences (see Section 7.2). Furthermore, it is interesting to note that several NRC-licensed facilities predict no significant off-site consequences for a postulated multi-ton UF_6 release taking place only several hundred feet from public facilities. Visits to several NRC-licensed facilities, while yielding a few new scenarios, did support the applicability of several UF_6 release accident scenarios.

Descriptions of UF_6 handling systems in both UF_6 production and fuel fabrication facilities are provided in Chapter 4. These descriptions, which include block flow diagrams of principal UF_6 handling operations and a list of equipment and operating conditions, are based primarily on material developed by PNL for NRC's Fuel Cycle Risk Assessment Program.

Major postulated accident scenarios involving the release of UF_6 at NRC-licensed facilities are introduced and discussed individually in Chapter 5 under general headings of cylinder failures, process system failures, criticality events, and operator errors. Because detailed scenario data for accidents involving the release of UF_6 were not found in NRC documents, a greater reliance on DOE experience and site visits to NRC-licensed facilities was necessary than originally anticipated for this project. The credibility, probability, and severity of consequences for each scenario are highly dependent on site-specific factors such as UF_6 inventory, UF_6 phase(s), UF_6 enrichment, facility and site design, operating procedures, emergency procedures, and operator training. The distance to plant boundaries and the off-site population density are important in assessing off-site consequences.

Chapter 6 reviews the applicability of currently available methods for analyzing UF_6 releases. Section 6.1 presents an evaluation of three codes developed for the AAH (TORAC, EXPAC, and FIRAC) with respect to their applicability to accidental UF_6 releases including several DOE methods. Three principal conclusions resulted from this review:

1. At least five areas were identified that must be addressed in the tornado analysis code (TORAC), the explosion code (EXPAC), and the fire analysis code (FIRAC) before they can simulate UF_6 transport without potentially large errors.
2. DOE has concentrated primarily on the simulation of UF_6 releases outside buildings, whereas NRC has concentrated on the simulation of hazardous material transport inside buildings; it is, therefore, believed that both agencies may benefit from an information exchange in these areas.
3. Several methods in the open literature exist that could be modified for estimating the UF_6 release rate from ruptured cylinders.

Chapter 7 has been included to bring some perspective to the scenarios introduced in Chapter 5 and to identify UF_6 release phenomena and analytical tools needed for analyzing UF_6 releases. Uranium hexafluoride accident scenarios are categorized in Sect. 7.1 by location, source, initial phase(s) prior to release, flow characteristics, release causes, initiating events, and inventory at risk. The latter method of categorization is used in Sect. 7.2 as a basis for discussing some bounding considerations for UF_6 release events because an inventory at risk can be defined for systems of equipment separated by batch operations. This discussion leads to the selection of at least three types of UF_6 releases that should be considered further:

1. release from a liquid-filled cylinder outdoors;
2. release from a pigtail or cylinder inside a steam chest; and
3. release indoors from either (a) a pigtail or liquid-filled cylinder or (b) other indoor system, depending on release rate and duration.

It is suggested that generic source terms for the release of UF_6 from pigtails and cylinders be developed because of their applicability to the above releases.

Section 7.3 discusses two general approaches to modeling indoor UF_6 releases as well as an overview of outdoor release phenomena. The two approaches are the use of either a batch-mixed or time-dependent homogeneous mixture model for determining source terms to a ventilation model or a more accurate hydrodynamic model when time-dependent, spatial variations in temperature, pressure, and composition are important. Analytical tools needed to model directed and explosive releases of UF_6 are also identified, and aspects of UF_6-hydrocarbon reactions in the presence of fire or inside a cylinder are briefly discussed.

Chapter 8 presents 28 calculational methods required for either a first-order approximation or a more accurate analysis of a postulated release of UF_6. The applicability of the methods to the scenarios presented in Chapter 5 is given as well as the current availability of those methods.

Conclusions, many of which have been discussed above, are listed in Chapter 9.

References for this study are given in Tables 1 and 4, which may be found in Chapter 3, and in the reference list following the text of this report. A bibliography of other documents relevant to UF_6 source term development is also provided. Uranium hexafluoride release studies, UF_6 physical and thermodynamic data, experimental studies, historical release studies, and other studies are cited in this bibliography.

3. LITERATURE REVIEW

A literature review was conducted to obtain currently available information on accident scenarios and analyses as well as to better understand the UF_6 handling operations at NRC-licensed facilities. This review was supplemented by information on DOE experience in enrichment facilities and by visits to several NRC-licensed facilities.

Documents pertaining to eight NRC-selected facilities including two UF_6 production plants and six fuel fabrication facilities were obtained via several routes. An initial search of the DOE library facilities in Oak Ridge yielded few documents. After requesting assistance from the NRC Project Manager, arrangements were made to inspect NRC-licensing files in Silver Spring, Maryland. This route yielded some useful documents, but time did not permit an in-depth review of all the available material. The NRC Public Document Room was also contacted for information on facilities of interest. A computer printout listing references for all docket materials filed for the selected facilities since 1978 was obtained along with a less exhaustive reference list of pre-1978 materials pertaining to the eight selected facilities. After reviewing these lists, a number of documents were obtained through the Public Document Room. The NRC Project Manager also supplied several requested documents. In total, about 7000 pages of NRC documents were reviewed.

Most information on major accident events was contained in Environmental Impact Assessments (EIAs) or in Radiological Contingency Plans (RCPs). The event usually considered in these documents was the release of UF_6 from a damaged cylinder containing liquid UF_6 or from associated auxiliary equipment. Release quantities postulated varied considerably (23 - 96% of cylinder contents) from one document to another. Although initiating events and detailed accident scenarios were not given, postulated conditions included rupture on heating from prior overfilling or contamination with foreign gas and failure of a cylinder valve or associated piping. Failure of a cold trap in a UF_6 production facility was also postulated to have consequences similar to a cylinder rupture. Table 1 lists dates of the most recent EIAs and RCPs for facilities of interest as well as sections of those reports that discuss accidents involving the release of UF_6. The EIAs and RCPs reviewed did not contain details of the analyses performed, although chemical and radiological exposures to individuals at several locations (e.g., nearest resident) were given in several reports.

Table 1. References to postulated UF_6 release accidents and criticality events found in environment impact assessments and radiological contingency plans

		Environmental Impact Assessment		*Radiological Contingency Plan*	
Facility and location	Docket number	Date published	Applicable sections	Date published	Applicable sections
UF_6 production					
1. Allied Chemical Metropolis, IL	40-3392	8-77	6.1.2, 6.1.3, 6.2.2	6-81[a]	3.1, 3.3
2. Kerr-McGee Gore, OK	40-8027	10-77	None	3-82	3.3
Fuel fabrication					
3. Combustion Engineering Hematite, MO	70-36	9-81	5.2.2, 5.3.2	1-82	3.1
4. Babcock & Wilcox Apollo, PA	70-135	10-78	6.2.3	8-81	None
5. Nuclear Fuel Services Erwin, TN	70-143	1-78	None	6-81[b]	None
6. General Electric Wilmington, NC	70-1113	6-75	None	1-82[c] Appendix G	3.3.3 &
7. Westinghouse Columbua, SC	70-1151	4-77	None	8-81[d]	None
8. Exxon Richland, WA	70-1257	8-81	5.2.1	8-81[e,f] 11-81[g]	None

Other documents

9. *Supplemental Environmental Information Related to Installation of Uranium Hexafluoride Conversion Capability, B&W Commercial Nuclear Fuel Plant Expansion, Lynchburg, Virginia,* BAW-1412, Annex (Draft), Battelle Pacific Northwest Laboratories, Richland, Washington, June 1976, Sects. 5.3 and 5.4.
10. *Potential Radiological and Chemical Toxicity Consequences of an Accidental UF_6 Gas Release in the Exxon Nuclear UO_2 Plant,* XN-NF-562, Exxon Nuclear, Inc., April 1981.
11. *Radiation Control at NFS-Erwin and Generic Considerations for Other Fuel Cycle and Materials Plants,* SECY-80-519, Nuclear Regulatory Commission, November 24, 1980.
12. *Environmental Survey of the Nuclear Fuel Cycle,* USAEC, November 1972, pp. E-32 to E-34.
13. C. M. Vaughn (GE, 70-1113), letter to NRC Director (to attention of W. T. Crow), Attachment 1, June 1, 1981. (Letter Subject: "Modification 2 to Application Amendment N-2, Expansion of Plant Conversion Capacity", 12-21-79).

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[a] Updated 1-82.

[b] Updated 3-82 and 4-82.

[c] Titled as *Radiological Contingency and Emergency Plan.*

[d] Titled as *Emergency Plan.*

[e] Titled as *Emergency and Radiological Contingency Plan.*

[f] Rev. 10 of Part I.

[g] Rev. 6 of Part II.

Several other documents containing analyses of postulated UF_6 releases are also listed in Table 1. Table 2 tabulates available information on postulated releases, including total UF_6 released, release duration, and other assumptions.

Two criticality events were postulated by General Electric (GE). In their Radiological Contingency and Emergency Plan (1-82, paragraph 3.3.3 and Appendix G), a criticality event is postulated to result from the introduction of UF_6 into a vessel containing water when the uranium enrichment exceeds the design basis enrichment. A letter from C. M. Vaughn (GE) to the NRC Director (June 1, 1981) included a complete criticality safety analysis for UF_6 cylinders in steam autoclaves based on 5% ^{235}U enrichment. Additional details of these postulated criticality events are given in Table 3 while additional reference information is given in Table 1.

Reported historical releases at facilities of interest ranged from much less than a pound to over 100 lb of UF_6. Several documents reporting these historical events are listed in Table 4. These events involve pigtails, valve seal or other valve failures, and piping gasket failures occurring in UF_6 feed vaporization areas of fuel-fabrication fabrication facilities and distillation sections and cold trap systems of UF_6 production facilities. Table 5 gives information on reported historical releases of UF_6.

Most other NRC documents that were reviewed did not contain information on postulated or historic UF_6 accidents; however, several documents repeated information contained in the documents noted above. These other documents included safety evaluation reports, radiological assessments of individual dose from routine operations, a health and safety manual, several emergency procedures predating the RCPs, and various licensing applications and renewals for the fuel fabrication facilities. In general, little information useful for estimating UF_6 release source terms for inclusion in the AAH was found in the eight NRC dockets searched.

Review of the NRC and NRC-licensee documents did not result in a comprehensive list of credible UF_6 release events. This was generally the result of the NRC and the licensees concentrating their efforts on postulating what they considered to be bounding UF_6 release accidents. Uniformly, the rupture of a cylinder containing liquid UF_6, either inside or outside a facility (but not both locations), was considered by NRC and their licensees to be a bounding UF_6 release event. Cylinder releases may not, however, represent

Table 2. Postulated UF_6 release events documented for NRC-licensed facilities

Event	Licensee and docket no.	UF_6 released (lb)	Release duration (min)	Av rate of release (lb/min)	Phase of UF_6 source	Other assumptions	Refs Table 1
Rupture of a 10-ton cylinder	Allied 40-3392	9200			Vapor	Temperature > 149°F UF_6 reacts totally with moisture in ambient air Released outside bldg	1. EIA
Rupture of a 10-ton cylinder or cold trap	Kerr-McGee 40-8027	4500	50	112	Vapor	1.5-in. hole in cylinder 100% of release in bldg leaves through roof vent Cylinder cooled with water spray to minimize release	2
Rupture of a 2.5-ton cylinder	GE 40-113	4800	long		Solid	Bounding release outside facility	6
Release of highly enriched uranium from a 16-kg cylinder	NFS 70-143	33				Particle size = 5 μm (3 μm AMAD) UF_6 reacts with water in atmosphere Highly enriched material	11
Valve or line failure of a cylinder being unloaded	Combustion 70-36	1200	15	80	Vapor/ solid	22% of cylinder contents released as vapor UF_6 reacts totally with moisture in ambient air	3, EIA
UF_6 transfer line leak	B&W	85–140	15–25	5.7	Vapor	Total UF_6 release in building goes to the environment Cylinder maintained at 212°F during release 1-in. line releases UF_6 at a rate of 340 lb/h	9

Table 2. (continued)

Event	Licensee and docket no.	UF_6 released (lb)	Release duration (min)	Av rate of release (lb/min)	Phase of UF_6 source	Other assumptions	Refs Table 1
Vaporizer line break inside	Exxon 70-1257	1100 (inside)				10% of UF_6 released inside is released to the environment	10
		110 (outside)	3	37		Rapid release to the environment via exhaust stack or out of building at ground level 5 wt % ^{235}U HF concentration outside at least ten times airborne uranium concentration UF_6 reacts totally with water vapor in air to produce UO_2F_2 at point of release to the environment	
Release from 2.5-ton cylinder inside an evaporator	B&W	50			Vapor	1% of cylinder contents is released to the environment Release via pressure relief valve and UF_6 scrubber, both of which function properly Evaporator temperature = 212°F	9

Table 2. (continued)

Event	Licensee and docket no.	UF_6 released (lb)	Release duration (min)	Av rate of release (lb/min)	Phase of UF_6 source	Other assumptions	Refs Table 1
Release from 2.5-ton cylinder inside an evaporator	B&W 70-135	2965 (evaporator) (258 lb UO_2F_2 to building)	50	18 lb/min of UO_2F_2 initially to environment		10% of UF_6 released vents to work area Fans without HEPA filters will not stop during release to work area 50% of release will deposit on building floor Rate of release to environment decays with time (half-life constant = 301 s) All UF_6 released reacts with water vapor in building air prior to release to the environment More than half of UO_2F_2 aerosol will deposit	4
Overfilled 2.5-ton cylinder	Generic fuel fabrication	1540 (inside) 15 (outside)	35	44		1% of released uranium escapes building 10% of HF formed escapes building HEPA filter plugs resulting in a slow release to the rest of the building	12

Table 2. (continued)

Event	Licensee and docket no.	UF_6 released (lb)	Release duration (min)	Av rate of release (lb/min)	Phase of UF_6 source	Other assumptions	Refs Table 1
Fire in cylinder storage area (cold storage)	B&W	555-2775	2.5-12.5	222	Vapor	Twelve 30A cylinders per 1000 ft^2 of concrete pad Truck crashes into cylinders releasing 100 gal of gasoline Truck ruptures two 2.5-ton cylinders Gasoline distributed over ⅓ of pad and burns 2.5 to 12.5 min Radiative heat transfer coefficient for a 2000°F fire and an 80°F cylinder = 32.4 $Btu/h\text{-}ft^2\text{-}°F$ Heat flux at 10 ft from center of 20-ft diameter pool of burning gasoline = 0.25 times the radiative heat transfer coefficient The cylinder-fire temperature difference = 1780°F, resulting in 6500 Btu/min of absorbed heat per cylinder	9
Tornado-induced release	B&W	4750	720	6.6		Tornado shears line from UF_6 evaporator All released UF_6 reacts with water in atmosphere to form UO_2F_2 particulates of <10 μm size	9

Table 3. Postulated criticality events involving UF_6

Event	Licensee and docket no.	UF_6 released (lb)	Release period (h)	Other assumptions	Refs, Table 1
Criticality due to high enrichment UF_6 introduction into vessel containing water	GE 70-1113			10^{18} fissions per event Vessel not safe for high enrichment UF_6 Volatile noble gases and iodines released	6
Steam autoclave criticality	GE 70-1113	Variable	<40	5% ^{235}U enrichment Water accumulates in annulus (>92 gal) or inside cylinder (>41 gal) following loss of containment	13[a]

[a] Information was taken from a complete criticality safety analysis for steam autoclaves in the GECO system.

Table 4. Documents reporting historical accidents

Preliminary Notices of Event or Unusual Occurrences

Facility	*Notice no.*	*Date*
1. GE	PNO-II-80-92	5-22-80
2. GE	PNO-II-81-76	9-16-81
3. Westinghouse	PNO-II-80-54	4-07-80
4. Westinghouse	PNO-II-80-133	7-31-80
5. Westinghouse	PNO-II-80-135	8-04-80
6. Exxon	PNO-V-82-11	2-26-82

Other documents

7. EIA for Allied Chemical, 8-77, Sect. 6.1.2.
8. A. L. Kaplan to J. T. Sutherland (NRC), January 19, 1979, letter and attachment.
9. *Radiation Control at NFS-Erwin and Generic Considerations for Other Fuel Cycle and Materials Plants*, SECY-80-519, Nuclear Regulatory Commission, Nov. 24, 1980.

Table 5. Summary of historical accidents involving UF_6 at selected NRC-licensed facilities[a]

	Licensee and docket no.	Date of release	UF_6 released (lb)	Cause	Refs. Table 4
1.	Allied 40-3392	12-6-68	95	Valve failure in UF_6 distillation section	7
2.	GE 70-1113	12-3-78	not known	Main line block valve opened after nitrogen purge	8
3.	NFS 70-143	8-7-79	< 6.6	Accidental venting of cylinder to exhaust stack	9
4.	GE 70-1113	5-20-80	< 2.2	Pipe flange failure	1
5.	GE 70-1113	9-15-81	< 163[b]	Flange gasket leak	2
6.	Exxon 70-1257	2-25-82	55[b]	Softening of Teflon seal on conversion line #1 vaporization chamber	6
7.	Kerr-McGee 40-8027		100	Overheated Teflon gasket while melting UF_6 in cold trap drain system	c

[a] Several nuisance releases of a few grams involving pigtail connections or removal of UF_6 plugs from pigtails are not listed (Table 4, Refs. 3, 4, 5).

[b] Most of the UF_6 released may have been collected by the ventilation cleanup system.

[c] Identified during site visit.

the bounding event with respect to off-site consequences. Other types of accidents were not postulated, although several lesser historical accidents have been documented. Apparently, only a few of the NRC licensees have released documentation of detailed calculations of the analysis of their bounding UF_6 release accidents. Other references useful to this study but not included in Tables 1 and 4 are provided in the bibliography for completeness.

Because detailed scenario data for accidents involving the release of UF_6 were not found in NRC documents, a greater reliance on DOE experience and site visits to NRC-licensed facilities was necessary than originally anticipated for their project. Project team members who have significant UF_6-related experience and who have participated in safety analyses of the DOE uranium enrichment facilities provided the greatest amount of information on potential accidents involving UF_6. Based on this experience, possible UF_6 accidents in UF_6 production plants and fuel fabrication facilities have been postulated (see Chapter 5).

After reviewing the NRC dockets for the eight NRC-selected facilities and gathering a list of potential accident scenarios involving the release of UF_6, it was decided that visits to several NRC-licensed facilities would be made. The purpose of the visits was to gain a greater familiarity with these facilities and to expand and/or confirm the list of potential UF_6 release scenarios for NRC-licensed facilities.

During the visits, it was noted that there is a variety of site specific factors that can strongly affect the potential for a UF_6 release. For example, tornadoes and high winds can be important safety considerations at some sites. Also, site specific designs and operating procedures very strongly affect the potential for UF_6 releases.

Informal discussions were held with operating and management personnel to develop or establish the credibility of scenarios that could result in significant UF_6 releases, but few new scenarios were identified. It was apparent from discussions and observations during these visits that the NRC licensees have adopted several engineering features to help prevent UF_6 releases. For example, legs were added to UF_6 cylinder carriages to prevent cylinder dropping in the event of carriage axle failure. From discussions with NRC licensees, it was concluded that features such as this resulted from an informal sharing of UF_6 release experience among fuel cycle facilities.

Discussions with licensees revealed no major UF_6 release; however, several minor releases not found through the literature review were mentioned. A release of about 100 lb of UF_6 resulted from the overheating of a Teflon gasket when an operator was attempting to melt UF_6 that had solidified in a cold trap drain system. In another incident, a cylinder valve was sheared off a cylinder containing solid UF_6. Since the cylinder contained solid UF_6, the amount of UF_6 released in the latter incident was very small.

At several sites, cold traps are elevated 10 to 15 ft above the plant floor; therefore, a seismic release scenario during a heating cycle may be plausible. At one facility where there is a potential for high wind or tornado damage, a special plant shutdown policy has been instituted to minimize the potential for a serious UF_6 release during periods when these conditions are likely.

Pigtail reliability was a major concern at one facility where each pigtail is replaced after using it to empty, at most, 15 cylinders. At a facility handling highly enriched material, criticality was a concern which led to the use of electrical heating for UF_6 feed vaporization; however, other facilities that handle highly enriched material use steam heat. Automatic UF_6 leak detection methods for enclosures where a UF_6 release might not be immediately evident to operators were of interest at UF_6 handling facilities.

Of major interest on one visit was a discussion about UF_6 release management goals. One goal of UF_6 release management might be to contain any UF_6 release inside a building. This goal is, however, in conflict with another possible goal of minimizing worker exposure within a process building to UF_6 and its hydrolysis products. Depending on the goal desired, various UF_6 handling facilities could develop quite different safety system designs, ventilation requirements, emergency procedures, etc.

4. DESCRIPTION OF UF_6 HANDLING SYSTEMS

Uranium hexafluoride is currently handled in three phases of the commercial nuclear fuel cycle: UF_6 production, uranium enrichment operations, and fuel fabrication. In this section, we are concerned with describing UF_6 operations at UF_6 production and fuel fabrication facilities licensed by NRC. Additional UF_6 handling process information can be found in a recent PNL report describing representative nonreactor facilities.[1]

4.1 UF_6 PRODUCTION FACILITIES

There are only two major UF_6 production facilities licensed by NRC. These facilities are located near Metropolis, Illinois, and Gore, Oklahoma, and are operated by Allied Chemical and Kerr-McGee, respectively. The handling of UF_6 at these two facilities differs significantly; the chief difference involves uranium purification. The Kerr-McGee facility uses solvent extraction to purify the uranium before fluorination, and the Allied facility uses distillation to purify the uranium as UF_6 after fluorination. These facilities served as generic models for the PNL report. A process flow diagram for UF_6 handling operations based on the fluorination - fractional distillation process is presented in Fig. 3 and another, based on the solvent extraction process, in Fig. 4. The various operations shown in Figs. 3 and 4 are discussed in subsequent paragraphs.

A summary of important parameters including UF_6 temperatures, pressures, inventories, and phase as well as numbers of vessels for UF_6 production facilities and fuel fabrication facilities is presented in Table 6. With the exception of cold product cylinders, UF_6 is handled at pressures ranging from slightly above atmospheric pressure to over 5 atm. These pressures help prevent inleakage of moist air that would react with UF_6 to roduce a UO_2F_2 deposit that could plug equipment and increase release potential.

4.1.1 Fluorination

Solid UF_4 is reacted with F_2 gas to produce UF_6 gas in this first UF_6 handling step. Process temperatures and pressures used in the two processes are similar. The fluorination-fractional distillation process

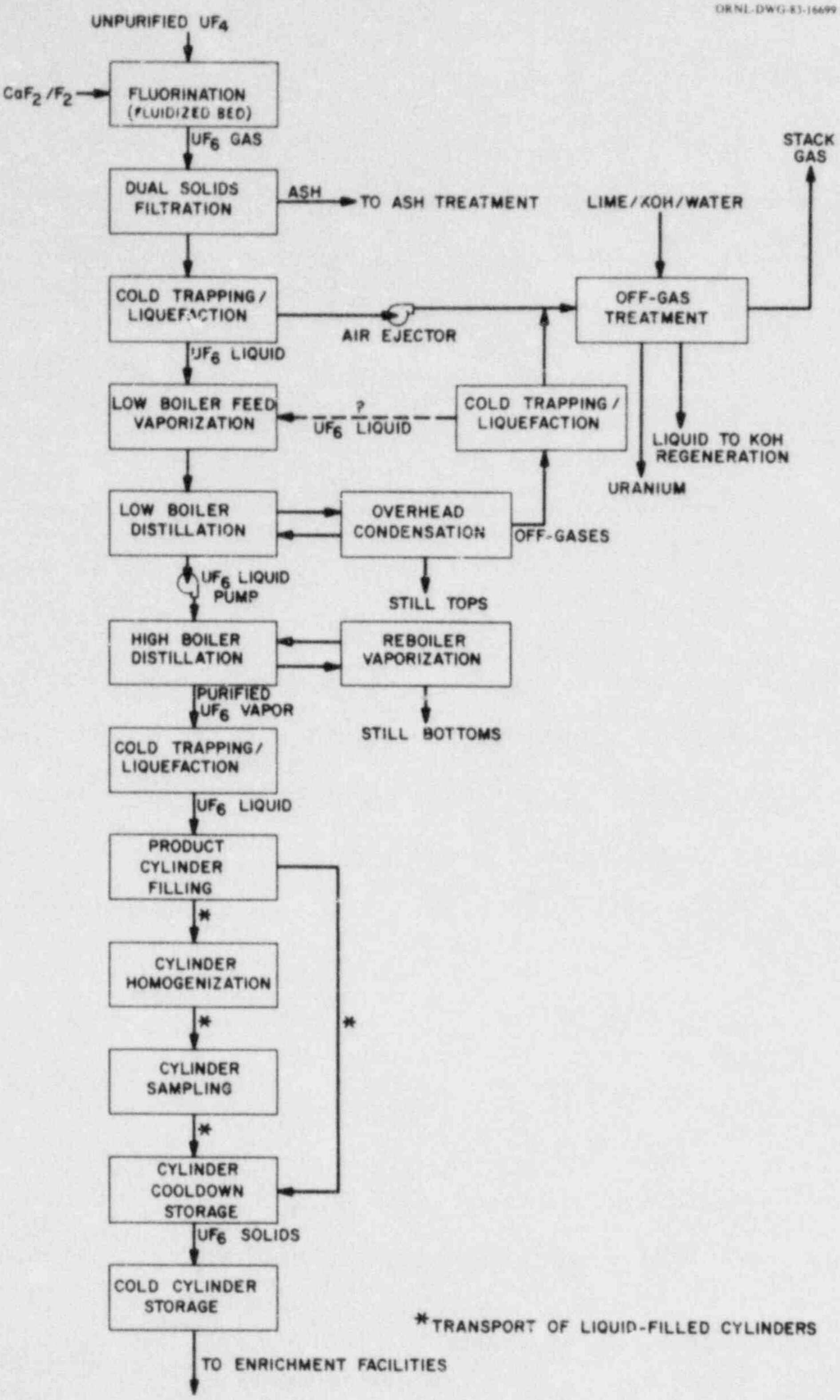

Fig. 3. **Flow diagram for UF_6 handling operations based on the fluorination-fractional distillation process.**

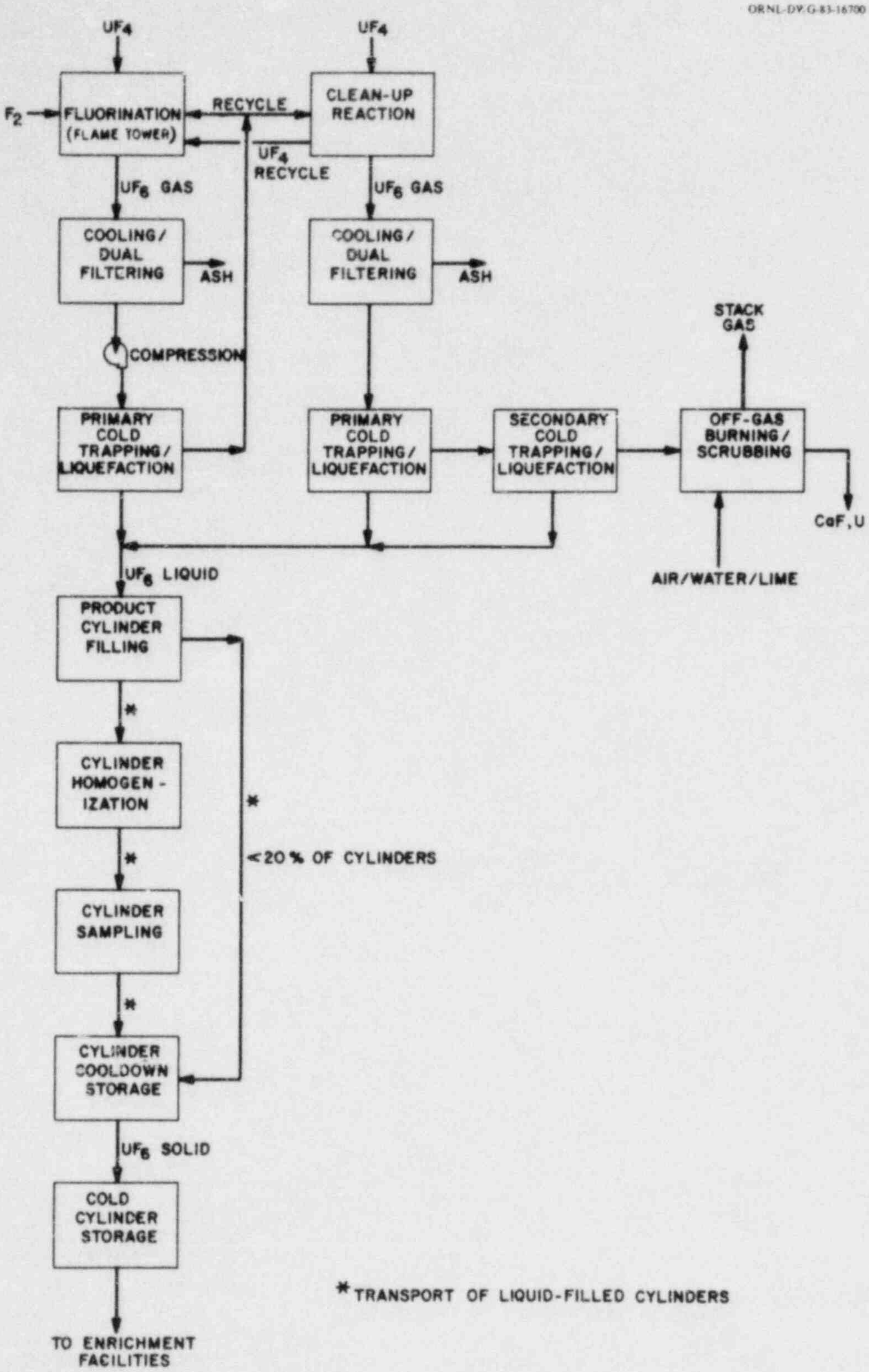

Fig. 4. Flow diagram for UF_6 handling operations based on the solvent extraction process.

Table 6. Important UF_6 process parameters at NRC-licensed facilities[a]

Process	Licensee	Stage	Approximate pressure (atm abs)	Approximate temp (°F)	UF_6 phase[b]	Number of units	Max UF_6 inventory (lb/unit)
Fluorination	Kerr-McGee	Primary	~1	750 ± 110	V	5	~3
		Compressor	~1	NA	V	2	NA
		Cleanup	(~ 1)	~850	V	2	NA
	Allied	Primary	~1	795-815	V	2 + 1 spare	NA
Cold trapping (collection)	Kerr-McGee	Primary	<1	36	V/S	4	21,000
		Secondary	<1	-67	V/S	2	3,000
	Allied	Primary	<1	-20	V/S	10	10,000
		Secondary	<1	NA	V/S	6	2,000
		Tertiary & sample	<1	NA	V/S	5	1,000
Cold trapping (liquefaction)	All	All	<1-7	147-250	L	NA	NA
Distillation	Allied	Still feed	~5.7	~200	V/L	3	20,000
		Vaporizer	~5.7	~200	V/L	1	10,000
		Low boiling column	5.7	200 (avg)	V/L	1	2,000
		Low boiler reboiler	~5.7	~200	V/L	1	10,000
		Low boiler condenser	~5.7	~200	V/L	4	1,000
		High boiling column	6.4	240 (avg)	V/L	1	1,000
		High boiler reboiler	~6.4	~240	V/L	1	10,000
		High boiler condenser	~6.4	~240	V/L	1	1,000
Cylinder filling and sampling	Kerr-McGee	Inside building	<1.7	Ambient-250	V/L/S	2	21,000–27,600
		Outside building/ Steam chests	<1-7	Ambient-250	V/L	3	21,000–27,600
	Allied	Inside building	<1-7	Ambient-250	V/L/S	NA	28,000
Cylinder storage	Kerr-McGee	Cooldown outside	<1-7	Ambient-250	V/L/S	<10	21,000–27,600
		Cold storage outside	<1	Ambient	S	>10	21,000–27,600
	Allied	Cooldown outside	<1-7	Ambient-250	V/L/S	<14	28,000
		Cold storage outside	<1	Ambient	S	>14	28,000
Cylinder heating/ steam chests	All fuel fab.		<1-6	Ambient-250	V/L/S	2–6	110[d]–4800
Hydrolysis	All fuel fab.		≥1	Near ambient	V	1–2	<50
UF_6 scrubbing	All		1	Ambient	V	1–2	~0

[a] NA = not available in the public domain.

[b] V = vapor or gas; L = liquid; S = solid.

[c] The actual inventory at risk in an accident situation may involve the inventory of several units depending on site specific configurations, operating procedures, and accident conditions.

[d] Highly enriched uranium.

uses a calcium fluoride (CaF_2) fluidized bed to carry out the reaction. The CaF_2 bed becomes contaminated by impurities in the UF_4 feed and must periodically be replaced. The spent catalyst or "ash" from the bed is sent to an ash treatment process to recover any uranium. The solvent extraction process uses a "flame tower". Imcompletely reacted uranium and some impurities in the process are collected at the bottom of the flame tower in an "ash receiver" and are recycled to recover uranium.

The fluorination reaction is strongly exothermic. The reaction temperature is controlled by the diluting effect of the calcium fluoride and by an air-cooled jacket in the fluidized bed. The flame towers are cooled by an external steam coil.

The fluorination product gases from the fluidized beds flow through two 10-μm sintered nickel filters and then on to the primary cold traps. Product gases from the flame towers are cooled, passed through two sintered metal filters and a bag filter, and then compressed prior to primary cold trapping.

4.1.2 UF_6 Collection and Gas Cleanup

In both processes, product gases from the fluorination reactors are passed through cold traps to condense UF_6 as a solid. Gases that pass through the cold trap, including unreacted F_2, HF, and other noncondensibles, as well as a trace amount of UF_6 are removed from the second primary cold trap by an air ejector or by pressure difference and, subsequently, pass to a gas cleanup system.

The gas cleanup system for the fluorination-fractional distillation process reacts cold trap off-gases with potassium hydroxide (KOH) in a two-step process and recycles the uranium precipitates. The gas cleanup approach in the solvent extraction process is to react excess F_2 in the off-gases with fresh UF_4 solid at elevated temperature in a cleanup reactor. After slightly cooling the cleanup reactor off-gases in a "screw cooler," the gases pass through two sintered metal filters and a bag filter. These filtered gases are then passed through a primary cold trap (36°F) and then a very cold secondary cold trap (-58°F) to condense UF_6. Off-gases from the secondary cold trap are mixed with air, burned, and fed to a burner/hydrofluoric acid scrubber before being released to the environment.

Once the cold traps are full, the UF_6 is melted and drained by gravity to the distillation feed vaporizer the fluorination-fractional distillation or directly to product cylinders in the solvent-extraction process.

4.1.3 UF_6 Distillation Purification

Saturated UF_6 vapor from the distillation feed vaporizer is fed to the low boiler stripping column that removes high boiling contaminants from the raw UF_6 as the overhead condenser product. Off-gases from the overhead condenser on the low boiler pass through a cold trap and are routed to the off-gas treatment system for uranium recovery and scrubbing. Stripped UF_6 liquids are pumped to the high boiler rectifying column where high boiling contaminants are removed as column bottoms. Purified UF_6 vapor from the high boiler column overhead is collected in cold traps The UF_6 is then melted in these traps and flows by gravity to a 10- or 14-ton product cylinder.

4.1.4 UF_6 Product Cylinder Handling

Filled UF_6 cylinders are either sampled or sent directly to a cool-down area outside. At one facility, filled cylinders are moved outside the building to be homogenized by heating in a near-atmospheric-pressure steam chest. The homogenized cylinders are then moved to a sampling station inside the facility where a sample of less than 5 lb is taken. After sampling, the cylinders are moved to a cool-down area outside the main building where they are left several days before being moved to a cold storage area. Cold cylinders are ready for shipment to enrichment facilities.

Product cylinders for UF_6 production facilities have nominal capacities of 10 or 14 tons. Some 14-ton cylinders have a wall thickness about half that currently acceptable for new cylinders.[2] Additional data on cylinders can be found in refs. 2 and 3.

4.2 FUEL FABRICATION FACILITIES

Details of UF_6 feed processes at NRC-licensed fuel fabrication facilities vary significantly depending on cylinder size, uranium enrichment, UF_6 oxidation process, etc. Most fuel fabrication facilities in this study handle UF_6 as shown in Fig. 5. Cold cylinders are moved by forklift or other device to either a steam autoclave (usually just a steam chest) or an enclosure where the cylinders can be heated by electrical resistance pads. Cylinder temperature and often pressure are monitored during cylinder heating. In the ammonium

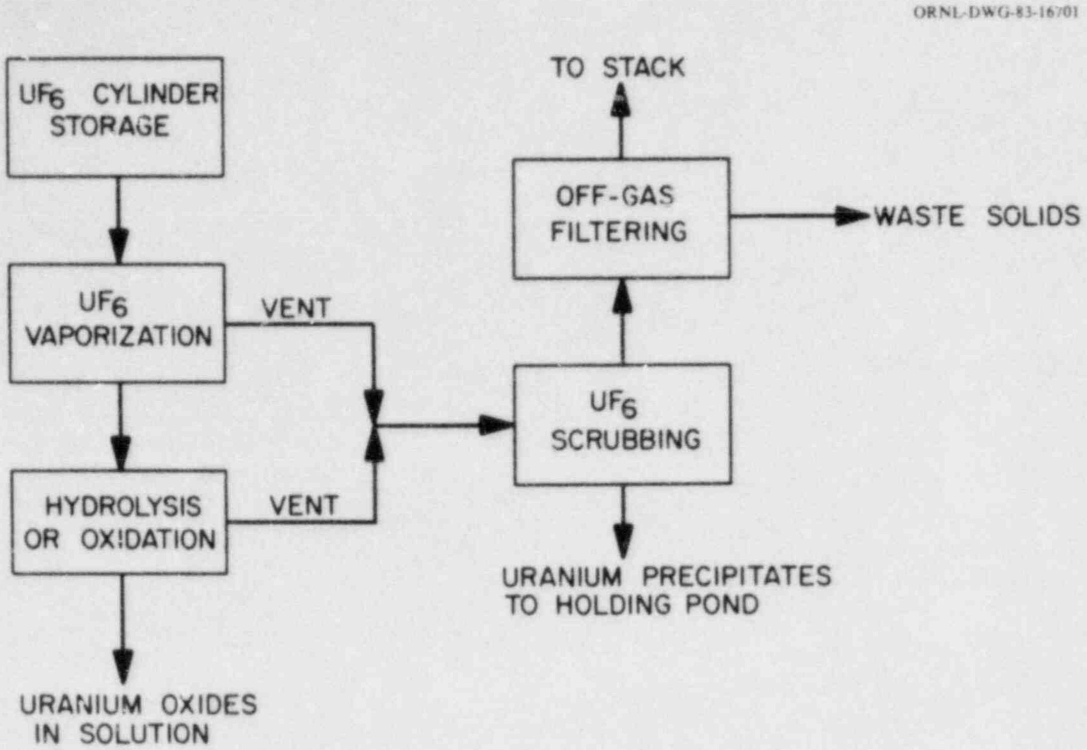

Fig. 5. Flow diagram for UF_6 handling operations at a typical fuel fabrication facility.

diuranate process for producing UO_2, UF_6 vapors (typically at about 230°F and 80 psia) are passed through heated piping to a hydrolysis unit where the UF_6 vapor reacts with water to produce UO_2F_2. A gas-phase hydrolysis process (direct conversion fluidized bed) is being investigated for future use by at least one fuel fabrication facility, but in any case all uranium in this UF_6 vapor is converted into nonvolatile uranium compounds. Effluent gases from these UF_6 conversion processes are passed through venturi or packed-tower scrubbers and then through roughing filters and a HEPA filter before they are vented to the atmosphere. It is not known whether all NRC-licensed facilities vent effluent gases to scrubbers and/or through HEPA filters.

5. UF_6 ACCIDENT SCENARIOS

Based on a review of available literature, experience at DOE facilities, and results of DOE enrichment facilities safety analyses, a list of generic scenarios for NRC-licensed UF_6 handling facilities (Table 7) has been developed. Many of these incidents are based on historical events.

Table 7. UF_6 accident scenarios

1. UF_6 ***cylinder failures***

    1.1 Introduction of reactive hydrocarbons into a cylinder
    1.2 Impact of a liquid-filled cylinder against an object or impact of an object on a cylinder
    1.3 Valve or pigtail failure due to movement of a connected cylinder containing UF_6
    1.4 Hydraulic rupture of a cylinder exposed to fire
    1.5 Hydraulic rupture of an overheated cylinder
    1.6 Hydraulic rupture of an overfilled cylinder
    1.7 Heating or filling a defective cylinder
    1.8 Heating a cylinder containing excessive volatile and/or gaseous contaminants
    1.9 Dropping a liquid-filled cylinder

2. UF_6 ***process system failures***

    2.1 Excessive heating of process equipment containing solidified UF_6
    2.2 Fatigue failure of a process system
    2.3 Impact on a process system containing UF_6
    2.4 Valve failure of a cylinder or a system containing UF_6
    2.5 Pigtail failure
    2.6 Process system loss of containment caused by natural phenomena
    2.7 Heating a cold trap containing excessive volatile and/or gaseous contaminants
    2.8 Heating an overfilled cold trap
    2.9 Overheating a cold trap
    2.10 Cold trap failure caused by corrosion, fatigue, or thermal shock
    2.11 Venting of UF_6 through a hydrolyzer

3. ***Nuclear criticality event***

    3.1 Nuclear criticality in a UF_6 vaporizer
    3.2 Nuclear criticality resulting from a safe spacing violation

4. ***Operator error***

    4.1 Valving a cold trap to a vacant position
    4.2 Bypassing safety controls
    4.3 Removing a valve from a cylinder containing UF_6

These postulated scenarios are believed to be credible, but their occurrence may be infrequent. Historically, few significant UF_6 releases have been experienced at UF_6 handling facilities within the three DOE uranium enrichment plants and the NRC-licensed facilities, and these releases have not resulted in fatalities to on-site or off-site personnel. As each reportable event occurred, its cause and consequence were evaluated, and in many cases, administrative or design fixes have been made to reduce the likelihood and/or the potential consequences of a future UF_6 release. Compliance with the American National Standard Institute (ANSI) standard, ANSI N14.1, entitled ***Packaging of Uranium Hexafluoride for Transport*** can prevent or minimize the consequences of future incidents involving cylinders.[2]

No attempt has been made to supply information on consequences or probabilities for the postulated scenarios. Consequence analysis requires such site specific details as cylinder size, isotopic enrichment, production capacity, building volumes, site boundaries, locations, population density, meteorological conditions, postulated natural phenomena, containment philosophy, process layout, operating procedures, and process parameters such as temperatures, pressures, and flow rates. Experience in consequence analysis for similar scenarios at uranium enrichment plants indicates that consequences will depend strongly on site specific details and that consequences can vary considerable between different operations within a facility. Similarly, personnel of specific UF_6 handling facilities should be involved directly in assessing the probability of occurrence based on site specific operating procedures, design parameters, and historical experience.

Although some scenarios may not be credible at all NRC-licensed UF_6 handling facilities (e.g., nuclear criticality in a UF_6 feed production facility), at least two events are believed to be credible at all such facilities: (1) release from a cylinder containing liquid UF_6 and (2) failure of a pigtail. Following approved operating procedures and using safety systems such as UF_6 containment devices may prevent the release of significant quantities of UF_6 from a facility.

In summary, consequence analysis of postulated UF_6 release scenarios for NRC-licensed fuel cycle facilities will require detailed site specific information. The plausibility of each scenario listed in Table 7 and described in the remainder of this section should be considered for each facility, as appropriate.

In the following scenario descriptions, an understanding of UF_6 physical properties is assumed, as well as a working understanding of equipment and terminology generic to UF_6 handling facilities. These scenarios appear capable of resulting in significant consequences under certain conditions; scenarios resulting only in small, nuisance-type releases are not included.

5.1 UF_6 CYLINDER FAILURES

Uranium hexafluoride cylinders are used to transport solidified UF_6 at subatmospheric pressure. A release may result if a cylinder is damaged in transport and the damage is not detected and acted upon prior to pressurizing the cylinder by heating.

Cylinders containing liquid UF_6 are susceptible to rupture when dropped during handling operations or when impacted. Cylinders that do not comply with ANSI N14.1 or thin-walled cylinders used at some UF_6 production plants are more susceptible to such failure; these cylinders have been accepted under the current version of the standard as existing equipment. Cylinder fill limits based on UF_6 purity specifications such that the liquid UF_6 occupies not more than 95% of the cylinder volume at 250°F are also specified in ANSI N14.1. Violations of these conditions increase the probability of the postulated release scenarios.

Although the mechanism of the chemical reaction between the UF_6 and hydrocarbons is somewhat uncertain, it is known that the reaction of gram to kilogram quantities of hydrocarbon contaminants with liquid UF_6 is capable of producing sufficient energy to explosively rupture equipment from the size of pigtails to cylinders, respectively. Because analytical techniques for detecting the presence of these contaminants are not practical for routine use, care must be exercised to prevent introduction of these contaminants into any UF_6 cylinder as specified in ANSI N14.1.

In the case of noncatastrophic cylinder failures, if effective corrective action is not or cannot be taken immediately when the failure occurs, most of the contents of a cylinder containing liquid UF_6 can be released. The exact quantity of UF_6 released will depend on the temperature and pressure of the liquid UF_6 prior to release as well as on the characteristics of the cylinder failure. For example, if a cylinder fails above the liquid level shortly after removal from an autoclave or electric heater system, and if the UF_6 within the cylinder is at 113°C and 5.61 atm prior to release, approximately 60% of the liquid UF_6 may be released as UF_6 vapor. The remaining 40% will form solid UF_6 particles. If a small hole or crack has formed, most of the solid UF_6 particles may be retained within the cylinder; however, a large crack may release most of the particles along with the gas. If a large cylinder breach occurs below the liquid level, nearly all of the UF_6 in the cylinder may be released.

Nine cylinder failure scenarios have been developed. Compliance with ANSI N14.1 could prevent or minimize the consequences of these postulated scenarios:

1.1 *Event*: Introduction of reactive hydrocarbons into a cylinder.

Description: The use of oil-lubricated vacuum pumps to evacuate residual UF_6 from cylinders could transfer oil to a cylinder containing UF_6 either by operator error or inadvertent pump shutdown. Subsequent refilling and then heating of the cylinder could result in an explosive reaction, thus releasing the cylinder contents.

Comments: Although the mechanism of the reaction between UF_6 and hydrocarbons is somewhat uncertain, several historical incidents have occurred during which cylinders were bulged or ruptured.

1.2 *Event*: Impact of a liquid-filled cylinder against an object or impact of an object on a cylinder.

Description: Operator error or equipment failure may subject a cylinder to an impact from a moving object or a cylinder may impact a stationary object while being transported.

Comments: Unprotected cylinder valves are vulnerable to such incidents. Operating procedures at some facilities require the use of protective valve covers when liquid-filled cylinders are being moved. The movement of such a cylinder as well as the lift heights are also minimized.

1.3 *Event*: Valve or pigtail failure due to movement of a connected cylinder containing UF_6.

Description: Inadvertent movement of a cylinder connected to the process system can be caused by operator error or failure of a cylinder support and could result in failure of the cylinder valve or connecting pigtail.

1.4 *Event*: Hydraulic rupture of a cylinder exposed to fire.

Description: Exposure of a cylinder to an intense heat source, such as burning fuel, could result in hydraulic rupture of a cylinder; however, slower release of the UF_6 due to solder failure in the valve coupling threads by melting is more probable. Fuel could come from sources such as a fuel storage tank or a fuel tank truck.

1.5 *Event*: Hydraulic rupture of an overheated cylinder.

Description: An operator error or the malfunction of temperature controls could result in cylinder failure while heating a cylinder during sampling or vaporizing operations.

Comments: UF_6 density changes from 318 lb/ft^3 at 68°F to 190 lb/ft^3 at 300°F. ANSI N14.1 specifies a maximum cylinder temperature o 250°F, where UF_6 density is 203 lb/ft^3. Rupture is more likely here than in scenario 1.4 because failure of the solder in the valve coupling threads by melting is not probable.

1.6 *Event*: Hydraulic rupture of an overfilled cylinder.

Description: Normal heating of a cylinder during sampling or vaporizing operations could result in hydraulic rupture if the cylinder fill limit has been exceeded.

Comments: Verification of cylinder weight and volume for compliance with ANSI N14.1 fill limits would preclude this event.

1.7 *Event*: Heating or filling a defective cylinder.

Description: Cylinders or cylinder valves may be damaged in handling or transport incidents. If a defect is not detected, a UF_6 release could occur when the cylinder is pressurized during heating or filling.

Comments: Compliance with ANSI N14.1 would reduce the probability of this event.

1.8 *Event*: Heating a cylinder containing excessive volatile and/or gaseous contaminants.

Description: Cylinder fill limits are based on UF_6 specifications defined in the Federal Register.[14] The presence of volatile impurities such as HF or fluorocarbons and/or gases such as air may cause excessive pressures and subsequent cylinder failure when contaminated cylinders are heated at normal temperatures.

1.9 *Event*: Dropping a liquid filled cylinder.

Description: Causes of cylinder drops include operator error in securing lifting devices, failure of cylinder support structures, failure of cylinder handling equipment hydraulic systems, and failure of crane components or lifting fixtures. The probability that a cylinder drop will result in a UF_6 release is believed to increase as the lift height (drop height) increases.

5.2 UF_6 PROCESS SYSTEM FAILURES

A significant UF_6 release may result from a failure of any of the following process equipment handling UF_6. The extent of the release is dependent on the effectiveness of corrective action.

Piping — Because of the high coefficient of thermal expansion of solid UF_6, piping and instrument tubing containing solidified UF_6 can rupture if heat is improperly applied. These systems are also subject to fatigue resulting from vibrations and cyclic stresses, and to impacts from falling or moving objects.

Valves — Cylinder or process valves can fail from leakage through the valve seat, valve body failure, valve stem packing failure, mechanical damage, or leakage through valve coupling threads as a result of solder melting as in a fire.

Pigtails — Failure of a pigtail connecting a cylinder to the process system can result from defective, damaged, or improperly designed pigtails, fatigue, overheating, or operator error.

Cold Traps — Cold traps may rupture if overfilled traps are heated to normal temperatures or if properly filled traps are overheated. Failure may result from excessive pressure if a trap contains excessive volatile impurities. Fatigue or thermal shock may also lead to trap failures.

Hydrolyzers — Inadvertent release of UF_6 from feed cylinders to the atmosphere through hydrolyzers or UO_2F_2 storage columns can result from inadvertent system shutdown or operator error.

Natural phenomena, such as seismic, tornado, high wind, or flooding events, may also disrupt processing equipment, cylinders, or their supports.

Eleven scenarios leading to releases from process equipment have been postulated:

2.1 *Event*: Excessive heating of process equipment containing solidified UF_6.

Description: A pigtail, a valve, or process piping containing condensed UF_6 may rupture if heat is improperly applied. This event may result from operator error or it may result inadvertently when system heat is restored after a system shutdown.

2.2 *Event*: Fatigue failure of a process system.

Description: Process piping, systems, and instrument tubing are subject to vibrations or cyclic stresses and can fail, causing significant UF_6 releases when systems contain UF_6.

2.3 *Event*: Impact on a process system containing UF_6.

Description: Inadvertent movement of maintenance equipment or process equipment being repaired in an operating area may impact on-stream systems, causing failures that result in loss of UF_6 containment.

2.4 *Event*: Valve failure of a cylinder or a system containing UF_6.

Description: Valves can fail from either seat leakage, valve body failure, or valve stem packing failure. The valve may be inadvertently removed from the cylinder by remote or automatic valve operators. Failure can also be caused by operator error, such as overtorquing while opening or closing, or by improper assembly.

Comments: Solidified UF_6 or corrosion productions within the valve often make valve operations difficult leading to the misoperation of overtorquing. Some valve components are vulnerable to stress corrosion.

2.5 *Event*: Pigtail failure.

Description: Failure of the flexible connection (pigtail) between a cylinder and the process system may be caused either by operator error involving improper fitting or by physical abuse, inadequate design, material fatigue, or overheating.

2.6 *Event*: Process system loss of containment caused by natural phenomena.

Description: Seismic, tornado, wind, or flooding events may disrupt processing equipment, cylinders, or their supports, resulting in failure and UF_6 release.

2.7 *Event*: Heating a cold trap containing excessive volatile and/or gaseous contaminants.

Description: Operator failure to monitor cold trap pressure instrumentation during the heating cycle can permit excessive system pressures, resulting in vessel failure and release of UF_6.

2.8 *Event*: Heating an overfilled cold trap.

Description: Operator error or failure of cold trap weight monitoring instruments, which permits the trap to be overfilled, may result in hydraulic rupture of the trap during the heating cycle.

2.9 *Event*: Overheating a cold trap.

Description: Operator error or failure of trap temperature controls may cause hydraulic rupture of the vessel during the heating cycle.

2.10 *Event*: Cold trap failure caused by corrosion, fatigue, or thermal shock.

Description: Exposure of cold traps to the corrosive UF_6 atmosphere and repeated thermal shocks may cause failures under normal operating conditions and result in UF_6 releases external to the trap or internal to the refrigerant system with ultimate release of UF_6 to the atmosphere.

2.11 *Event*: Venting of UF_6 through a hydrolyzer.

Description: Atmospheric venting of UF_6 from feed cylinders through hydrolyzers and UO_2F_2 storage columns can be caused by the inadvertent shutdown of a recirculating water system, or by operator error which could either terminate the water flow or overload the system capacity by introducing excessive feed from the feed cylinders.

5.3 NUCLEAR CRITICALITY EVENTS

Postulated scenarios include release of enriched assay UF_6 into a steam-heated vaporizer containing an excessive accumulation of condensate or violation of safe spacing of enriched assay containers. Criticality is dependent on the enrichment of the uranium involved, the presence of a neutron moderator, and the shape and dimensions of the space in which the accident is postulated to occur. Therefore, analysis on a case-by-case basis is required to determine whether or not an accident can occur. The following postulated accidents would not be expected in UF_6 production facilities because natural uranium presents no plausible criticality hazard. These accidents may occur, however, in fuel fabrication facilities where enriched uranium is present. These scenarios should be considered illustrative of the types of criticality events that could occur.

5.1 *Event*: Nuclear criticality in a vaporizer.

Description: A UF_6 release from a cylinder or pigtail into a steam-heated vaporizer of unsafe geometry containing an excessive accumulation of condensate could result in nuclear criticality. Causes of the excessive condensate accumulation include operator error, condensate trap failure, or obstruction of a condensate drain line in a vaporizer.

3.2 *Event*: Nuclear criticality resulting from a safe spacing violation.

Description: Operator error or mechanical failure could cause a violation of nuclear safe spacing of cylinders containing enriched UF_6, resulting in nuclear criticality.

5.4 OPERATOR ERRORS

A number of the events described in Sects. 5.1, 5.2, and 5.3 can be initiated or allowed to progress as a result of operator error. Several other events are described in this section that can be directly attributed to operator error. These events, which can result in significant releases of UF_6, include opening cold trap drain valves to a position that is not connected to a receiving cylinder, circumventing pressure or temperature controls required for safety, or inadvertent removal of the valve from a cylinder containing UF_6.

4.1 *Event*: Valving a cold trap to a vacant position.

Description: Operator error involving misvalving a cold trap to a position that is not connected to a receiving cylinder could result in a significant release of UF_6.

4.2 *Event*: Bypassing safety controls.

Description: If controls required for safety, such as UF_6 system pressure or temperature controls, are circumvented, subsequent failures could result in significant releases of UF_6.

4.3 *Event*: Removing a valve from a cylinder containing UF_6.

Description: Operator error while attempting to open a valve can result in valve removal if condensed UF_6 or corrosion products cause a valve stem to freeze. Most cylinder valves are screwed into the cylinder head. Opening the valve can result in removal of the valve if excessive torque is applied by using a mechanical lever rod, for example.

6. APPLICABILITY OF AVAILABLE METHODS FOR ANALYZING UF_6 RELEASES

This chapter discusses available methods for analyzing UF_6 releases. The first section reviews the applicability of several codes developed by LANL and PNL for the AAH for simulating UF_6 release phenomena. Methods that have been used or developed for analyzing UF_6 releases are discussed in the second section.

6.1 APPLICABILITY OF AAH CODES

The tornado analysis code (TORAC), the explosion analysis code (EXPAC), and the fire analysis code (FIRAC), as described in Appendices A, B, and C, respectively, of draft material for the AAH, have been evaluated with respect to (1) their applicability to accidental UF_6 releases and (2) their ability to simulate such releases. In this respect, the review investigated the basic assumptions and physical phenomena but not the details of the mathematical formulation or the adequacy of the models for purposes other than UF_6 applications. Based on this review, at least five areas were identified with respect to UF_6 releases that should be addressed:

1. phase changes and chemical reactivity of UF_6 and UF_6 hydrolysis products are neglected;
2. a uniform temperature and chemical composition within a compartment is assumed;
3. an approximate gravity settling depletion model within a compartment is used;
4. the ability to simulate changing particle size distribution as a function of time is limited; and
5. chemical degradation effects of UF_6 and its hydrolysis products on the performance of plant equipment such as fans, filters, and ducts are not considered.

With respect to the first area listed above, consideration should be given to

1. inclusion of water, UF_6, UF_6 hydrolysis products, and their thermo-physical properties in the models;
2. simulation of chemical reactions of UF_6 and UF_6 hydrolysis products with water, hydrocarbons, ventilation duct walls, filters, fans, etc.;

3. inclusion of phase changes such as UF_6 sublimation and HF condensation; and

4. incorporation of the effects of energy released by these chemical reactions.

Because HF polymerization has only a small effect on the final specific volume, pressure, and temperature that results from a UF_6 release inside a compartment, the neglect of HF polymerization is believed to be reasonable.

The models should include the simulation of the transport and chemical reaction of water, UF_6, and UF_6 hydrolysis products. Although FIRAC does allow the user to model the transport of inert substances, the user cannot model the transport of a chemically reacting species, such as UF_6. TORAC and EXPAC can model the transport of only a single inert material. To obtain reasonably accurate results, transport of a multicomponent mixture must be modeled during the simulation of accidental UF_6 releases. Specifically, the models should consider, at a minimum, the multispecies transport and chemical reactions of air, H_2O, UF_6, UO_2F_2, and HF. The hydrolysis of UF_6 and the vapor-liquid equilibrium of HF and H_2O should be simulated because they significantly affect temperature, pressure, specific heats, molecular weights, deposition rates, and particle size distributions of materials inside a compartment. Also, phase changes such as UF_6 sublimation as well as HF-H_2O vapor-liquid equilibrium should be simulated.

Because accidental releases of UF_6 inside a building can produce large changes in the building atmospheric temperature and pressure it is important to include the heat of reaction, which is strongly exothermic.

Several observations can be made about UF_6 releases inside a building by considering a release of UF_6 into a compartment containing moist air at a specified initial temperature, pressure, and relative humidity. This case can be analyzed by assuming that a UF_6 release inside an airtight compartment will result in a homogeneous mixture of air, UF_6, and UF_6 hydrolysis products and by not considering heat transfer to plant equipment and to the building itself. For example, if the air in the compartment is initially at 1 atm and 80°F with a 60% relative humidity, the estimated resulting temperature and pressure in the closed compartment following an instantaneous UF_6 release are those shown in Figs. 6 and 7, respectively. As can be seen in Fig. 6, the temperature rise resulting from some releases can be

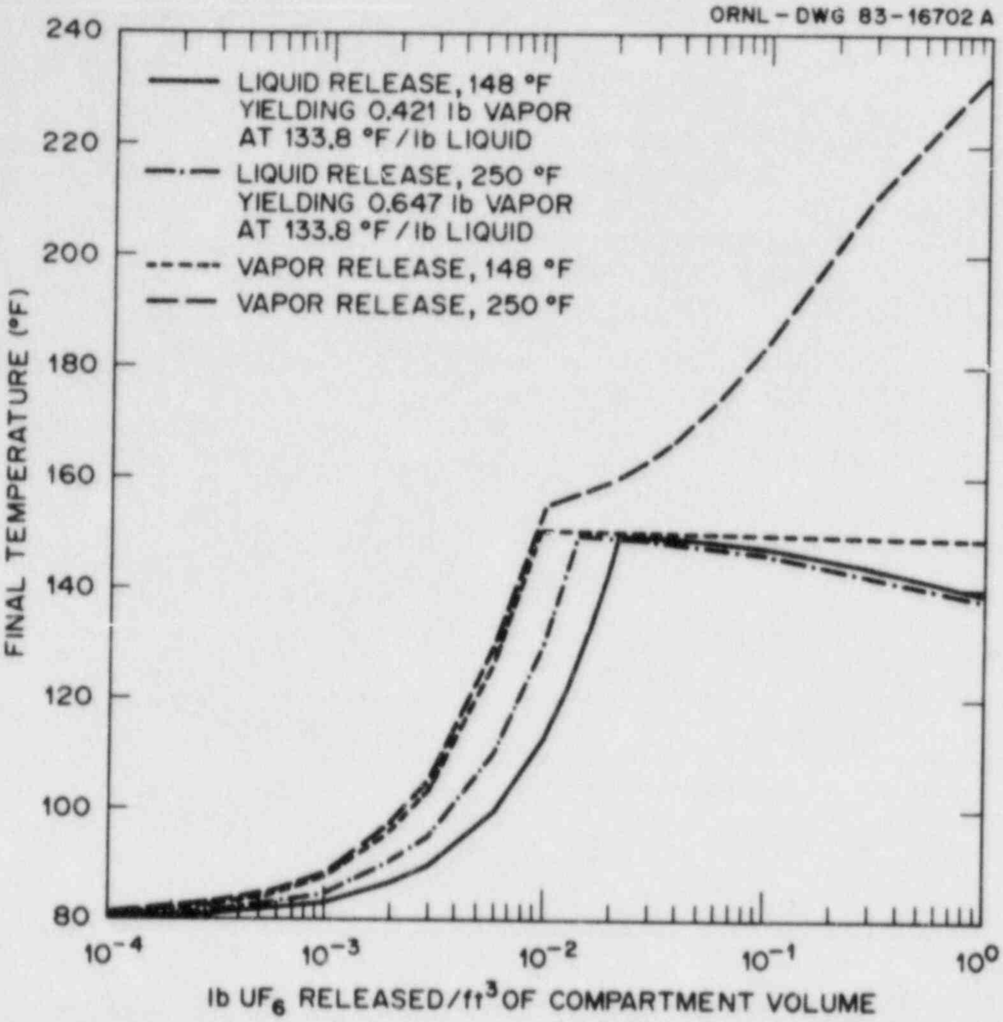

Fig. 6. Compartment temperature change due to an instantaneous UF_6 release assuming perfect mixing of released UF_6 in a closed compartment containing air at atmospheric pressure and 80°F with a relative humidity of 60%. UF_6 temperatures were selected based on ANSI N14.1 concerning cylinder fill limits (95% of cylinder volume at 250°F and the triple point of UF_6 (147.2°F).

large. The pressure rise, due to both the heat and the additional moles of gas generated from the hydration of UF_6 and its hydrolysis product HF, may, under certain circumstances, be enough to damage the building and/or to increase leakage from ducts, rooms, etc. The "no leakage" or airtight compartment assumption previously noted for this model may not be realistic for many existing facilities handling UF_6, but it does yield an upper bound estimate of the pressure rise within a compartment. This idealized prediction of expected pressure rise does suggest, however, that total containment of a UF_6 release into the building atmosphere may be an impractical, if not undesirable, goal.

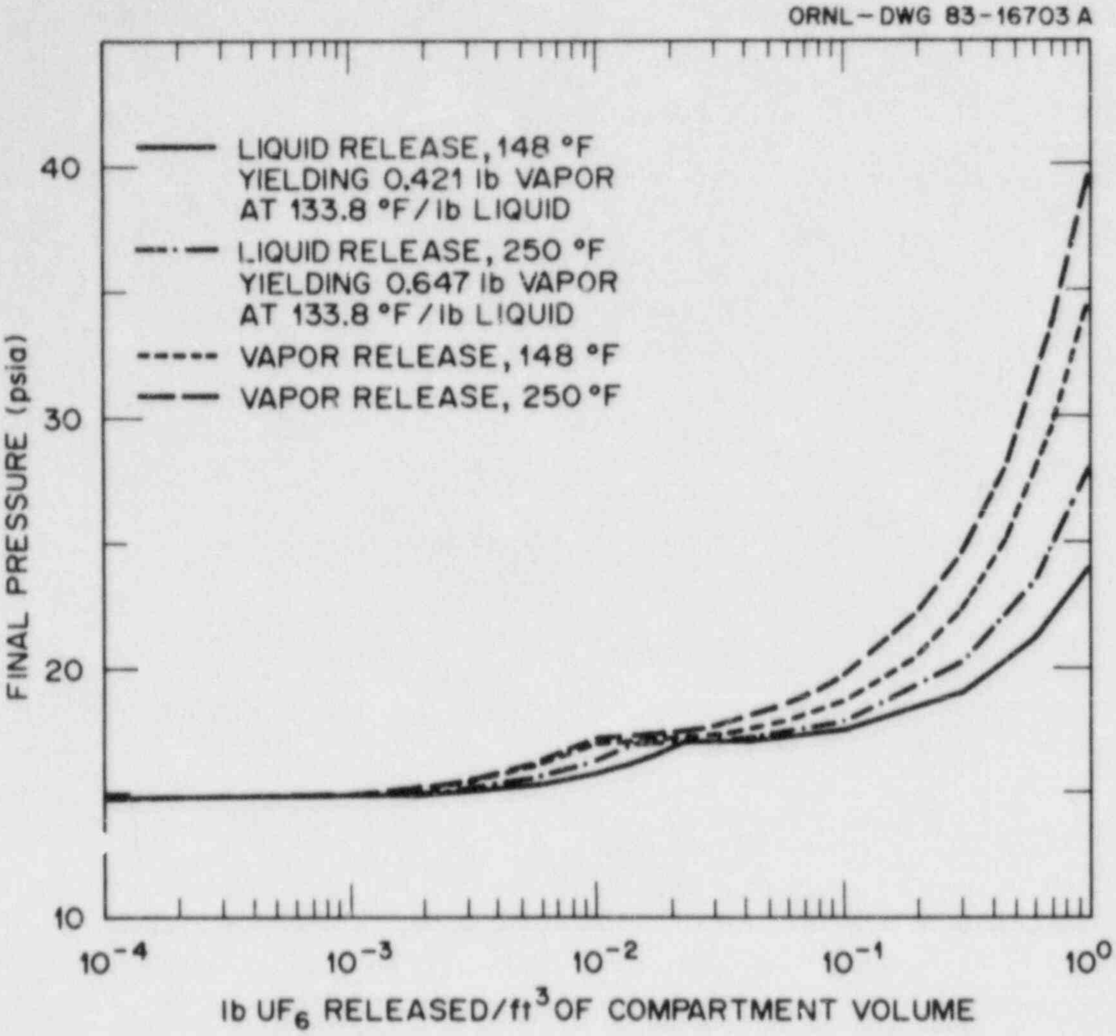

Fig. 7. Compartment pressure change due to an instantaneous UF_6 release assuming perfect mixing of released UF_6 in a closed compartent containing air at atmospheric pressure and 80°F with a relative humidity of 60%. UF_6 temperatures were selected based on ANSI N14.1 concerning cylinder fill limits (95% of cylinder volume at 250°F) and the triple point of UF_6 (147.2°F).

The second area that must be addressed is the assumption that the composition and temperature are uniform throughout a compartment. Although this should not be a problem with the multidimensional models being developed by LANL, the problem will exist at least until those multidimensional models are completed and are available for use. In actual circumstances, concentration and thermal gradients will exist in a building after an accidental UF_6 release and their effects could be significant. For example, low concentration areas of UF_6 could totally react with incoming moisture and leave the higher concentration areas of UF_6 unreacted. This points out the need to model multidimensional spatial variations in chemical reactions, temperature, and concentration, especially if time considerations such as evacuation and response time are important.

The third area to be addressed is that the deposition model uses only a gravity settling correlation. Other effects, for example, condensation on solid surfaces of species such as HF, may have a significant impact on the rates of deposition of UF_6 and UF_6 hydrolysis products. The deposition models used could affect which reactant is predicted to limit the reactions.

The fourth area of concern is the method of simulation of particle size distributions and agglomeration rates. For FIRAC, the deficiency is not the inability to deal with changing particle size distributions over time, which FIRAC can do crudely, but the requirement that the user specify the time-dependent distributions. For TORAC and EXPAC, the user can only specify the average particle size of the distribution; however, size distributions of particles are expected to have a wide range of shapes that are complex functions of the temperature, pressure, humidity of the air, and the condition of the UF_6 prior to release. Therefore, specifying only an average particle size may lead to large errors when, for example, removal mechanisms for certain particle sizes are significantly different from those for the other sizes. The state of the art has not advanced enough to accurately compute changing size distributions with the physical data available.

The requirement that the user specify the particle size distribution in FIRAC will probably cause the user to take one of two approaches. The first approach is using iterative computer runs to estimate the time-varying particle size distributions because changing conditions will change the size distributions over time. Changing size distributions can alter the conditions that determine subsequent size distributions through such mechanisms as filter plugging or heat generation rates. The second approach is assuming one distribution for all time. This latter approach will probably lead to significant errors; for example, the removal of relatively small particles by a filter is much different from removal after significant agglomeration has occurred.

The fifth area to be addressed is the inability to simulate corrosive effects of UF_6 and its hydrolysis products on equipment performance in a building. This would include possible degradation of filters, fans, ducts, and other systems as a result of chemical reactions with UF_6 and its hydrolysis products during a release. Possible adverse effects that corrosive UF_6 and UF_6 hydrolysis products may have on systems and equipment performance should be taken into account in the ventilation systems' modeling and simulation effort.

Several areas that should be addressed in the models to properly simulate accidental UF_5 releases have been noted. Not addressing these areas may result in poor simulation of stream compositions, pressures, and temperatures which, in turn, may lead to large errors in estimated concentrations, flow rates, and directions of flows. The overall effect of temperature and pressure changes on the flow distributions will be system and accident dependent. It is known that the estimated pressure drops will be incorrect, because a change in the composition will result in a change in the density and viscosity of the mixture.

6.2 OTHER AVAILABLE METHODS

The methods discussed in the preceding section have been developed for inclusion in the AAH, but they have not been developed specifically for UF_6 releases. This section discusses methods used or specifically developed for analyzing UF_6 releases, including information from NRC and their licensees, methods from the open literature, and preliminary information on available DOE source term models.

6.2.1 NRC Licensee Models

Most of the methods used by NRC licensees for analyzing accidental UF_6 releases have been concerned with modeling atmospheric dispersion rather than dispersion within a building. Because atmospheric dispersion is outside the scope of this project, no comments on the techniques used will be given. No detailed source term models or methods were described in the NRC and licensee documentation reviewed to date: however, assumptions made by NRC licensees in analyzing UF_6 releases are summarized in Table 2 and briefly discussed in Chapter 3.

6.2.2 Methods from the Open Literature

A review of the open literature likewise revealed no methods for analyzing releases of UF_6 inside a building, but two reports were found with information that is applicable to the NRC AAH.

The first report by Okamoto and Kiyose[5] described analytical methods and indicated the predicted UF_6 vapor release rate to the atmosphere as a function of time from a gas line connected to a heated cylinder (type 30A). The results were summarized in a plot of cumulative UF_6 vapor released versus time for various initial cylinder temperatures. The expected effects (including failure) of UF_6 hydrolysis products on HEPA filters were also discussed assuming that all UF_6 had been hydrated.

The second report by Ericsson and Grundfelt[6] described analytical methods and results that provide estimates of the mass flow rate of gaseous UF_6 as a function of time from an unheated cylinder (type 30B) containing liquid UF_6. It also discussed the volumetric flow rates of ambient air necessary to totally react the UF_6 released and the dispersion of the hydrated UF_6 plume in the atmosphere assuming a neutrally buoyant, chemically inert plume. It is unclear whether the solid UF_6 formation within the cylinder is properly modeled. The results of this report should be used with caution.

6.2.3 DOE Source Term Methods

A number of methods are used by DOE for analyzing accidental UF_6 releases. Some of these methods might be useful for developing source terms or for modifying the NRC codes. It should be recognized that these methods are preliminary in nature; they have not been documented, nor have they been verified by field experience.

One method is a batch-mixing homogeneous compartment model for predicting the final average composition, pressure, and temperature following a postulated accidental release of UF_6 and/or HF inside a single closed compartment with allowance for HF polymerization. The program requires as input data the building's volume and its initial pressure, temperature, and relative humidity as well as the mass of UF_6 and/or HF released, the temperature of the UF_6 and/or HF released, the molecular weight of uranium, and the UF_6 phase (liquid or vapor but not a mixture of both). Output from the program includes the final average pressure (assuming the ideal gas law and polymerized HF), the final average temperature, and the final mass and average mass fraction of each component in the compartment's atmosphere.

A second method is a transient homogeneous compartment model that computes as a function of time the average composition, pressure, and temperature following a postulated accidental release of UF_6 or HF inside a compartment with allowance for HF polymerization and deposition of UO_2F_2 and/or hydrate. The program requires as input data the volume, initial pressure, initial temperature, initial relative humidity, and ventilation rate of the compartment and the ambient pressure, temperature, and relative humidity as well as the total mass and temperature of the source, the mass flow rate from the source as a step function of time, and the UF_6 phase (i.e., the mass flow rates of solid and gas). The program's output includes the average pressure, temperature, and composition of the compartment's atmosphere at user-specified times.

A third method, which is based on the Hirst model for axisymmetric jets, has been formulated; however, there are currently no plans to develop and implement this method. The modification would extend the Hirst model to negatively buoyant flows such as postulated accidental UF_6 releases. The modified Hirst model requires as input data the radius, density, and horizontal and vertical velocities of the exit jet and the ambient density and horizontal velocity. Such a method can predict the entrainment velocity of moist air into the jet, and from that the mass of moist air entrained into the jet can be estimated. This model can be developed by combining a homogeneous mixture model with an entrainment rate model (modified Hirst model) and by solving horizontal and vertical momentum equations.

A fourth method can be used to calculate the gaseous UF_6 release rate and the total mass of UF_6 released as a function of time from a UF_6 cylinder. The calculations assume that UF_6 is an ideal gas that undergoes an isentropic expansion with unchoked flow. The calculations allow for the cooling of the UF_6 and the cylinder due to the release of the UF_6 gas. The input data are the initial cylinder temperature and pressure, the volume of the cylinder, and the cross-sectional area of the opening in the cylinder. The output data include at specified times the cylinder pressure and temperature, the mass flow rate of UF_6 out of the cylinder, and the total amount of UF_6 released.

A fifth method is a tool for evaluating an arbitrary UF_6 flow system that is defined by the user. The method is applicable to a steady-state adiabatic release of nonideal UF_6 gas in either choked or unchoked flow through pipes, valves, orifices, and/or a nozzle. The input data include pressure and temperature of UF_6 in a cylinder and the piping, valve, orifice, and/or nozzle arrangement. Other data may be required as input for the desired output data. For example, the output may include nozzle dimensions, orifice dimensions, and either the mass flow rate or the exit velocity.

The above calculational methods require UF_6 physical and thermodynamic property data as well as UF_6 hydrolysis product characterization. The bibliography includes some reference documents for such information.

7. PERSPECTIVES OF UF_6 ACCIDENT SCENARIOS AND ANALYSIS

A list of accidental UF_6 release scenarios was presented and discussed in Chapter 5. The individual scenarios may be grouped in a number of ways to permit greater understanding or insight that could lead to an overall approach for considering scenario analysis and consequence assessment. Section 7.1 discusses various methods for categorizing the scenarios. A particular method of categorization is considered further in Sect. 7.2 that may aid in selecting specific events for analysis. UF_6 release phenomena and modeling considerations are discussed in Sect. 7.3. Section 7.4 provides a summary of this chapter.

7.1 METHODS FOR CATEGORIZING SCENARIOS

The scenarios presented in Chapter 5 were grouped for convenience under four general headings that are neither independent nor of the same general nature. In this section, no attempt will be made to separate scenarios into independent groups; however, the various groupings presented may lead to some insights as to an overall approach for considering scenario analysis and consequence assessment. The various groupings, which include location release source (equipment), phase of release, flow characteristics, release causes, initiating events, and inventory groupings, are summarized in Table 8 and are discussed below.

7.1.1 Location

Accident scenarios can be divided into those occurring indoors, which may offer additional levels of containment, and those occurring outdoors. Process equipment and piping for UF_6 is generally assumed to be located indoors. A further consideration is the possible (though perhaps marginal) containment afforded by steam chests used to homogenize UF_6 in cylinders at UF_6 production facilities and to vaporize UF_6 at fuel fabrication facilities. While most steam chests are located indoors, some are located outdoors (at least at one UF_6 production facility). Therefore, three location categories are used: indoors, outdoors, and inside steam chests.

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Table 8. Correspondence between postulated scenarios and various methods for catagorizing those scenarios

	Location			Release source (equipment)					Phase of release				Flow characteristics		Release causes					Some possible initiating events				Inventory groupings				
	Indoors	Outdoors	Inside steam chest[a]	Cylinders	Cylinder fittings	Cold traps	Vessel type equipment	Other process equipment	Liquid	Liquid plus vapor	Vapor plus solid	Vapor	Jet release	Explosive release	Mechanical failure of containment caused by overpressure	Mechanical failure of containment caused by impact	Mechanical failure of containment caused by dropping	Mechanical failure of containment under normal process conditions	Operator error[b]	Operator error[b]	Equipment failure under normal conditions[c]	Natural phenomena	Fire	Fluorination/cold trapping	Distillation system	Cylinder filling and indoor cylinder handling	Outdoor handling and storage of liquid filled cylinders	Homogenization and fuel fabrication feed
1. UF_6 cylinder failures																												
1.1 Introduction of reactive hydrocarbons into a cylinder	•	•	•	•					•	•			•	•	•					•						•	•	•
1.2 Impact of a liquid filled cylinder against an object or impact of an object on a cylinder	•	•		•	•				•	•			•			•	•			•	•	•				•	•	
1.3 Valve or pigtail failure due to movement of a connected cylinder containing UF_6	•	•	•		•				•	•	•	•	•							•		•				•		•
1.4 Hydraulic rupture of a cylinder exposed to fire	•	•		•					•	•		•	•	•	•								•			•	•	•
1.5 Hydraulic rupture of an overheated cylinder	•	•	•	•					•	•			•	•	•					•								•
1.6 Hydraulic rupture of an overfilled cylinder	•	•	•	•					•	•	•		•	•	•					•								•
1.7 Heating or filling a defective cylinder	•	•	•	•					•	•	•	•	•	•				•		•						•		•
1.8 Heating a cylinder containing excessive volatile and/or gaseous contaminants	•	•	•	•					•	•	•		•	•	•					•								•
1.9 Dropping a liquid filled cylinder	•	•		•					•	•			•				•			•	•	•				•	•	
2. UF_6 process system failures																												
2.1 Excessive heating of process equipment containing solidified UF_6	•			•	•		•	•			•		•	•	•					•			•	•	•	•		•
2.2 Fatigue failure of a process system	•				•			•	•	•	•	•	•					•						•	•	•		•
2.3 Impact on a process system containing UF_6	•			•	•	•	•	•	•	•	•	•	•			•				•	•	•		•	•	•		•
2.4 Valve failure of a cylinder or a system containing UF_6	•	•	•		•			•	•	•	•	•	•			•		•	•	•	•			•	•	•	•	•
2.5 Pigtail failure	•		•		•				•	•	•	•	•					•		•		•				•		•
2.6 Process system loss of containment caused by natural phenomena	•	•	•	•	•	•	•	•	•	•	•	•	•			•	•					•		•	•	•	•	•
2.7 Heating a cold trap containing excessive volatile and/or gaseous contaminants	•					•			•	•		•	•	•	•					•			•		•	•		
2.8 Heating an overfilled cold trap	•					•			•	•		•	•	•	•					•			•		•	•		
2.9 Overheating a cold trap	•					•			•	•		•	•	•	•					•			•		•	•		
2.10 Cold trap failure caused by corrosion, fatigue, or thermal shock	•					•			•	•	•	•	•					•						•	•	•		
2.11 Venting of UF_6 through a hydrolyzer	•						•					•	•						•	•	•							•
3. Nuclear criticality events[d]																												
3.1 Nuclear criticality in a UF_6 vaporizer[e]			•																	•	•							
3.2 Nuclear criticality resulting from a safe spacing violation	•	•																		•		•						
4. Operator errors																												
4.1 Valving a cold trap to a vacant position	•					•			•	•	•	•	•						•	•						•		
4.2 Bypassing safety controls	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•			•				•	•	•	•	•
4.3 Removing a valve from a cylinder containing UF_6	•			•					•	•	•	•	•						•	•						•	•	•

[a] A steam chest may be located indoors or outdoors. Some facilities use other means for heating cylinders (scenarios 1.5 through 1.8), which may also be indoors or outdoors.

[b] Operator error can be directly responsible for a release, as in scenario 4.1, or operator error can initiate or contribute to the course of an accident.

[c] Equipment failure refers to failure of noncontainment related equipment that initiates an accident leading to loss of containment (e.g., a lifting device failure could initiate scenario 1.9).

[d] These events are illustrative of types of criticality events.

[e] A UF_6 release in the absence of safety controls may lead to criticality.

7.1.2 Release Source (Equipment)

Due to their frequent handling and use, it is believed that pigtails are the most likely source for release of UF_6, followed by cylinders and their associated valves and fittings. Fixed process equipment and piping are expected to be less vulnerable. Scenarios are divided by equipment into several release source groups: cylinders; fittings (including pigtails) for charging and discharging cylinders; cold traps; vessel-type equipment (tanks, distillation columns, etc.); and other process equipment (including fixed piping systems with their pumps, valves, etc.).

7.1.3 Phase of Release

All accidents involving liquid UF_6 released to atmospheric pressure will ultimately release solid UF_6 particles and UF_6 vapor that will react with moisture in the ambient environment to form UO_2F_2 or UO_2F_2-coated UF_6 particles. Prior to release, UF_6 will exist in either the liquid or vapor phase or in two-phase equilibrium of either liquid and vapor or vapor and solid. UF_6 in piping systems will probably be in a single phase, but UF_6 in cylinders or vessel-type equipment will always exist in two phases. For practical purposes, however, a cold cylinder containing UF_6 may be assumed to contain only solid UF_6 because the UF_6 vapor available would produce only a niusance release.

7.1.4 Flow Characteristics

The flow characteristics of a UF_6 release will be important, particularly if a very exact simulation of a release is attempted. The flow characteristics will set release rates and the rate of mixing of UF_6 with the ambient atmosphere. There are three categories of initial release characteristics that can be conceptualized following loss of containment: an explosive release, a jet, and a slowly expanding cloud. A release that can be categorized as a slowly expanding cloud is expected to result only from an accident involving solid UF_6; therefore, because the release will not be significant, this release category is not considered further. However, an explosive release or a jet release may often be characterized by a slowly expanding cloud after the initial momentum of the release has been transferred to entrained air.

A hydrodynamic model (see Sect. 7.3) can then be used to analyze the mass transport of UF_6 in a compartment. Releases involving liquid UF_6 will generate large amounts of vapor as the liquid flashes to solid and vapor as it expands to 1 atm. A jet may originate from either a regular opening (e.g., a circle when a pipe breaks) or an irregular opening (e.g., a rupture in a cylinder wall). Releases from irregular openings are normally approximated by jets resulting from well-defined openings (e.g., circles, rectangles, slots, etc.). Releases from very large openings may often be approximated as instantaneous releases if the release time is relatively short. If equipment has relatively weak areas, possibly caused by corrosion or defective welds, overpressurization will be more likely to cause a rupture resulting in a jet. If the equipment has no weak areas or if overpressurization occurs rapidly, however, the equipment may explode and form fragments. Analysis methods for directed jets and explosive releases are discussed further in Sect. 7.3.

7.1.5 Release Causes

A release of UF_6 may result from a sequence of events or one event. A release cause is defined as the end event; that is, the last event in a sequence that results in the release of UF_6 (e.g., overpressure for scenario 1.5 and operator error for scenario 4.1). Possible release causes include mechanical failure from overpressure, impact, or dropping, mechanical failure under normal process conditions, and operator error. A comparison of primary release causes and release sources yields several generic events that may be analyzed in a similar manner:

1. loss of cylinder containment by overpressure (1.1, 1.5, 1.6, 1.7, 1.8, 1.4);
2. loss of cylinder containment by impact/dropping (1.2, 1.9, 4.3);
3. loss of cold trap containment by overpressure (2.7, 2.8, 2.9, 2.10); and
4. pigtail failure (1.3, 2.1, 2 3, 2.5).

Actual conditions for a generic event may vary depending on the specific scenario under consideration (1.7 could occur at or below normal operating conditions), and post release analysis could be complicated [e.g., consequences of a UF_6 release in a fire (1.4) may differ significantly from other cylinder releases]. Scenarios 1.1 and 1.4 may require special analytical consideration because of the possibility of a rapid pressure rise.

7.1.6 Initiating Events

Initiating events include operator error, equipment failure under normal conditions [e.g., failure of a cylinder lifting device may lead to rupture of a liquid-filled cylinder (scenario 1.9)], natural phenomena, and fire. An initiating event may be the primary release cause, as in the case of scenario 4.1.

7.1.7 Inventory Groupings

The UF_6 handling processes described in Chapter 4 may be grouped into several systems that are separated by batch operations and that have a definable maximum inventory of UF_6 that is placed at risk following a breach of containment. These systems are

1. System A: Fluorination and Cold Trapping,
2. System B: Distillation,
3. System C: (C.1) Cylinder Filling and (C.2) Indoor Handling of Liquid-Filled Cylinders,
4. System D: (D.1) Outdoor Handling of Liquid-Filled Cylinders and (D.2) Cooldown Storage of Liquid-Filled Cylinders, and
5. System E: (E.1) Homogenization of Cylinder Contents and (E.2) Fuel Fabrication Feed.

All systems except System E.2 are applicable to UF_6 production facilities. System E.2 (and possibly Systems C.2, D.1, and D.2) is applicable to fuel fabrication facilities. Each of these systems consists of process equipment and/or cylinders as well as associated piping; therefore, an accident involving any portion of a system places the total inventory of that system at risk. It should be noted that cold traps operate in several modes, including cooling, heating, and standby. The systems defined above assume that cold traps are being operated in the mode appropriate for that system. Interconnecting piping systems between cold traps operating in different modes are assumed closed in the following discussion;

however, operator error in opening and/or closing valves could combine several systems together. For clarity, such interconnecting piping is not shown in figures illustrating the systems.

Systems A, B, and C.1 are illustrated in Fig. 8 for a UF_6 production facility based on the fluorination-fractional distillation process. The inventory of UF_6 in System A (Fluorination and Cold Trapping) includes the UF_6 produced in the fluorination reactor as well as the UF_6 in the cold traps; however, the UF_6 in the cold traps is primarily solid, so it can probably be neglected in determining the UF_6 inventory. Therefore, the "inventory" at risk in System A consists primarily of the UF_6 production rate multiplied by the time required to shut down after a breach of the system. System B (Distillation) contains several major vessel, of which the distillation columns are assumed to operate continuously. If the distillation feed tanks operate in a batch mode, then this system could be divided into two systems: feed tank filling and distillation. The maximum UF_6 inventory at risk in this system is the sum of the UF_6 initially in the head end cold trap (or traps, if several are drained simultaneously into the feed tanks), the UF_6 in the feed tanks, and the UF_6 in the distillation columns and associated

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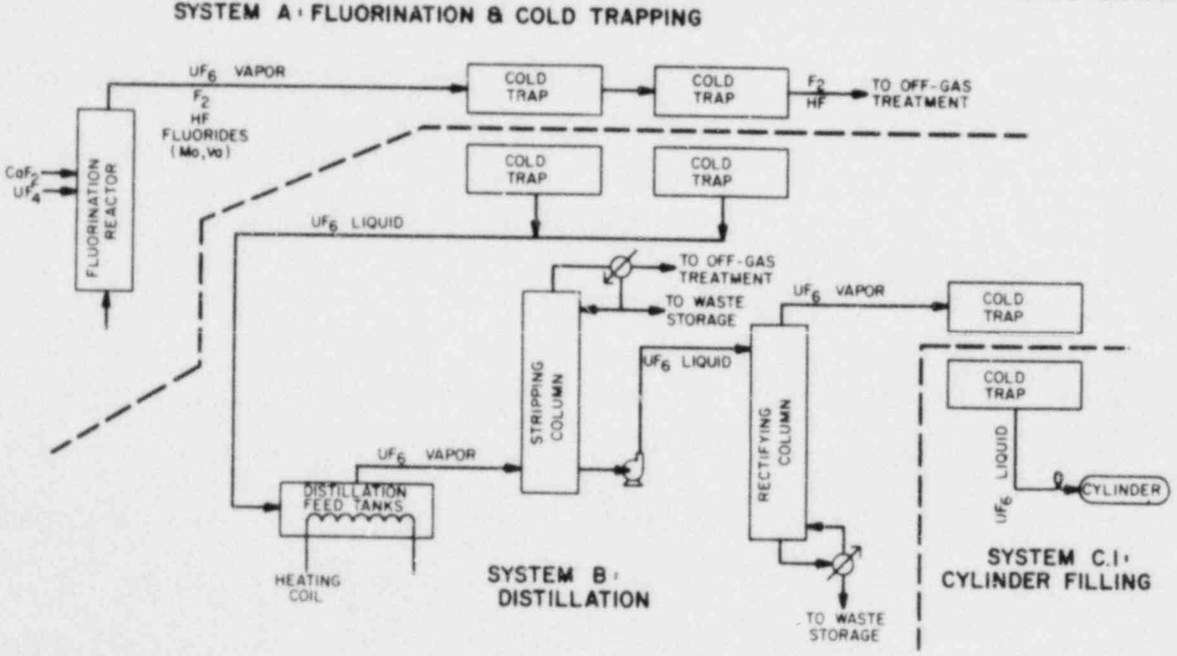

Fig. 8. Major UF_6 handling components and flow paths in a UF_6 production facility based on the fluorination-fractional distillation process illustrating Systems A, B, and C.2 (see Chapter 4 and Fig. 3 for additional process details). Interconnecting piping between systems is assumed closed and is not shown for clarity.

equipment. UF_6 in the tail end cold trap should be solidified and, therefore, would not be a major concern. The inventory of System C.1 (Cylinder Filling), which could total about twice the inventory of a full cylinder, is the sum of the UF_6 initially in the cold trap and of the UF_6 heel initially in the cylinder. All of these systems are assumed to be indoors.

For a facility based on the solvent extraction process, Systems A and C.1 are illustrated in Fig. 9. Note that some details of System A differ between the two facilities but that the major contributor to the UF_6 "inventory" at both facilities is the UF_6 production rate of the fluorination reactor. Because cold traps and cylinders usually used in a facility have approximately the same nominal capacity, Systems C.1 and C.2 (Indoor Handling of Liquid-Filled Cylinders) are similar and are therefore grouped together. Systems C.2, D.1 (Outdoor Handling of Liquid-Filled Cylinders), and D.2 (Cooldown Storage of Liquid-Filled Cylinders), which are not illustrated, consist of a cylinder containing liquid UF_6 along with a small amount of UF_6 vapor. These systems differ only in location and whether or not the cylinder is in transit. The UF_6 at risk in Systems C.2, D.1, and D.2 is the inventory of UF_6 in the cylinder.

System E.2 (Fuel Fabrication Feed), which is found in fuel fabrication facilities, is illustrated by Fig. 10. System E.1 (Homogenization of Cylinder Contents), which is found in UF_6 production facili-

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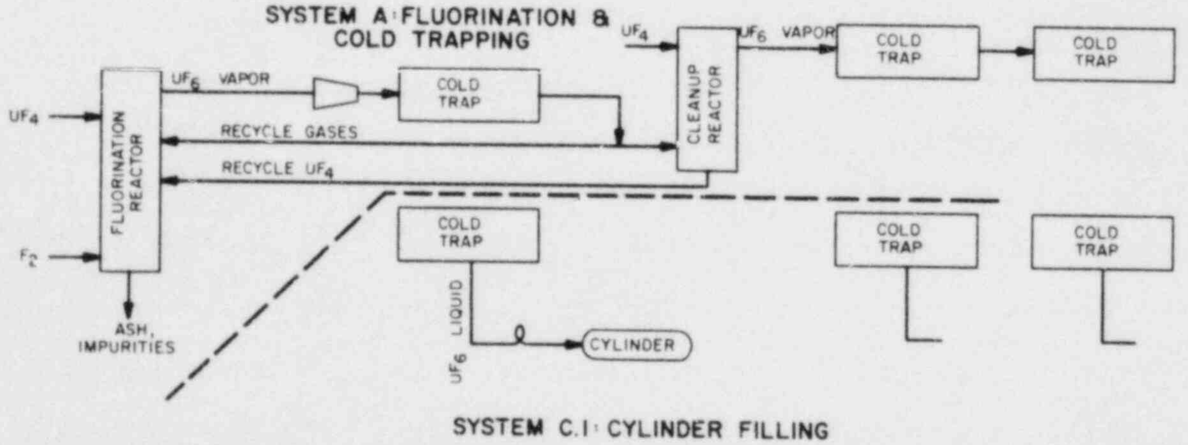

Fig. 9. Major UF_6 handling components and flow paths in a UF_6 production facility based on the solvent extraction process illustrating Systems A and C.1 (see Chapter 4 and Fig. 4 for additional process details). Interconnecting piping between systems is assumed closed and is not shown for clarity.

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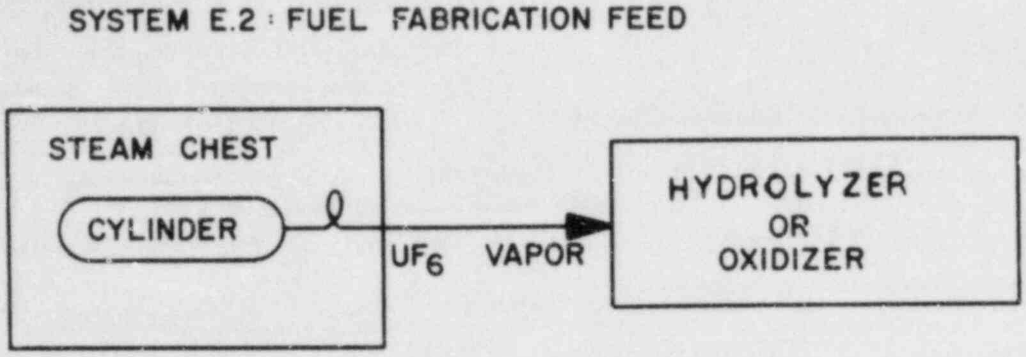

Fig. 10. Major UF_6 handling components and flow paths in a typical fuel fabrication facility illustrating System E.2 (see Chapter 4 and Fig. 5 for additional process details).

ties, is similar to System E.2 except that there is no UF_6 flow out of the cylinder. System E.2 is usually located indoors and will handle cylinders having a smaller capacity than those found in System E.1, which may be located either indoors or outdoors. The maximum UF_6 inventory for System E is the contents of a filled cylinder.

These systems as defined above are based on the assumption that a plant is operating in its normal configuration. If interconnecting piping or manifolds are opened, possibly by operator error, to more than one system, or to parallel systems, different consequences would be expected because of combined UF_6 inventories.

7.2 BOUNDING CONSIDERATIONS FOR UF_6 RELEASE EVENTS

A list of scenarios such as that given in Chapter 5 (see Table 7 or 8) is desirable for identifying potential problem areas and for taking steps to avoid them; however, a consequence analysis for each scenario would be time consuming and probably unnecessary. On the other hand, selecting appropriate release events to hopefully bound the consequences of the various scenarios can be difficult due to the many factors that must be considered. While it may at first appear reasonable to select appropriate release events for consequence analysis based on the total amount of UF_6 released, such a basis may not yield the most severe consequences (health effects, etc.). For example, a low-flow-rate, long-duration release may be more severe than a high-flow-rate, short-duration release even though less total UF_6 is released in the former case than in the latter. Nevertheless, as a first pass, use of total UF_6 released as a major factor for selecting bounding cases may be reasonable (unless UF_6 of several different assays is being handled). A review of the scenario list reveals a number that involve cylinders either directly or indirectly via pigtails. Each scenario places the same amount of UF_6 at risk. Such reasoning, when extended to other equipment, leads to consideration of UF_6 release events based on systems rather than on specific pieces of equipment. Representative systems have been described in the last part of Sect. 7.1 under Inventory Groupings. It should be reiterated that release consequences are not necessarily proportional to the quantity of UF_6 released but that the rate and duration of a release and the location within a facility where the loss of containment occurs can also be important factors.

In looking at potentially bounding events, Systems C, D, and E can be most easily considered. All three systems involve liquid UF_6 in cylinders. The maximum inventory for Systems C.2, D, and E is the cylinder capacity, while that of System C.1 may be greater than cylinder capacity (perhaps by about a factor of 2) depending on cylinder filling procedures (e.g., topping off an almost full cylinder from a full cold trap). Differences between the systems indicate that UF_6 could be released indoors, outdoors, or into a steam chest that may be located indoors or outdoors depending on the facility. At a UF_6 production facility, the nominal capacities of the cylinders handled are 10 and 14 tons, while 2.5-ton and 55-lb cylinders are handled at fuel fabrication facilities, depending on the uranium enrichment of the UF_6. The results of preliminary calculations at saturated conditions (see Fig. 11) indicate that more than 40% of the liquid UF_6 released from a cylinder will flash to vapor when released to the atmosphere. As the temperature of the liquid UF_6 increases, so does the amount of vapor produced. The two curves shown in Fig. 11 thermodynamically bound the initial vapor mass fraction expected as a function of temperature.

The primary contributor to the inventory at risk in System A is the fluorination reactor. Existing facilities in the United States have nominal production rates of 55 and 77 lb/min.[1] Based on a rate of 77 lb/min, it would take over 100 min to produce 8000 lb of UF_6 vapor (40% of the capacity of a

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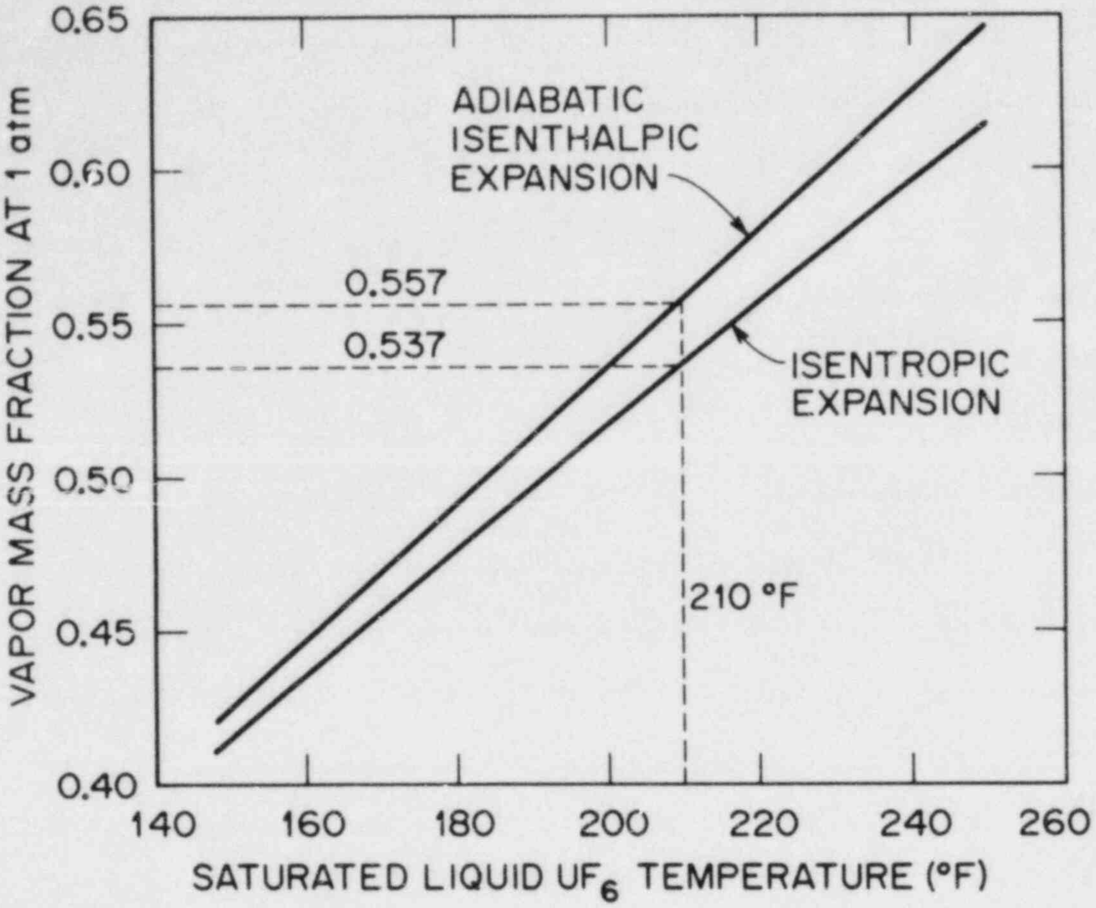

Fig. 11. Initial vapor mass fraction resulting from a release of saturated UF_6 liquid to a pressure of 1 atm. (Example: for saturated UF_6 liquid at 210°F, the initial vapor mass fraction will be between 0.537 and 0.557 when a release to a pressure of 1 atm occurs.)

10-ton cylinder). If the fluroination system can be shut down within that time frame, analysis of an indoor cylinder release may bound a release from the fluorination process.

The distillation system (System B) is the most complex system of the five considered, and its inventory will probably exceed that of a system containing a cylinder. In fact, this system may yield the greatest indoor UF_6 release potential at a UF_6 production facility utilizing distillation to remove impurities found in the natural uranium. If this system can be subdivided because of batch operation of the feed tanks, then the inventory that could be released would be reduced for the two new systems that are subsystems of System B. A further partial reduction in the inventory released might also occur, depending on system configuration and where in the system a breach of containment occurs.

The primary factors in determining which system (A, B, C, or E) presents the greatest release potential indoors are the release rate and release duration. For example, the rate of UF_6 production in the fluorination reactor may or may not exceed the rate of UF_6 release from a ruptured cylinder. Thus, the flow rate of UF_6 out of a cylinder or cylinder containing system is needed as a function of time and cylinder size, and in both cases an analyst would also need to know the maximum duration of the release (i.e., the maximum time required to bring the release under control) to determine and compare the release potential. Similarly, UF_6 flow rates from breaks in the distillation system, which is pressurized, would need to be determined before an appropriate bounding indoor release could be chosen.

At least three types of release events appear reasonable to evaluate at UF_6 handling facilities: (1) a release from a liquid-filled cylinder outdoors (System D), (2) a release from a pigtail or cylinder inside a steam chest (System E), and (3) a release indoors from either (a) a pigtail or liquid-filled cylinder (System C) or (b) other indoor system (Systems A and B). It should be noted that one or more of these events may not be applicable to a specific facility. For example, if liquid-filled cylinders are not handled external to the steam chest at a fuel fabrication facility, then releases directly to the indoor and outdoor environment (as in cases 1 and 3) need not be considered; however, the steam chest should not be assumed to contain the UF_6 unless designed to do so.

Selection of the more severe indoor release will require the determination of release rates and release potentials given the time required to bring a release under control. Facility design may require consideration of more than one indoor release event. A release from a pigtail or a cylinder inside a steam chest differs from the other releases because of the high ambient moisture and the secondary (although perhaps marginal) containment afforded by the steam chest.

While facility design and procedures may greatly affect the ultimate consequences of a release, development of source terms for pigtail and cylinder releases is desirable because such source terms could be used for any facility. Such source terms should be functions of process conditions and UF_6 inventory (e.g., cylinder or cylinder plus cold traps).

The discussion in this section has so far been limited to the release of UF_6 from a single breach that occurs during normal operation. In the event of a more extensive accident (explosion, fire, earthquake, etc.), UF_6 could be released from multiple source points [e.g., several cylinders, a cylinder (fragmented) and other vessels (ruptured by the impact of cylinder fragments), etc.]. Also, if operator error has resulted in opening interconnecting piping or manifold systems, the inventory of several parallel or series systems could be released.

Fire, as a heat source, has the potential for causing vessels containing UF_6 to fail from overpressurization or by weakening welds or walls of vessels or pipes. Once released, UF_6 may react with unburned hydrocarbons. The amount of UF_6 in jeopardy will depend on facility construction and the ability to extinguish the fire. Releases that occur within a building may or may not be closed off from the environment. Outdoor fires could jeopardize cylinder storage areas.

Natural phenomena, such as earthquakes, high winds, tornadoes, and floods, may also jeopardize UF_6 operations. For example, earthquakes could lead to failure of elevated vessels and piping, tornadoes could generate missiles that could penetrate process equipment, and flooding could lead to criticality or equipment damage.

7.3 RELEASE PHENOMENA AND MODELING CONSIDERATIONS

Previous sections of this chapter have introduced a number of variables and approaches useful for analyzing potential UF_6 accident scenarios. This section will address more specifically the phenomena that could be observed following a breach of containment and the types of models that would be needed for simulating these phenomena. The status of some currently existing models applicable to UF_6 release analysis has been discussed in Chapter 6.

7.3.1 Initial Characteristics of UF_6 Releases

Postulated UF_6 release scenarios at NRC-licensed fuel cycle facilities include releases from process equipment, piping, or cylinders containing UF_6. The release form may be a multiphase mixture of UF_6

solid, liquid, and vapor; a multiphase gas-solid mixture; or a single-phase vapor release. The release can be either a short release that may be approximately modeled as an instantaneous release or a longer release that must be modeled as a finite duration release. For many engineering applications, a release lasting less than a few minutes may be approximated as an instantaneous release. The process and ambient conditions prior to the release, as well as the physical characteristics of the breach in the cylinder or pressure equipment, must be considered in developing a source term for a postulated UF_6 release.

At NRC-licensed facilities during normal operation, UF_6 may exist as a vapor, a solid-vapor mixture (e.g., in a cold trap), a liquid-vapor mixture (e.g., in a cooling cylinder, a cold trap on its heating cycle, or distillation column), or as a solid. Batch operations of cold traps and cylinders will result routinely in either liquid-vapor or vapor-solid mixtures being present, but three-phase mixtures would not be expected. Thermodynamic conditions for the existence of UF_6 as a single-phase or as a multiphase mixture can be seen in Fig. 12, a UF_6 temperature-entropy diagram.

Some characteristics of UF_6 behavior following a breach of containment can be illustrated by considering rupture under various initial conditions. For practical purposes a cold cylinder contains only UF_6 solid, although a small amount of UF_6 vapor and trace amounts of noncondensable gases fill the void space within a cylinder at subatmospheric pressure. Therefore, the rupture of a cold cylinder will result only in a small nuisance release limited by the rate of sublimation rather than in a significant health hazard. If a defective cylinder is not inspected prior to subsequent heating, however, a significant release may occur on heating because the undetected damage would result in a weak spot susceptible to failure during heating. On the other hand, the failure of a cylinder containing either pressurized liquid UF_6 or a large amount of UF_6 vapor (up to several hundred pounds in a 10-ton cylinder containing only saturated UF_6 vapor) can result in a significant release. The UFf_6 phase composition (i.e., solid-vapor fraction) after the released material has expanded to 1 atm will depend on the process conditions prior to the release and the release process.

Upper and lower limits of the UF_6 vapor fraction can be estimated from the thermodynamic considerations. If the expansion to 1 atm is assumed to be a reversible, constant entropy (isentropic)

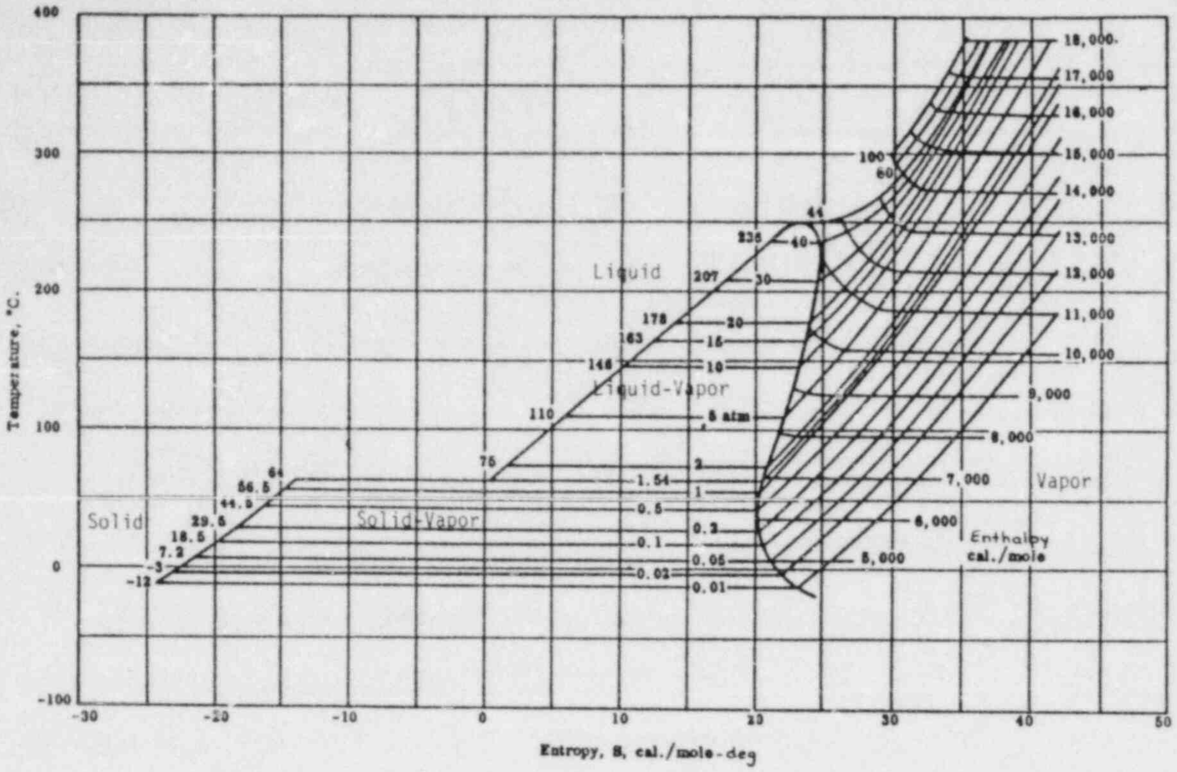

Fig. 12. An approximate temperature-entropy diagram for UF_6 (adapted from ref. 4.4, p. 102). The reference point for both entropy and enthalpy is liquid UF_6 at the triple point.

process, a lower bound on the vapor fraction can be estimated. If an adiabatic, constant enthalpy (isenthalpic) process is assumed, an upper bound on the vapor fraction and an upper bound on the change in entropy can be estimated. As shown in Fig. 11, the vapor fraction after an expansion of liquid to 1 atm will increase with an increased change in entropy. Because the change in entropy is proportional to the exhaust rate of a high velocity release, the vapor fraction for many release scenarios will increase with an increase in the exhaust rate.

7.3.2 Characteristics of Equipment Failure

There are two primary causes for equipment failure: internal overpressure and external mechanical forces (impact or dropping). Potential causes of overpressure include overheating, heating when fill limits or contaminant limits have been exceeded, and chemical reactions between UF_6 and a hydrocarbon(s). Depending on the condition of the equipment, the rate of overpressurization, and the magnitude of the overpressure, the equipment will either rupture (e.g., weld failure, formation of a crack, etc.) or explosively fragment.

If the equipment has relatively weak areas, possibly caused by corrosion or defective welds, or, in the case of cylinders, by transportation damage, an equipment rupture will be the more likely result of overpressurization. However, if the equipment has no weak areas or if the overpressure results from a rapid pressure rise, it may explode and form fragments. These fragments may cause secondary failures by impacting other equipment, and they may represent a significant safety hazard to personnel in the vicinity of the accident.

To determine the failure mode, the postulated accident scenario must be known. For example, if a cylinder containing UF_6 is impacted, it may rupture; however, if a cylinder containing UF_6 fails from an overpressure, it could either rupture or explode. A stress analysis can be used to predict the possible failure mode(s) using information related to the mechanical and thermal loads on the process equipment.

7.3.3 Introduction to Release Analysis

Consideration of the equipment failure modes discussed above leads to the conclusion that at least two generic failure modes are possible: a directed release through an equipment rupture (including pipe breaks and leaking valves) and a multidirectional explosive release. Therefore, multiple analysis tools may be required to develop source terms for postulated releases from equipment containing UF_6. There are two different approaches that the analyst can pursue in characterizing a release into a compartment from equipment containing UF_6 that will be discussed before looking more closely at analyzing the release from the equipment.

The simpler, less accurate approach is to neglect the detailed concentration, pressure, and temperature profiles that develop within the compartment. For certain instantaneous or finite duration releases inside building compartments, a satisfactory source term (for a ventilation model) can be developed by assuming a homogeneous mixture of UF_6, air, and UF_6 hydrolysis products that may vary uniformly within a compartment as a function of time. This type of model will be most accurate when the release is rapid, the ventilation rate from the compartment is sufficiently low, and the size of the compartment is sufficiently small to allow the UF_6 hydrolysis products to become well mixed prior to release from the compartment. If the ventilation rate is high or if the compartment is large, the homogeneous mixture assumption may be significantly in error.

As an alternative to the homogeneous mixture model, the analyst may elect to use a more accurate approach--a hydrodynamic model--to calculate ventilation flow patterns and temperature, pressure, and composition profiles inside the compartment. The use of a hydrodynamic model would yield more accurate estimates and becomes necessary if time-dependent, spatial variations in concentrations of UF_6 and its hydrolysis products are important. Its use, however, would be expensive, not only because a single run would be more expensive, but also because multiple runs may be required to fully characterize potential releases (e.g., a liquid-filled cylinder could be dropped at several different points in a compartment with each drop having different results). The source term for such a hydrodynamic model would probably be described by source characteristics at the release point such as the release rate, direction, composition, and exhaust area, rather than a description of the process conditions prior to the release and the failure mode of the UF_6 containment. However, the error that may be associated with the attempt to model the mixing of a chemically reacting substance such as UF_6 within a compartment or a section of a compartment may be deemed sufficiently large to justify the use of the less rigorous homogeneous mixture model.

7.3.4 Analysis of a Directed Release

A directed release can be categorized according to the nature of the flow (i.e., choked or unchoked) and the level of interaction with solid surfaces. If the flow is choked, the release rate can be determined from the process conditions and flow area at the choked flow location. However, if the flow is not choked, a flow analysis must be used to determine the release rate from the pressure differential across the flow passage and the geometry of the flow passage. As noted in Sect. 6.2, several techniques are available for predicting UF_6 flow rates through pipes, nozzles, valves, and other flow passages. The calculated flow rate could then be used as a source term either for the homogeneous compartment model or the more accurate hydraulic models.

After the UF_6 release rate from a rupture has been determined, the next step is to analyze the initial flow characteristics of a directed release. As shown in Fig. 13, there are three basic configurations: a vertical release directed down, a vertical release directed up, and a horizontal release.

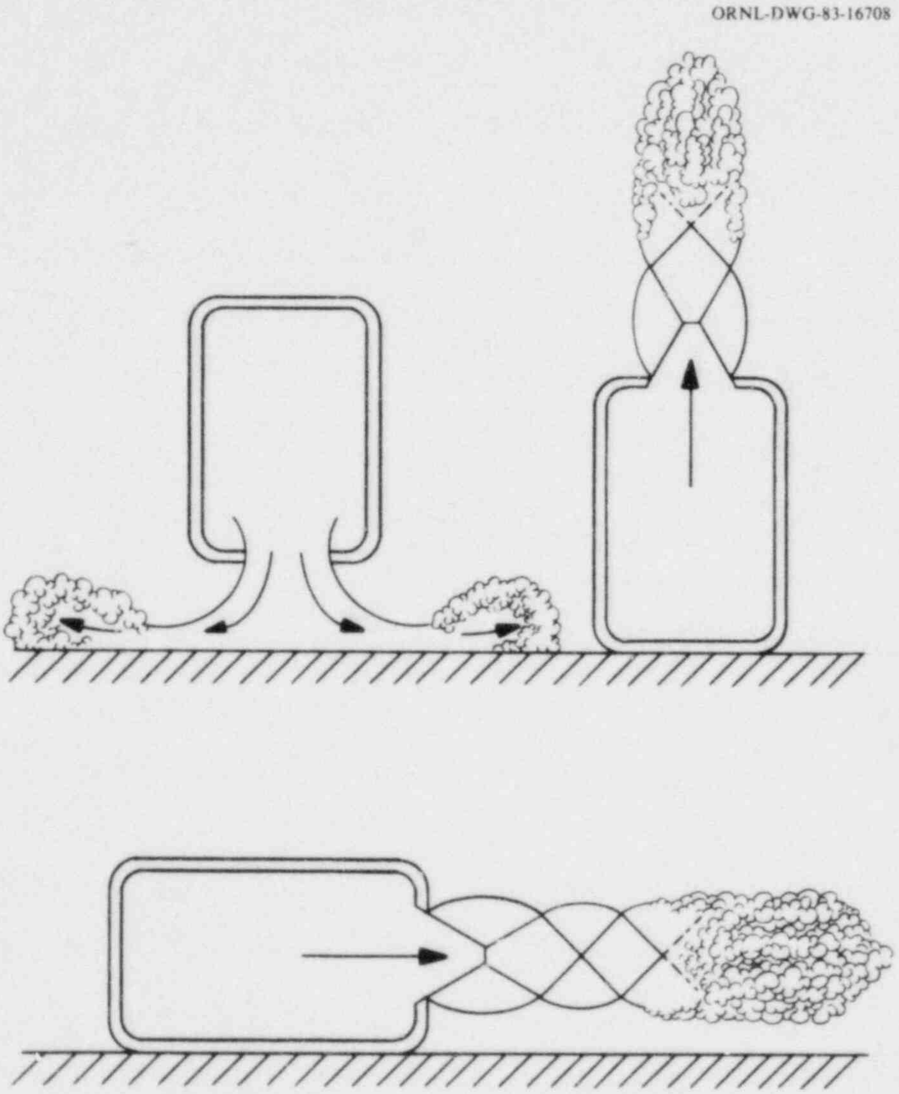

Fig. 13. Three basic configurations for a directed release.

If a release is directed down, usually the exhaust stream will impinge on the ground (or floor of a compartment), resulting in an "axisymmetric," expanding, ground-hovering cloud of UF_6. However, for low velocity or elevated releases, the downward momentum may be completely transferred to the surrounding air through entrainment, resulting in a UF_6 cloud below the release point.

If the release is directed up, the UF_6 will usually be diluted with ambient air through entrainment prior to significant interaction with process equipment or the walls and ceiling of the compartment. However, if the release has a large initial horizontal velocity component, the UF_6 will often have significant interactions with process equipment and/or compartment enclosures.

The initial flow characteristics of a directed UF_6 release that does not impinge on process equipment or compartment enclosures may be analyzed using a jet method such as the one described in Sect. 6.2 Such a method can be used to predict the initial trajectory of the directed UF_6 release, the dilution rate with the ambient air, the chemical reactions with the ambient moisture entrained into the jet. etc. After the jet has expanded to 1 atm and after the initial momentum has been dissipated to the entrained air, the jet characteristics can be used to develop the input data for a hydrodynamic model of the compartment.

If UF_6 contacts solid surfaces, such as process equipment, the velocity, direction, and temperature of the UF_6 may be significantly altered. A multidimensional hydrodynamic model is required to predict the characteristics of the mixture of air, UF_6, and UF_6 hydrolysis products that result from a directed UF_6 release. The model must be able to predict the flow of the mixture of UF_6 and UF_6 hydrolysis products in the vicinity of solid surfaces (e.g., around process equipment) and the exothermic chemical reactions associated with UF_6 hydrolysis, if composition, temperature, and pressure profiles are to be "accurately" predicted. The accuracy of such a model would be further improved if heat transfer to solid surfaces and depletion mechanisms are also simulated. It is believed that a significant effort would be required to develop such a model.

7.3.5 Analysis of an Explosive Fragmentation

As noted previously, if a piece of equipment fails explosively, the resulting fragments may form projectiles that may endanger personnel in the vicinity of the accident and that may cause significant damage and additional failures by impacting process equipment. The number of projectiles, their sizes, and their velocities may be estimated using standard techniques.[7] If UF_6 hydrolysis is neglected during the initial expansion, the explosive release of UF_6 vapor can also be characterized (temperature, pressure, velocity, etc.) by using available techniques for the analysis of a pressurized gas release.[8] If the effects of UF_6 hydrolysis are included, a hydrodynamic model similar to the model described above will be required to accurately predict composition, pressure, and temperature profiles during the initial expansion of a UF_6 vapor release. Alternatively, a homogeneous mixture model may be used to develop a source term (temperature, pressure, composition, etc.) for a ventilation model.

The analysis of an explosive liquid UF_6 release is very complex. The liquid UF_6 will flash to form a gas-liquid mixture as the UF_6 expands to the triple point at 1.54 atm. As the UF_6 mixture further expands to 1 atm, it becomes a vapor-solid mixture. Therefore, an explosive release of UF_6 liquid may result in a three-phase "cloud" containing a mixture of UF_6 liquid, solid, and vapor. Because the standard techniques for analyzing an explosion assume the isentropic expansion of an inert perfect gas,[9] they are inapplicable for the proper analysis of a flashing chemically reacting substance such as UF_6.

If liquid UF_6 is rapidly depressurized, a rarefaction wave will pass through the liquid UF_6, forming small UF_6 vapor bubbles. Although only trace amounts of UF_6 bubbles will be present initially, the presence of these bubbles can reduce the sonic velocity in the liquid UF_6 significantly (see Figs. 14 and 15 for some preliminary results). As the rarefaction wave passes through the UF_6, the outer layer of liquid UF_6 will form an expanding cloud of UF_6. The rate of this expansion will be limited by the sonic velocity of the UF_6 mixture and that of air. The analysis of this expansion should account for shock waves either in the UF_6 or in the ambient air, flashing of liquid UF_6 in the cloud, and the UF_6 hydrolysis reaction.

7.3.6 Analysis of a UF_6 Release in the Presence of a Fire

The analysis of a fire inside a UF_6 handling facility will include characterization of the fire phenomenon itself and associated heat transfer to process equipment, the failure of process equipment due to the effects of the fire, and the interactions between released UF_6 and the fire. The fire transport

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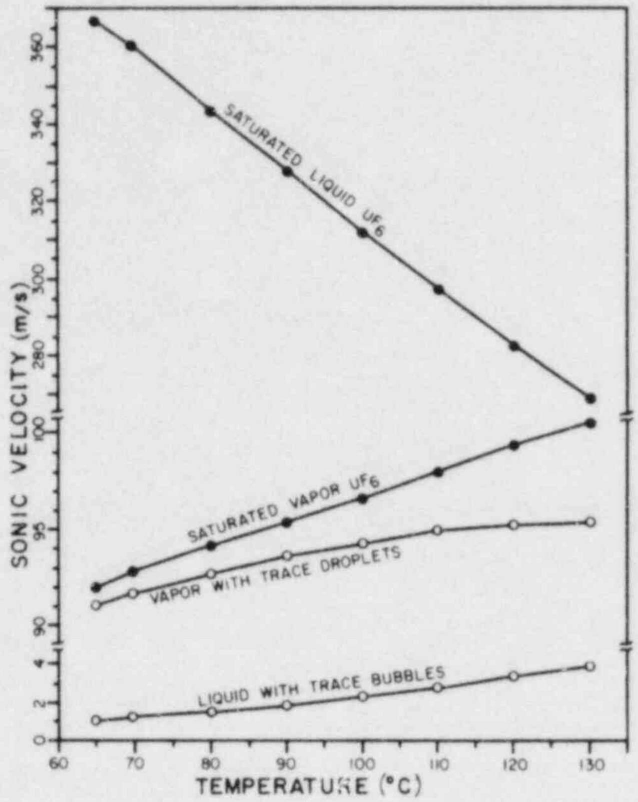

Fig. 14. Predicted sonic velocities as functions of temperature for UF_6 at saturated conditions.

and energetics can be simulated by codes such as FIRAC prior to the release of UF_6, and possible failures of process equipment may be predictable given the fire characteristics. When UF_6 is released from containment, however, the chemical reactions between UF_6 and hydrocarbons present in the fire will be much harder to characterize. Therefore the more important UF_6-hydrocarbon reactions should be incorporated into FIRAC as it is further refined and developed.

7.3.7 UF_6-Hydrocarbon Reactions*

The reaction between UF_6 and hydrocarbons is expected to only marginally increase the severity of a fire from the standpoint of total heat generated; however, the rate of combustion may increase. If

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* Based on Ref. 10 and personal communication with E. J. Barber, Oak Ridge Gaseous Diffusion Plant, Oak Ridge, Tennessee, February 24, 1983.

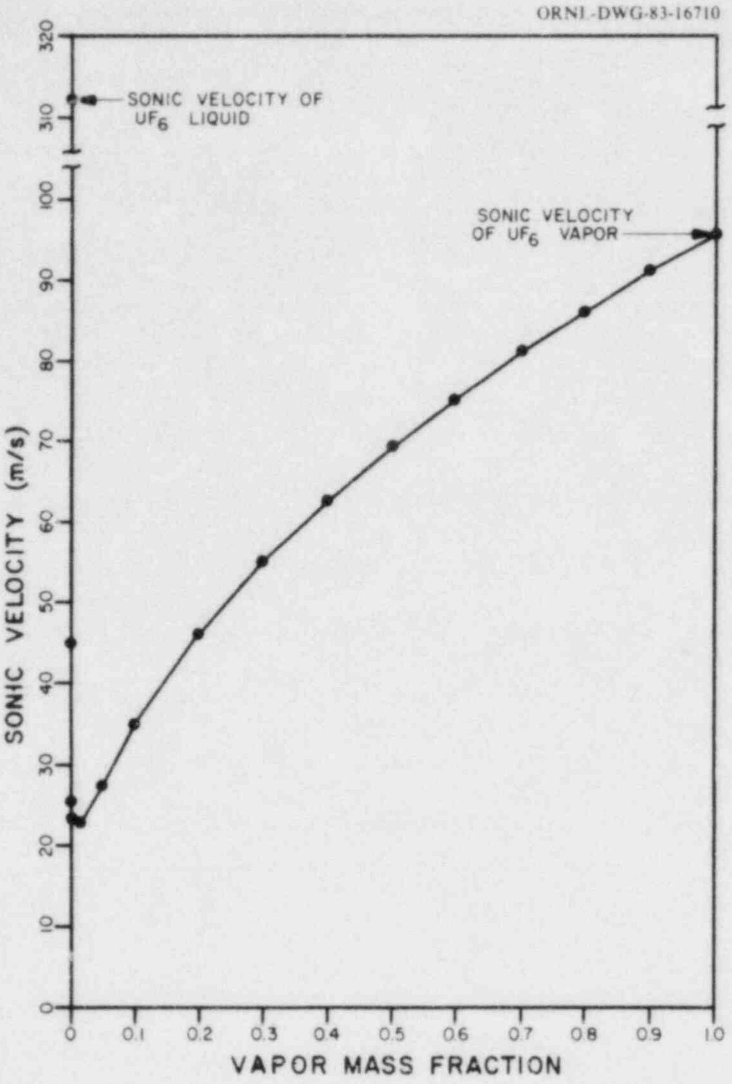


Fig. 15. Predicted sonic velocity as a function of vapor mass fraction for saturated UF_6 at 100°C and 4.12 atm.

UF_6 reacts with water formed by hydrocarbon combustion,the fire could be slightly more severe than if UF_6 reacted only with hydrocarbons. The UF_6-hydrocarbon reactions will form carbon-based fluorides (such as CF_4), UF_4, and HF.

UF_6 liquid can also react with hydrocarbons inadvertently introduced into a cylinder and may lead to failure of the cylinder by overpressure if sufficient hydrocarbons are present. The rate of reaction between liquid UF_6 and hydrocarbons is expected to increase with time as UF_6 dissolves into the oil phase. The energy release rate may reach such a velocity that the reacting UF_6-oil phase actually detonates.

7.3.8 Special Concerns When Handling Highly Enriched Uranium

Some fuel fabrication facilities handle highly enriched uranium (including fully enriched uranium that is approximately 97% ^{235}U). In addition to criticality, another concern beyond the scope of this study that should be kept in mind when assessing consequences of postulated accidents involving UF_6 is the high alpha activity resulting from the presence of ^{234}U in the highly enriched uranium because the concentration of ^{234}U is also increased over its natural concentration by the enrichment process. It is possible that radiological concerns may become primary in assessing the consequences of a postulated release at those facilities handling highly enriched uranium while chemical toxicity effects will probably be of greater concern to facilities handling only low enriched uranium.

Methodologies for determining conditions that may result in criticality have not been considered during this study.

7.3.9 Analysis of a UF_6 Release Outdoors

A release of UF_6 from damaged equipment outdoors at ground level results in a direct intrusion of UF_6 into the environment. Although source term determination for an outdoor release can follow approaches similar to those discussed for indoor releases, analysis of the dispersion of UF_6 and its hydrolysis products after the release is very complex in both the near- and far-field zones. Near-field analysis may be greatly affected by buildings and other structures and site topography. UF_6 may be trapped between buildings or on the downwind side of a building and only slowly be entrained into the bulk flow of air. The presence of ventilation system air intakes near a release may draw UF_6 into buildings. Such near-field concerns, if inadequately addressed, could lead to nonconservative estimates of on-site worker exposure. Other complicating factors to consider include the use of plugs (to stop the release) and knock-down procedures (to "wash out" UF_6 from the air) used to minimize the release of UF_6.

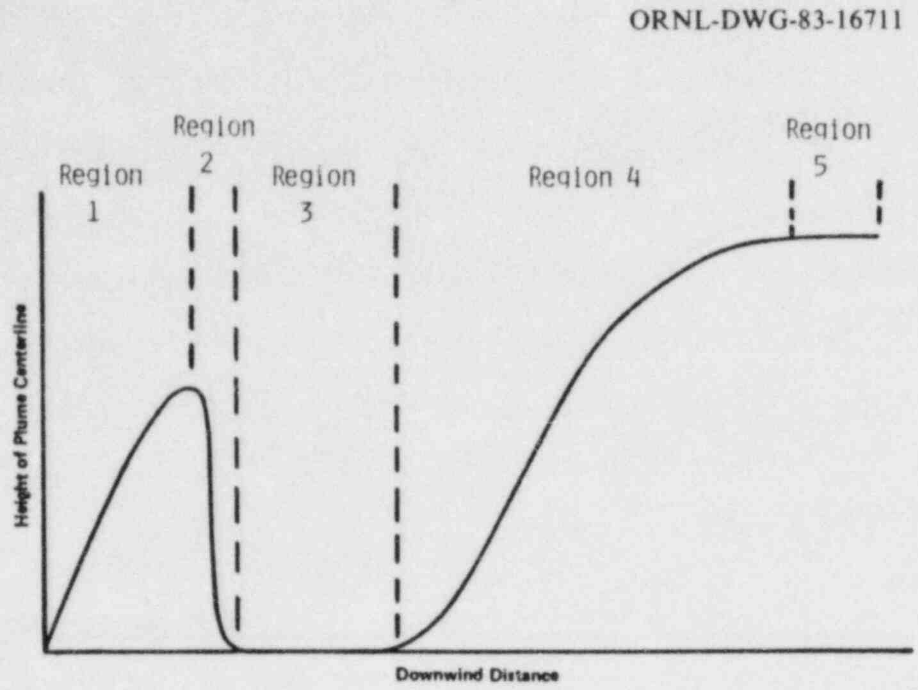
Far-field analysis will be complicated because of the unique aspects of UF_6 plume behavior. The plume may be positively, negatively, or neutrally buoyant, depending on its composition and temperature, and it may be elevated or ground hovering (gravity spreading). Exothermic reactions associated with the hydrolysis of UF_6 and HF will occur and solid UF_6 particles may sublimate while HF hydrates and condenses. Plume density may decrease significantly as UF_6 reacts with ambient moisture and the plume is diluted by entrained air (the density of UF_6 is about 0.93 lb/ft^3, while the density of air is about 0.076 lb/ft^3 at 60°F). Figure 16 illustrates the possible behavior of a plume following a moderate-velocity, vertical release of UF_6.

7.4 PERSPECTIVE SUMMARY

UF_6 accident scenarios can be categorized by location, source, initial phase(s), flow characteristics, release causes,and inventory at risk. Release locations include indoors, outdoors, and inside a steam chest. Sources for UF_6 releases include cylinders, cylinder fittings (including pigtails and valves), cold traps, and other process equipment. Immediately prior to release UF_6 may exist as a liquid or vapor or as a multiphase mixture of liquid and vapor or vapor and solid. Flow characteristics can be represented by a jet release or an explosive release. A number of primary causes for release were identified to show that some accident scenarios could be consolidated for analysis of event consequences. Some initiating events were also identified.

A basis for discussing some bounding considerations for UF_6 release events was to define systems of equipment that are separated by batch operations and that have a definable maximum inventory at risk. Subsequent discussion led to the selection of at least three types of UF_6 releases that should be considered further:

1. a release from a liquid-filled cylinder outdoors;
2. a release from a pigtail or cylinder inside a steam chest; and
3. a release indoors from either (a) a pigtail or liquid-filled cylinder or (b) other indoor system.



Region 1: A negatively buoyant mixture of UF_6, air, water, and UF_6 hydrolysis products rises until the initial vertical momentum is "transferred" to the entrained air and water.

Region 2: The negatively buoyant plume will fall to the ground unless the decrease in density resulting from chemical reactions and entrained air is sufficient to form a buoyant plume prior to plume touchdown.

Region 3: A ground-hovering (gravity-spreading) plume is transported downwind, while entraining air and water at a reduced rate, until the plume becomes buoyant.

Region 4: The buoyant plume lifts off from the ground, rises until further entrainment and UF_6 hydrolysis produces an inert, neutrally buoyant plume.

Region 5: The plume may be adequately modeled as a Gaussian plume.

Fig. 16. Example of a possible plume trajectory from a moderate-velocity, vertical release of UF_6 vapor.

Selection of an indoor release would be based on an evaluation of release rates from the various systems containing UF_6.

It is suggested that generic source terms for the release of UF_6 from pigtails and cylinders be developed because of their applicability to the above releases. These source terms should be functions of process conditions and UF_6 inventory and would be time dependent.

There are two general approaches to modeling indoor UF_6 releases. One approach is to analyze a worst case scenario using approximate models to obtain a conservative estimate. This approach would use a homogeneous mixture model for determining source terms for a ventilation model. A more accurate (and also more expensive) approach is to characterize release behavior in the momentum-dominated zone of a compartment by using a directed or explosive release model and in the rest of the compartment by using a hydrodynamic model to determine the time-dependent, spatial variation in temperature, pressure, and composition. The relative benefit of using one model over the other would need to be considered with respect to the relationship between release rate, ventilation rate, and compartment size; the accuracy of the ventilation system and atmospheric dispersion models to be used; and the type of information desired (e.g., the time available for evacuating the room with respect to operator location).

Analysis of directed UF_6 releases will require analytical tools to predict

1. the perturbations in process conditions caused by the release;
2. the flow characteristics through process equipment to determine release rate, composition, and temperature;
3. the behavior of a jet in the region where the jet's momentum and buoyancy dominate the jet trajectory;
4. interactions between a jet and solid surfaces (e.g., change in flow direction, deposition, and heat transfer);
5. the behavior of the resulting cloud of UF_6 and UF_6 hydrolysis products when diffusion and convective processes are dominant (including hovering plumes); and

6. the time-dependent composition, temperature, pressure, etc., of the compartment atmosphere during and following the release (homogeneous or hydrodynamic model).

Analysis of explosive-type UF_6 release will require analytical tools to predict

1. possible failure mode(s) of equipment (e.g., weld failure, explosive fragmentation);
2. the number of fragments, as well as their sizes and velocities;
3. the behavior of flashing liquid UF_6;
4. the flow characteristics of an expanding cloud of UF_6; and
5. the time-dependent composition, temperature, pressure, etc., of the compartment atmosphere during and following the release (homogeneous or hydrodynamic model).

A few additional problem areas of particular interest when analyzing UF_6 accident scenarios were also discussed briefly. These areas included fire-related releases of UF_6, UF_6-hydrocarbon reactions, the release of high-assay UF_6, and UF_6 plume behavior outdoors.

8. CALCULATIONAL METHODS NEEDED FOR ANALYZING UF_6 RELEASES

Based on the scenarios presented in Chapter 5 and the modelling considerations discussed in Chapter 7, a list of 28 calculational methods required for either a first-order approximation or a more accurate analysis of a postulated UF_6 release was prepared. The applicability of the 28 methods to the 25 accident scenarios is given in Table 9 based on whether the scenario can result in a directed or an explosive release of UF_6. Table 10 shows the availability of the various methods and the level of need (first-order approximation or more accurate analysis). Methods 8 through 13 and 21 are considered as necessary for a first-order approximation. Some requirements for these methods are briefly discussed below in the same order as they appear in Tables 9 and 10.

8.1 METHODS FOR PREDICTING FAILURE MODES

The first six methods appearing in Tables 9 and 10 are useful for predicting the failure mode of equipment containing UF_6. Methods 1 and 2 are concerned with predicting internal forces acting to breach the containment, while methods 3 through 5 deal with external forces. Method 6 applies applicable forces to the containment to determine potential failure modes and characteristics of the breach.

1. Liquid UF_6 — Hydrocarbon Chemical Reactions

   An estimate of the heat liberated from these reactions, the rates of reaction, and the change in chemical composition is required to predict the pressure and temperature inside a containment vessel (e.g., a cylinder).

2. Physical and Thermodynamic Conditions Immediately Prior to Failure of Containment

   The temperature and pressure of the process stream immediately prior to failure must be known to determine the possible failure mode(s). The characteristics of the process stream (e.g., phase, composition, etc.) must be known to evaluate the initial release rate. Temperature-pressure time histories may be required for some stress analyses.

3. Effects of Natural Phenomena (Earthquakes, Tornadoes, High Winds, etc.)

The effects of natural phenomena, such as pressure of impulse loading, must be known to predict possible failure modes. For example, the pressure force resulting from a high wind might cause a crane to fall with a resultant loss of containment through an impact on a containment vessel.

4. Characteristics of an Impact on Process Equipment

The characteristics of an impact including the mass, inertia, and shape of projectile(s) and their point(s) of impact are required to predict the failure mode of an impacted piece of equipment. For example, a highly localized impact force could puncture the containment vessel, while a distributed force could result in a weld failure.

5. Characteristics of a Drop of Process Equipment

As for an impact on process equipment, the prediction of the failure mode of a dropped piece of process equipment requires the evaluation of the impact forces. Analysis will use the mass, inertia, shape, and orientation of containment at the point of impact and the characteristics of the impact surfaces.

6. Failure Mode(s) of Containment

To predict the release rate after a loss in UF_6 containment, a failure mode must be predicted. If a directed release is predicted (e.g., from a weld failure, valve failure, etc.), the geometric characteristics of the flow channel must be known to predict the release rate.

8.2 METHODS FOR PREDICTING SECONDARY FAILURES

The seventh method appearing in Tables 9 and 10 is useful for evaluating secondary effects following loss of containment from the primary equipment of interest.

7. Number of Fragments, Their Sizes and Velocities

If an explosive-type release is postulated, the resultant projectiles may cause secondary failures by impacting other equipment.

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Table 9. Applicability of calculational methods to analysis of postulated UF$_6$ release scenarios

Calculational methods	UF$_6$ cylinder failures									UF$_6$ process system failures											Nuclear criticality events		Operator errors[a]		
	1.1 Introduction of reactive hydrocarbons into a cylinder	1.2 Impact of a liquid-filled cylinder against an object or impact of an object on a cylinder	1.3 Valve or pigtail failure due to movement of a connected cylinder containing UF$_6$	1.4 Hydraulic rupture of a cylinder exposed to fire	1.5 Hydraulic rupture of an overheated cylinder	1.6 Hydraulic rupture of an overfilled cylinder	1.7 [illegible] H$_2$O filling a defective cylinder	1.8 Heating a cylinder containing excessive volatile and/or gaseous contaminants	1.9 Dropping a liquid filled cylinder	2.1 Excessive heating of process equipment containing solidified UF$_6$	2.2 Fatigue failure of a process system	2.3 Impact on a process system containing UF$_6$	2.4 Valve failure of a cylinder or a system containing UF$_6$	2.5 Pigtail failure	2.6 Process system loss of containment caused by natural phenomena	2.7 Heating a cold trap containing excessive volatile and/or gaseous contaminants	2.8 Heating an overfilled cold trap	2.9 Overheating a cold trap	2.10 Cold trap failure caused by corrosion, fatigue, or thermal shock	2.11 Venting of UF$_6$ through a hydrolyzer	3.1 Nuclear criticality in a UF$_6$ vaporizer	3.2 Nuclear criticality resulting from a safe spacing violation	4.1 Valving a cold trap to a vacant position	4.2 Bypassing safety controls	4.3 Removing a valve or from a cylinder containing UF$_6$
1. Liquid UF$_6$ – hydrocarbon chemical reactions (e.g., inside a cylinder)	B																								
2. Physical and thermodynamic conditions immediately prior to failure of containment (time history may be required for some stress analyses)	B	D	D	B	B	B	B	B	D	B	D	D	D	D	D	B	B	B	D	D			D	B	D
3. Effects of natural phenomena (earthquakes, tornadoes, high winds, etc.)															D										
4. Characteristics of an impact on process equipment (includes the mass, inertia, and shape of projectile(s) and their point(s) of impact)		D										D													
5. Characteristics of a drop of process equipment (includes the mass, inertia, shape, and orientation of containment at the point of impact and the characteristics of the impact surface)									D																
6. Failure model(s) of containment (including geometric description of failure)	B	D	D	B	B	E	B	B	D	E	D	D	D	D	D	B	B	B	D	D			D	B	D
7. Number of fragments, their sizes and velocities	E			E	E	E	E	E		E						E	E	E						E	
8. Characteristics of flow through equipment and piping	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D			D	D	D
9. Characteristics of flow through a rupture in containment	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D			D	D	D
10. Time dependent, physical and thermodynamic conditions during release	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D			D	D	D
11. Characteristics of flashing liquid UF$_6$	B	D	D	D	B	B	B	B	D	B	D	D	D	D	D	B	B	B	D	D			D	B	D
12. Choke flow criteria for multiphase UF$_6$ systems (sonic velocity)	B	D	D	B	B	B	B	B	D	B	D	D	D	D	D	B	B	B	D	D			D	B	D
13. Chemical reactions between UF$_6$ and moist air (including energy balances, density changes, etc.)	B	D	D	B	B	B	B	B	D	B	D	D	D	D	D	B	B	B	D	D			D	B	D
14. UF$_6$-steam interactions inside a steam chest	D		D		D	D	D	D					D	D	D									D	
15. Release of UF$_6$ and UF$_6$ hydrolysis products from a steam chest	D		D		D	D	D	D					D	D	D									D	
16. Deposition rates of UF$_6$ and UF$_6$ hydrolysis products	B	D	D	B	B	B	B	B	D	B	D	D	D	D	D	B	B	B	D	D			D	B	D
17. Agglomeration rates of UF$_6$ and UF$_6$ hydrolysis products	B	D	D	B	B	B	B	B	D	B	D	D	D	D	D	B	B	B	D	D			D	B	D
18. "Free" jet characteristics (including effects of a chemically reacting mixture of UF$_6$ and UF$_6$ hydrolysis products. – Note: Jets resulting from irregular openings are often approximated using jets from regular openings)	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D			D	D	D
19. Flow characteristics of a chemically reacting jet impinging on a surface	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D			D	D	D
20. Characteristics of an expanding cloud of UF$_6$ and UF$_6$ hydrolysis products in a compartment (including effects of a chemically reacting mixture of UF$_6$ and UF$_6$ hydrolysis products)	B	D	D	B	B	B	B	B	D	B	D	D	D	D	D	B	B	B	D	D			D	B	D
21. Average physical and thermodynamic properties within a compartment (homogeneous compartment model – can be used to predict a steady state or transient source term for a ventilation model given the release rate, duration, and composition)	B	D	D	B	B	B	B	B	D	B	D	D	D	D	D	B	B	B	D	D			D	B	D
22. Characteristics of an expanding cloud of UF$_6$ and UF$_6$ hydrolysis products resulting from an outdoor release near the release point	B	D	D	B	B	B	B	B	D				D		D									B	
23. UF$_6$ – hydrocarbon reactions in the presence of fire				B																					
24. Mass transport within a fire				B																					
25. Mass transport that results from an explosion	E			E	E	E	E	E		E						E	E	E						E	
26. Filtration efficiency	B	D	D	B	B	B	B	B	D	B	D	D	D	D	D	B	B	B	D	D			D	B	D
27. Transport of UF$_6$ and UF$_6$ hydrolysis products through ventilation systems	B	D	D	B	B	B	B	B	D	B	D	D	D	D	D	B	B	B	D	D			D	B	D
28. Criticality model																					✓	✓			

[a] Operator error can also initiate or contribute to postulated scenarios in categories 1, 2, and 3.

KEY

B = method applicable to both a directed and an explosive release for the postulated scenario

D = method applicable to a directed release for the postulated scenario

E = method applicable to an explosive release for the postulated scenario

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Table 10. Status of calculational methods for analysis of postulated UF_6 release sceanrios

Calculational methods	Method applicability and level of need				Method status: Documentation available			Method status: Documentation must be revised or prepared				Method status			
	Jet release	Explosive type release[a]	Criticality	Candidate for inclusion in the 1983 A&H draft material	1. Standard technique (found in handbooks or textbooks)	2. Standard numerical technique (computer codes)	3. Method publically available	4. Method developed but documentation needs to be revised to reflect "recent" developments	5. Modify and/or expand existing method (minor revision)	6. Modify and/or expand existing method (major revision)	7. Method formulated but not implemented	8. Method thought to exist or readily formulated from existing technology	9. Some applicable information available but method not formulated	10. Method not known to exist	11. Method exists but not publically available (i.e., proprietary or classified)
1. Liquid UF_6 – hydrocarbon chemical reactions (e.g., inside a cylinder)	C	C											✓	✓	
2. Physical and thermodynamic conditions immediately prior to failure of containment (time history may be required for some stress analyses)	C	C										✓			
3. Effects of natural phenomena (earthquakes, tornadoes, high winds, etc.)	C				✓	✓									
4. Characteristics of an impact on process equipment (includes the mass, inertia, and shape of projectile(s) and their point(s) of impact)	C				✓	✓							✓		
5. Characteristics of a drop of process equipment (includes the mass, inertia, shape, and orientation of containment at the point of impact and the characteristics of the impact surface	C				✓	✓							✓		
6. Failure mode(s) of containment (including geometric description of failure)	C	C			?	✓							✓		
7. Number of fragments, their sizes and velocities		C			✓										
8. Characteristics of flow through equipment and piping	S			✓			*b*		*b*	*b*					
9. Characteristics of flow through a rupture in containment	S			✓			*b*		*b*	*b*					
10. Time dependent, physical and thermodynamic conditions during release	S			✓					✓	?					
11. Characteristics of flashing liquid UF_6	S			✓					✓				✓		
12. Choke flow criteria for multiphase UF_6 systems (sonic velocity)	S	C		✓			*c*								
13. Chemical reactions between UF_6 and moist air (including energy balances, density changes, etc.)	S	C		✓				✓				✓			
14. UF_6 steam interactions inside a steam chest	C			✓									✓	✓	
15. Release of UF_6 and UF_6 hydrolysis products from a steam chest	C			✓									✓	✓	
16. Deposition rates of UF_6 and UF_6 hydrolysis products	C[d]								*e*	*e*			*e*		
17. Agglomeration rates of UF_6 and UF_6 hydrolysis products	C[f]								*e*	*e*			*e*		
18. "Free" jet characteristics (including effects of a chemically reacting mixture of UF_6 and UF_6 hydrolysis products. – Note: Jets resulting from irregular openings are often approximated using jets from regular openings)[g]	C[h]												*i*		
19. Flow characteristics of a chemically reacting jet impinging on a surface	C									✓				✓	
20. Characteristics of an expanding cloud of UF_6 and UF_6 hydrolysis products in a compartment (including effects of a chemically reacting mixture of UF_6 and UF_6 hydrolysis products)	C	C						?		✓				✓	
21. Average physical and thermodynamic properties within a compartment (homogeneous compartment model) – can be used to predict a steady state or transient source term for a ventilation model given the release rate, duration, and composition)	S	S		✓				*j*							
22. Characteristics of an expanding cloud of UF_6 and UF_6 hydrolysis products resulting from an outdoor release near the release point	S	S								✓			✓	✓	
23. UF_6 – hydrocarbon reactions in the presence of fire	C	C											✓	?	
24. Mass transport within a fire	C	C								*k*					
25. Mass transport that results from an explosion		C								*l*					
26. Filtration efficiency	S	S							✓	?					
27. Transport of UF_6 and UF_6 hydrolysis products through ventilation systems	S	S							*m*	*m*					
28. Criticality model			✓									✓			

KEY

S = needed for first order approximation as well as for more accurate analysis (order of analysis may affect formulation of method)

C = useful for more accurate analysis

Footnotes to Table 10: "Status of Calculational Methods for Analysis of Postulated UF_6 Releases Scenarios"

[a] An explosive-type release is considered much less likely than a directed release. Although several postulated scenarios could possibly culminate in an explosive-type release, only scenario 1.1 (introduction of reactive hydrocarbon into a cylinder, which results in a UF_6-hydrocarbon reaction) is considered reasonably likely to occur.

[b] The fourth and fifth methods discussed in Sect. 6.2 under DOE Source Term Methods as well as the two reports discussed earlier in the same section under Methods from the Open Literature, include some information applicable to these Calculational Methods (8 and 9). These reported methods do not cover all release possibilities. The DOE methods need to be documented.

[c] Information is generally available for estimating sonic velocities.

[d] This method is needed if particle deposition rates are required. This method can also be used to improve the accuracy of analytical results.

[e] Additional data are needed to apply these methods.

[f] This method is needed if particle size distributions are required. This method can also be used to improve the accuracy of analytical results.

[g] Two levels of methods for "free" jet characteristics need to be developed. First, a "free" jet method needs to be developed for a chemically reacting jet, then this method needs to be expanded to handle flashing in a multiphase jet.

[h] A "free" jet method is not believed to be required to obtain a reasonable first-order approximation of a source term for an indoor release; however, a "free" jet method may be required to obtain a reasonable approximation outdoors.

[i] The third method discussed in Sect. 6.2 DOE Source Term Methods has not been implemented or documented.

[j] The first and second methods discussed in Sect. 6.2 DOE Source Term Methods are documented in internal memoranda. These documents need to be revised to reflect changes in the computer programs they describe.

[k] FIRAC may be applicable with modifications to handle UF_6 (see Sect. 6.1).

[l] EXPAC may be applicable with modifications to handle UF_6 (see Sect. 6.1).

[m] FIRAC, TORAC, and/or EXPAC may be applicable with modifications to handle UF_6 (see Sect. 6.1).

8.3 METHODS FOR PREDICTING RELEASE RATES

Methods 8 through 12 listed in Tables 9 and 10 are needed for determining release rates from breached equipment. Four of the methods — 8, 9, 11, and 12 — deal with flow phenomena, while method 10 deals with the behavior of UF_6 within the equipment following loss of containment.

8. Characteristics of Flow Through Equipment and Piping

   The pressure drop of a compressible, flashing mixture needs to be calculated for flow through pipes, valves, etc. Some correlations exist that reduce to equations for single-phase, incompressible flow under appropriate conditions.

9. Characteristics of Flow Through a Rupture in Containment

   This methodology estimates the flow rate through an irregular opening. The methodology would probably assume a rough pipe, developing flow, and an equivalent diameter approximation.

10. Time-Dependent, Physical and Thermodynamic Conditions During Release

    A methodology will be needed for predicting the temperature, pressure, and UF_6 phase(s) inside a UF_6 cylinder during a postulated release.

11. Characteristics of Flashing Liquid UF_6

    A model to predict the solid/vapor split of liquid UF_6 after either an isentropic or an isenthalpic expansion to a given pressure will be needed.

12. Choke Flow Criteria for Multiphase UF_6 Systems

    Choke flow criteria are needed to bound the release rate of UF_6. This method may involve predicting the sonic velocity of a multiphase UF_6 mixture and the sonic velocities of UF_6 liquid and vapor.

8.4 METHODS FOR PREDICTING THE BEHAVIOR AFTER RELEASE

Methods 13 through 22 given in Tables 9 and 10 are useful for evaluating the physical consequences of a release of UF_6. Method 13 deals with chemical reactions and phase equilibria associated with the hydrolysis of UF_6. Method 21 is the simplest — and most uncertain — method for analyzing the behavior of

UF_6 in a compartment following a release. Methods 14 and 15 incorporate basic information used in methods 13 and 21 along with characteristic information related to steam chests. The other methods are much more complex models needed for advanced levels of analysis requiring spatial resolution of the characteristics of a release.

13. Chemical Reactions Between UF_6 and Moist Air

    The primary reaction associated with UF_6 hydrolysis must be incorporated into a methodology for estimating the resulting composition and temperature after hydrolysis.

14. UF_6-Steam Interactions Inside a Steam Chest

    This method would be similar to Method 13 except that the pressure and temperature inside the steam chest must be predicted.

15. Release of UF_6 and UF_6 Hydrolysis Products from a Steam Chest

    The methodology for predicting the release rate from a steam chest considers the scenario in which a release from a steam chest is through a short piece of pipe following the "failure" of a rupture disk.

16. Deposition Rates of UF_6 and UF_6 Hydrolysis Products

    Deposition rate data and a deposition rate model are needed to determine the fraction of the released material that is deposited on surfaces within a building or ventilation system. If reentrainment can be neglected, the deposited material will not be released to the ambient environment.

17. Agglomeration Rates of UF_6 and UF_6 Hydrolysis Products

    An agglomeration rate model is required to predict particle size distributions as functions of time. Deposition rates and filter efficiencies will usually be strongly dependent on the average particle size.

18. "Free" Jet Characteristics

    A free jet model is required if either spatial variations of jet characteristics in the momentum-dominated flow regime are to be predicted or if a source term is needed to simulate an expanding cloud (see Method 20). Important jet characteristics include the jet size, trajectory, composition, temperature, and concentration profile. The model should include the effect of a chemically reacting mixture of UF_6 and UF_6 hydrolysis products. Jets resulting from irregular openings would be approximated using jets from regular openings.

19. Flow Characteristics of a Chemically Reacting Jet Impinging on a Surface

An estimate of the flow field associated with a chemically reacting jet impinging on a surface may be required if spatial variations are important. Heat transfer, deposition processes, and chemical reactions with solid surfaces may be important.

20. Characteristics of an Expanding Cloud of UF_6 and UF_6 Hydrolysis Products in a Compartment

This model is also required if spatial variations are important. Because this model requires the results of method 18 as input and because it will provide information similar to the jet model, methods 18 and 20 could be combined in a single model. The effects of a chemically reacting mixture of UF_6 and UF_6 hydrolysis products should be included.

21. Average Physical and Thermodynamic Properties within a Compartment (Homogeneous Compartment Model)

This model can be used to predict a batch-mixed or transient source term for a ventilation model given the release rate, duration, and phase composition of a postulated UF_6 release. Output from this model would include the time-dependent, spatially averaged composition and the temperature within a compartment. This model can be used as an alternative to methods 18 through 20 if spatial gradients are not important.

22. Characteristics of an Expanding Cloud of UF_6 and UF_6 Hydrolysis Products Resulting from an Outdoor Release Near the Release Point

This model would be similar to Model 20 except that ambient characteristics such as wind and precipitation may be important.

8.5 METHODS FOR PREDICTING BEHAVIOR IN A FIRE OR EXPLOSION

Methods 23, 24, and 25 (see Tables 9 and 10) deal with phenomena associated with fires and explosions.

23. UF_6-Hydrocarbon Reactions in the Presence of Fire

The methodology simulates UF_6-hydrocarbon reactions in a fire including changes in composition, heats of reaction, etc.

24. Mass Transport Within a Fire

A transport model is required to simulate the movement of UF_6 and UF_6 "combustion products" within a fire.

25. Mass Transport that Results from an Explosion

A transport model is required to simulate the mass transport that results from an explosion. Phenomena such as shock waves and flashing of liquid UF_6 may be important.

8.6 METHODS NEEDED TO MODEL FLOW THROUGH A VENTILATION SYSTEM

Methods 26 and 27 (see Tables 9 and 10) are useful for evaluating the effects of a ventilation system on the UF_6 release products vented to the atmosphere.

26. Filtration Efficiency

A model to predict the fraction of UF_6 hydrolysis products retained by a filter is required if flow through a filter is to be simulated.

27. Transport of UF_6 and UF_6 Hydrolysis Products through Ventilation Systems

A ventilation transport model, which considers the effects of UF_6 hydrolysis, is required if a significant quantity of UF_6 is transported through a ventilation system containing moisture.

8.7 CRITICALITY METHOD

The last method appearing in Tables 9 and 10 is needed because of the radioactive nature of uranium compounds.

28. Criticality Method

Existing criticality methods can be used for evaluating the plausibility of nuclear criticality resulting from an accident.

9. CONCLUSIONS

This study and this report have focused on determining the various possible accident scenarios in NRC-licensed fuel cycle facilities that involve the release of UF_6 to identify and evaluate the analytical methods needed and available for determining source terms for such accidents. The study is part of a program that will lead to documentation of the necessary analytical techniques and data bases for realistic accident assessments in a *Fuel Cycle Facility Accident Analysis Handbook* (AAH).

Conclusions derived from this study are as follows:

1. Review of available NRC and NRC-licensee documents did not reveal a comprehensive list of credible UF_6 accident scenarios or any specific analytical methods for assessing the consequences of such accidents.
2. Heavy reliance on site visits to NRC-licensed facilities and on operating experience from uranium enrichment facilities was necessary to establish a list of credible UF_6 accident scenarios (Table 7), many of which are based on historical events.
3. No attempt has been made to assess the probabilities and/or consequences of the listed scenarios. Such an assessment requires detailed site-specific information and is best done on a case by case basis. Criticality events and radiological concerns related to the release of high assay UF_6 have been touched on briefly but need to be addressed further.
4. UF_6 thermodynamic, chemical, and physical characteristics and behavior are unique and are considerably different than those for most other compounds. Therefore, modifications to most available analytical methods, including those currently being developed for the NRC AAH, are necessary for them to be applicable for assessing situations involving UF_6 releases.
5. In addition to classical methods for determining UF_6 flow rates through process equipment (e.g., pipes, valves, orifices, etc.), DOE/UCC-ND has several other analytical methods that are within the scope of the AAH that are in various stages of development but that are not formally documented.
6. The procedures and criteria for selecting (a) bounding release events to be analyzed, and (b) the minimum generic analytical tools to be developed for and/or documented in the AAH are very complex.

This report, and especially Chapters 7 and 8 on perspectives and calculational methods, respectively, gives the basic material for arriving at such selections.

7. Consideration of the inventories, relative probabilities, and generic nature involved leads to the identification of at least three types of releases that are definitely worth investigating:

   a. release from q liquid-filled cylinder outdoors;

   b. release from a pigtail or cylinder inside a steam chest; and

   c. release indoors from either (1) a pigtail or liquid-filled cylinder or (2) other indoor system.

REFERENCES

[1] K. J. Schneider, *Nuclear Fuel Cycle Risk Assessment: Descriptions of Representative Non-Reactor Facilities*, NUREG/CR-2873 (PNL-4306), Vol. 1, Pacific Northwest Laboratory, Richland, Washington, September 1982, Sects. 11 and 13.

[2] *Packaging of Uranium Hexafluoride for Transport*, ANSI N14.1-1982, American National Standards Institute, Inc., New York, July 6, 1981.

[3] *Uranium Hexafluoride: Handling Procedure and Container Criteria*, ORO-651, Rev. 4, Oak Ridge Operations Office, U.S. ERDA, Oak Ridge, Tennessee, April 1977.

[4] "Uranium Hexafluoride," *Fed. Regist.*, 32 (230), pp. 16289–16291, November 29, 1967.

[5] T. Okamoto and R. Kiyose, "Evaluation of UF_6 Vapor Release in Postulated Accident," *J. Nucl. Sci. Technol.*, 15(6), 455–460, June 1978.

[6] A. Ericsson and B. Grundfeld, "Atmospheric Dispersion and Consequences of a UF_6 Release Caused by Valve Rupture on a Hot 30B Cylinder," *Proceedings of the Specialists' Meeting on the Safety Problems Associated with the Handling and Storage of UF_6*, Boekelo, Netherlands, June 27–29, 1978, Organization for Economic Corporation and Development, Paris, France (contains several errors).

[7] Departments of the Army, the Navy, and the Air Force, *Structures to Resist the Effects of Accidental Explosions*, TM 5-1300, NAVFAC P-397, AFM 88-22, June 1969.

[8] C. Grelecki, *Fundamentals of Fire and Explosion Hazards Evaluation*, AIChE Today Series, American Institute of Chemical Engineers, New York, 1976.

[9] G. F. Kinney, *Explosive Shocks in Air*, The Macmillan Company, New York, 1962.

[10] D. F. Norsworthy and C. Howarth, "Safety Consideration Involved in the Choice of Containers for Storage of UF_6 *Tails*", *Proceedings of the Specialists' Meeting on the Safety Problems Associated with the Handling and Storage of UF_6*, Boekelo, Netherlands, June 27–29, 1978, Organization for Economic Corporation and Development, Paris, France.

SELECTED BIBLIOGRAPHY OF DOCUMENTS RELEVANT TO NRC UF_6 RELEASE SOURCE TERM DEVELOPMENT

Standards, Process and System Descriptions, and Cylinder Descriptions

See Refs. 1, 2, 3, and 4.

Postulated and Actual Scenarios Involving the Release of UF_6

A. Price, "Safety Aspects of Uranium Hexafluoride Manufacture and Reconversion at Springfields Works", *Proceedings of the Specialists' Meeting on the Safety Problems Associated with the Handling and Storage of UF_6*, Boekelo, Netherlands, June 27–29, 1978, Organization for Economic Co-operation and Development, Paris, France.

Methods for Analyzing UF_6 Releases

See Ref. 5, 6, and 10.

H. Bouzigues, M. Mezin, and E. Mestre, "Fundamentals of UF_6 Accidental Release," *Proceedings of the Specialists' Meeting on the Safety Problems Associated with the Handling and Storage of UF_6*, Boekelo, Netherlands, June 27–29, 1978, Organization for Economic Corporation and Development, Paris, France.

E. A. Hirst, *Analysis of Round, Turbulent, Buoyant Jets Discharged to Flowing Stratified Ambients*, U.S. AEC Report No. ORNL-4685, June 1971.

P. Maitre, T. Meslin, and P. Pages, *Evaluation of Safety in the Transportation of Natural Uranium Hexafluoride*, Report No. 4, Centre d'Etude sur l'Evaluation de la Protection dans le Domaine Nucleaire, Fontenay-aux-Roses, 92 (France), May 1977, (also, BNWL-tr-269, Battelle Northwest Laboratory, Richland, Washington, September 1977).

A. Raggenbass, M. Berlin, and J. C. Malet, "Experimental Approach of Main Parameters for Safety Evaluation of Uranium Hexafluoride Industrial Utilizations", *Proceedings of the Specialists' Meeting on the Safety Problems Associated with Handling and Storage of UF_6*, Boekelo, Netherlands, June 27–29, 1978, Organization for Economic Corporation and Development, Paris, France.

W. Thomas, "Environmental Impact of a Potential UF_6 Release Resulting from an Accident in a UO_2 Fuel Fabrication Facility", *Proceedings of the Specialists' Meeting on the Safety Problems Associated with Handling and Storage of UF_6*, Boekelo, Netherlands, June 27–29, 1978, Organization for Economic Corporation and Development, Paris, France.

Physical Characterization Data for UF_6 and UF_6 Hydrolysis Products

Allied Chemical Corporation, *Hydrofluoric Acid*, Morristown, New Jersey, 1978.

S. P. Anderson, *A Study of the Hydrolysis of Uranium Hexafluoride by Fourier Transform Infrared Spectroscopy*, master's thesis, The University of Tennessee, Knoxville, Tennessee (in preparation).

S. P. Anderson, *Prolog to Studies on the Hydrolysis of Uranium Hexafluoride*, background data for master's thesis, Chemistry Department, The University of Tennessee, Knoxville, Tennessee, August 1982 (in preparation).

R. DeWitt, *Uranium Hexafluoride: A Survey of the Physioco-Chemical Properties*, GAT-280, Goodyear Atomic Corporation, Portsmouth, Ohio, January 29, 1960.

J. Ishida, H. Ishigro, and J. Kato, "Investigation of the UF_6 Aerosol Behavior in Air (II) — Experimental Results", *Semiannual Progress Report of Power Reactor and Nuclear Fuel Development Corporation*, Tokai Works, Tokai, Ibaraki (Japan), January–June 1978, PNCT-831-78-01, January 1979, pp. 109–113.

J. Ishida, et al., "Investigation of the UF_6 Aerosol Behavior in Air (II) — Experimental Results", *Semiannual Progress Report of Power Reactor and Nuclear Fuel Development Corporation*, Tokai Works, Tokai, Ibaraki (Japan), January–June 1978, PNCT-831-78-01, January 1979, pp. 151–158.

J. Ishida, et al., "Investigation of the UF_6 Aerosol Behavior in Air (IV) — The Characteristic of the Monitors Detection UF_6 Release," *Semiannual Progress Report of Power Reactor and Nuclear Fuel Development Corporation*, Tokai Works, Tokai, Ibaraki (Japan), July-December 1979, PNCT-831-79-02, July 1980, pp. 203–207.

H. Ishigro, J. Ishida, and J. Kato, "Investigation of the UF_6 Aerosol Behavior in Air (I) — Summary of the Instrument", *Semiannual Progress Report of Power Reactor and Nuclear Fuel Development Corporation*, Tokai Works, Tokai, Ibaraki (Japan), January–June 1978, PNCT-831-78-01, January 1979, pp. 109–110.

G. K. Johnson, "The Enthalpy of Formation of Uranium Hexafluoride", *J. Chem. Thermodynam.*, 11, 483–490, 1979.

J. J. Katz and E. Rabinowitch, *The Chemistry of Uranium, Part 1*, 1st ed., McGraw-Hill Book Company, New York, 1951.

I. E. Knudsen, et al., *A Fluidized-Bed Process for the Direct Conversion of Uranium Hexafluoride to Uranium Dioxide*, U.S. AEC ReportNo. ANL-6606, February 1963.

W. H. McCulla, *Determination of the Rate of HF Hydration and the Effects of HF on Moisture Condensation*, K/PS-155, Oak Ridge Gaseous Diffusion Plant, Oak Ridge, Tennessee, April 30, 1982.

P. A. G. O'Hare and J. G. Malm, "Thermochemistry of Uranium Compounds XIII. Standard Enthalpies of Formation at 298.15°K of Uranium Oxide Tetrafluoride (UOF_4) and Uranyl Fluoride (UO_2F_2) Thermodynamics of (Uranium + Oxygen + Fluorine)", *J. Chem. Thermodynam.*, 14, 331–336, 1982.

B. H. Parks and D. W. Burton, *Thermodynamic Properties of Gaseous Uranium Hexafluoride*, K-1458, Oak Ridge Gaseous Diffusion Plant, Oak Ridge, Tennessee, July 1973.

P. W. Pickrell, *Characterization of the Solid Product(s) Formed when UF_6 is Released into Ambient Air in a Contained Volume (U)*, K/ET-503, Oak Ridge Gaseous Diffusion Plant, Oak Ridge, Tennessee, May 7, 1980.

P. W. Pickrell, *Characterization of the Solid, Airborne Materials Created by the Interaction of UF_6 with Atmospheric Moisture in a Contained Volume*, K/PS-144, Oak Ridge Gaseous Diffusion Plant, Oak Ridge, Tennessee, April 30, 1982.

Historical Releases

D. J. Bodeau, et al; *Data Base for Radiation Events in the Commercial Nuclear Fuel Cycle 1950-1978*, ANL/ES-123 and NUREG/CR-2429, Argonne National Laboratory, Chicago, Illinois, December 1981.

A. J. Ducouret, "An Experience of Accidental Release of UF_6," *Proceedings of the Specialists' Meeting on the Safety Problems Associated with the Handling and Storage of* UF_6, Boekelo, Netherlands, June 27-29, 1978, Organization for Economic Co-operation and Development, Paris, France.

G. T. Hull, UF_6 *Release Experience and Prevention in United States Gaseous Diffuson Plants*, KY-690, Oak Ridge Gaseous Diffusion Plant, Oak Ridge, Tennessee, June 27, 1978.

A. J. Legeay, "Handling of UF_6 in U.S. Gaseous Diffusion Plants", *Proceedings of the Specialists' Meeting on the Safety Problems associated with the Handling and Storage of* UF_6, Boekelo, Netherlands, June 27-29 1978, Organization for Economic Corporation and Development, Paris, France (also, K/P-6452, Oak Ridge Gaseous Diffusion Plant, Oak Ridge, Tennessee, 1978).

A. J. Mallett, *ORGDP Container Test and Development Program Fire Tests of* UF_6*-Filled Cylinders*, K-D-1894, Oak Ridge Gaseous Diffusion Plant, Oak Ridge, Tennessee, January 12, 1966.

Methods for Analyzing Explosions

See Refs. 7, 8, and 9.

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This report identifies and discusses potential scenarios for the accidental release of UF_6 at NRC-licensed UF_6 production and fuel fabrication facilities based on a literature review, site visits, and DOE enrichment plant experience. Calculational methods needed for analyzing such releases are also reviewed. Accident scenarios are presented under the headings of cylinder failures, process system failures, criticality events, and operator errors and are categorized by location, release source, UF_6 phase prior to release, release flow characteristics, release causes, initiating events, and UF_6 inventory at risk. Releases identified for further examination include: (1) a release from a cylinder outdoors, (2) a release from a pigtail or cylinder in a steam chest, and (3) an indoor release from either (a) a pigtail or cylinder or (b) other indoor source depending on facility design and operating procedures. Indoor release phenomena may be analyzed using a time-dependent homogeneous compartment model or a more complex hydrodynamic model if time-dependent, spatial variations in concentrations, temperature, and pressure are important. Analytical tools for modeling directed jets and explosive releases are discussed as well as some of the complex phenomena to be considered in analyzing UF_6 releases both indoors and outdoors.

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