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Nuclear Criticality Safety Assessment of the Proposed CFC Replacement Coolants

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Computing Applications Division

NUCLEAR CRITICALITY SAFETY ASSESSMENT OF THE PROPOSED CFC REPLACEMENT COOLANTS

W. C. Jordan
H. R. Dyer

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ABSTRACT

The neutron multiplication characteristics of refrigerant-114 (R-114) and proposed replacement coolants perfluorobutane (C_4F_{10}) and cycloperfluorobutane (C_4F_8) have been compared by evaluating the infinite media multiplication factors of UF_6/HF/coolant systems and by replacement calculations considering a 10-MW freezer/sublimer. The results of these comparisons demonstrate that R-114 is a neutron absorber, due to its chlorine content, and that the alternative fluorocarbon coolants are neutron moderators. Estimates of critical spherical geometries considering mixtures of UF_6/HF/C_4F_{10} indicate that the flourocarbon-moderated systems are large compared with water-moderated systems. The freezer/sublimer calculations indicate that the alternative coolants are more reactive than R-114, but that the reactivity remains significantly below the condition of water in the tubes, which was a limiting condition. Based on these results, the alternative coolants appear to be acceptable; however, several follow-up tasks have been recommended, and additional evaluation will be required on an individual equipment basis.

1. INTRODUCTION

The Paducah and Portsmouth gaseous diffusion plants are currently evaluating alternative coolants to replace the chlorofluorocarbon, R-114 ($C_2Cl_2F_4$), currently in use at the plants. Two alternative coolants identified as possible replacement coolants are C_4F_{10} and C_4F_8. The coolant used in the diffusion plant must satisfy a number of criteria: acceptable heat transfer properties; acceptable temperature/pressure characteristics; and acceptable chemical compatibility with materials of construction, UF_6, and other cascade gases. The coolant must also be acceptable from a nuclear criticality safety perspective. The purpose of this report is to present a brief comparison of the neutron multiplication characteristics between R-114 and the proposed alternative coolants. This report is not intended to cover every detail of cascade equipment and operation where R-114 is currently used. The scope is limited to a comparison of the characteristics of the alternative coolants with those of R-114 in sufficient detail to conclude that there are no insurmountable criticality safety issues associated with their use. Areas of concern will be identified. Additional evaluation will be required for individual equipment and operations at the time the criticality safety evaluation for operational approval is prepared.

Of primary importance in the nuclear criticality safety of cascade operations is the restriction on the use of materials, coolants, lubricants, or other chemical compounds which, if contacted with UF_6, could result in the formation of a deposit and/or could moderate a uranium-containing deposit. R-114 satisfies this restriction and, as an intermediate heat transfer media between the cascade and the recirculating cooling water (RCW) system, helps satisfy the NCS requirements of dual wall isolation between a moderator (the RCW) and UF_6 in the cascade. R-114 is not a moderator and does not react chemically with UF_6. Any alternative coolant should satisfy these requirements.

The coolant C_4F_{10} has been identified as the most likely replacement.[1] The majority of calculations were performed with C_4F_{10}. The differences between the C_4F_{10} and C_4F_8 will be discussed in more detail later. Two series of calculations were performed in which R-114 was compared with C_4F_{10}. In the first series, reactivity calculations were made comparing the neutronic characteristics of the coolants. Several critical spherical geometry systems were analyzed. In the second series of calculations, the effect of the replacement coolant on the reactivity of a freezer/sublimer (F/S) was evaluated.

The results of these calculations indicate that C_4F_{10} or C_4F_8 are acceptable coolants from a criticality safety perspective. However, they are neutronically different than R-114, and several follow-up tasks have been recommended in the conclusions.

2. CALCULATIONAL METHODOLOGY

2.1 DESCRIPTION OF THE CODES

All calculations performed in this study were run using a configuration-controlled version of SCALE-4.2, which is on the IBM workstation designated as CA02.CAD.ORNL.GOV.[2,3]

Table 1 presents the program name, creation date, and version number for each module used in the calculations. All the programs were from directory /home/x4s/scale/exe, and data were from directory /home/x4s/scale/datalib.

Table 1. Program QA information

Program	Creation date	Production code	Version
csas	4/22/93	csas	2.0
o0o001	5/19/93	xsdrn	2.1
o0o002	6/14/93	nitawl	2.1
o0o007	3/19/93	ice	2.0
o0o008	3/19/93	bonami	2.0
o0o009	7/09/93	kenova	2.2

All calculations were performed utilizing the SCALE 27-group cross-section library. The codes with the 27-group library have not been formally validated; however, the code is substantially the same as the nuclear criticality safety software (NCSS) version of SCALE used by Martin Marietta Energy Systems (MMES) for safety evaluations.[4] The functionality of the codes has been verified, and a validation using the SCALE 44-group ENDF/B-V cross-section library has been performed.[5] In future validation, consideration should be given to including experiments with characteristics similar to the systems calculated here (such as low uranium density, graphite-moderated systems). The use of this code and the 27-group cross sections for the comparison of the alternative coolants to R-114 is considered acceptable in that (1) only a comparative analysis is being performed, (2) the majority of the systems analyzed are outside the range of existing validation, and (3) no calculational acceptance is being used for establishing the safety of a system.

2.2 PHYSICAL CHARACTERISTICS OF THE COOLANTS

The physical characteristics of the coolant of greatest interest in the criticality evaluation are the chemical composition, density, and the range of pressure/temperature conditions that the coolant would be as a liquid as opposed to a vapor (vapor pressure as a function of temperature). The chemical composition of the coolant determines the neutronic characteristics of absorption and moderation. Impurities are also of importance in determining these characteristics. The density of

the coolant affects the size of a critical system. The vapor pressure characteristics allow an evaluation of when and where the liquid coolant could be present and must be considered. The chemical characteristics of the coolant may also be important from the aspect of solubility of UF_6, HF, or other materials in the coolant, or the solubility of the coolant in these materials and any effects each may have on the others vapor pressure.

In general, fissile systems that involve a solid or liquid are of greater concern than vapor-phase systems because of the significantly smaller critical geometries of the liquid and solid systems. The infinite media multiplication factor is not a function of the density of the system but only of the composition of the system. Generally, criticality is not possible in gas-phase systems in the diffusion plants because the geometry of the cascade equipment is sufficiently small, the gas is low density, and there is the absence of unique reflectors (e.g., beryllium, graphite, etc.).

The infinite media calculations discussed in Sect. 3 were based on mixtures of UF_6, HF, and coolant, which were assumed to be volume-additive. A temperature of 23°C was used to estimate the theoretical densities of the materials in the mixture. The density and vapor pressure for R-114 were estimated from figures on pages 42 and 51 of ref. 6, considering a temperature of 23°C (73.4°F). Information for the density and vapor pressure of C_4F_{10} and C_4F_8 was provided by D. W. Langenberg.[7,8] The two fluorocarbons were sufficiently similar that the density and vapor pressure were taken to be the same for both materials. The values of density and vapor pressure are given in Table 2.

A temperature of 15°C was used to estimate the density of the UF_6/HF mixture used in the F/S calculations. The R-114 density used in the origional F/S analysis was 1.455 g/cc which corresponds to a temperature of 25°C. These values were used to be consistent with the original F/S analysis. The densities of the alternative coolants were estimated at 15°C and are given in Table 2.

Table 2. Comparison of physical properties of compounds

Temp.	Compound	Density (g/cc)	Vapor press. (psia)
23°C (73.4°F)	UF_6	5.07325	1.89
	HF	0.95162	16.3
	R-114	1.46530	29
	C_4F_{10} (C_4F_8)	1.50380	36.200
15°C (59°F)	UF_6	5.11525	1.07
	HF	0.96877	12.0
	C_4F_{10} (C_4F_8)	1.53520	27.661

Impurities that might be found in the coolant are of interest in that they may react with and/or provide moderation to UF_6 freeze-outs or deposits in the cascade. Generally, the most significant moderator of concern is hydrogen. A. J. Saraceno and L. D. Trowbridge provided references on impurity specifications and measurements that have been made on shipments of C_4F_{10} used in evaluation testing.[9,10] These references indicate that the specification hydrogen content is <0.017 wt %, and that measurement of the hydrogen content in two lots was on the order of 0.0008 wt %. The hydrogen impurity is extremely low and will not be of concern, except in systems which involve a large quantity of coolant with low concentrations of uranium.

The possibility exists that fluorocarbon coolants may form solutions with UF_6 and/or HF under accident conditions. In this event, the hydrogen content could significantly exceed the specification limits. A review of the limited available data on solubility of HF and UF_6 in R-114 is presented in K/ETO-134,[11] and indicates that solubilities should be low. Cascade locations should be identified where the coolant could conceivably enter the process gas system and still remain in the liquid state.

3. CALCULATIONAL RESULTS AND DISCUSSION

3.1 REACTIVITY COMPARISONS BETWEEN R-114 AND C_4F_{10}

Infinite media calculations were performed for theoretical mixtures of UF_6 /HF/coolant considering 5 wt % ^{235}U enriched uranium. The coolants C_4F_{10} and C_4F_8 are very similar in chemical form and neutronic behavior. The diffusion plants are tending toward using C_4F_{10}, and for this reason only C_4F_{10} was considered in the infinite media calculations. However, the reactivity of systems containing C_4F_8 will be a little higher due to the fewer fluorine atoms per molecule. Given that C_4F_{10} and C_4F_8 have the same density, C_4F_8 has a larger atomic density. Systems involving C_4F_8 will result in smaller critical dimensions due to the larger reactivity and the larger atomic density of C_4F_8 compared with C_4F_{10}.

A volume-additive density relationship was developed for mixtures of UF_6/HF/R-114 and UF_6 /HF/C_4F_{10}, which is a function of a specified hydrogen-to-uranium (H/U) atom ratio and carbon-to-uranium (C/U) atom ratio, where the carbon is that associated with the coolant. These density relationships are given in Appendix A, along with the mixture component densities. The results and figures are presented in terms of hydrogen-to-fissile uranium (H/X) and carbon-to-fissile uranium (C/X) atom ratio. For 5 wt % enriched uranium, the uranium ratio and fissile ratio are related by a factor of 19.76 (i.e., H/X = 19.76 × H/U).

Table A.1 provides the infinite media neutron multiplication factor, k_∞, results for UF_6/HF/C_4F_{10} mixtures over a range of C/X ratios from 0 to 50,000, and a range of H/X ratios from 0 to 800. Also included in the table is the density (in units of g/cm^3) of the uranium, UF_6, HF, and C_4F_{10} in the mixture for each C/X and H/X. Table A.2 provides k_∞ results for UF_6/HF/R-114 mixtures over a similar range of C/X ratios, but only for H/X ratios of 0 and 300. For comparison purposes, Table 3 provides the k_∞ results for the UF_6/HF/R-114 and the UF_6/HF/C_4F_{10} mixtures at an H/X = 0 and H/X = 300 over a range of C/X from 0 to 50,000.

The k_∞ results are graphically depicted in Figs. 1 and 2. Figure 1 provides a plot of the k_∞ as a function of C/X for the results presented in Table 3; Fig. 2 provides a plot of k_∞ as a function of C/X and H/X for all the results in Table A.1. As seen in Fig. 1 the reactivity for the UF_6/HF/R-114 systems is a maximum at C/X = 0 and continuously decreases as the relative amount of R-114 increases (C/X increases). The reactivity of the UF_6/HF/C_4F_{10} system behaves differently. At H/X = 0, the reactivity decreases initially as the relative amount of C_4F_{10} increases. As more C_4F_{10} is added to the system, the reactivity passes through a minimum, then rises to exceed k_∞ = 1.0, which indicates that criticality is possible in a finite system. The infinite media multiplication becomes greater than 1.0 between C/X = 1,000 and 3,000, which corresponds to a uranium density between 115 and 39 gU/L. The infinite media multiplication remains greater than 1.0 until C/X = 15,000 is exceeded, which corresponds to a uranium density of 7.9 gU/L (0.395 g^{235}U/L). As seen in Table 3, the infinite media multiplication for UF_6/HF/C_4F_{10} at an H/X = 300 remains greater than 1.0 until the C/X ratio exceeds 10,000.

Table 3. Values for k_∞ for UF_6/HF/coolant mixtures at an H/X = 0 and 300

	k_∞			
	H/X = 0		H/X = 300	
C/X	UF_6/HF/R-114	UF_6/HF/C_4F_{10}	UF_6/HF/R-114	UF_6/HF/C_4F_{10}
0	0.7063	0.7063	1.4149	1.4149
1	0.7026	0.7062	1.3599	1.4147
3	0.6954	0.7064	1.2620	1.4142
5	0.6881	0.7063	1.1775	1.4137
10	0.6696	0.7050	1.0094	1.4126
30	0.5992	0.6921	0.6465	1.4081
50	0.5395	0.6754	0.4795	1.4039
100	0.4311	0.6485	0.2981	1.3941
300	0.2428	0.6531	0.1331	1.3621
500	0.1713	0.7052	0.0930	1.3373
1000	0.1000	0.8242	-	1.2923
3000	-	1.0315	-	1.1980
5000	-	1.0858	-	1.1429
10000	-	1.0658	-	1.0381
30000	-	0.7863	-	0.7475
50000	-	0.6018	-	0.5771

Based on these results it can be seen that R-114 reduces the reactivity of the systems because it contains chlorine, which is a neutron absorber. In contrast, C_4F_{10} is a neutron moderator, and criticality can be achieved over a broad range of conditions, including very low uranium concentrations. The range of C/X and H/X over which k_∞ is greater than 1.0 may be seen in Fig. 2. The presence of any hydrogen in the mixture tends to increase k_∞. The simple hydrogen-moderated system, C/X = 0 (i.e., without coolant present), appears to have the largest reactivity, which indicates that the hydrogen-moderated systems will probably have the smallest critical geometries.

Several calculations were performed to determine the critical spherical radii of UF_6/HF/C_4F_{10} systems. Unreflected spheres and spheres reflected with 90 cm of concrete were considered. The results are presented in Table 4. The estimated critical radii are large, as are the corresponding critical masses.

These calculations indicate that the critical size and critical mass of C_4F_{10}-moderated systems are large compared with water-moderated (or HF-moderated) systems. Equipment such as RCW heat exchangers and coolant storage and makeup tanks should be evaluated for the potential of containing

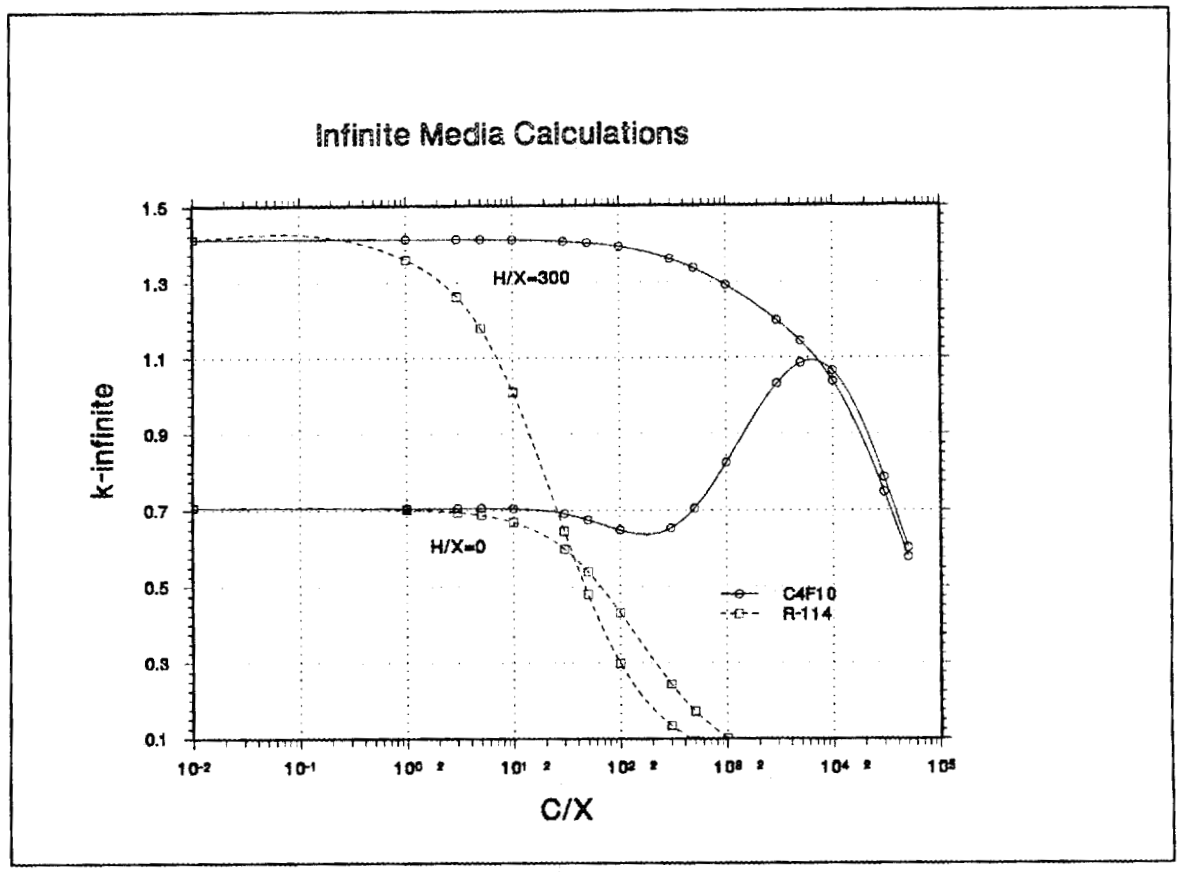

Fig. 1. k_∞ vs C/X for UF_6/HF/coolant mixtures at an H/X = 0 and 300.

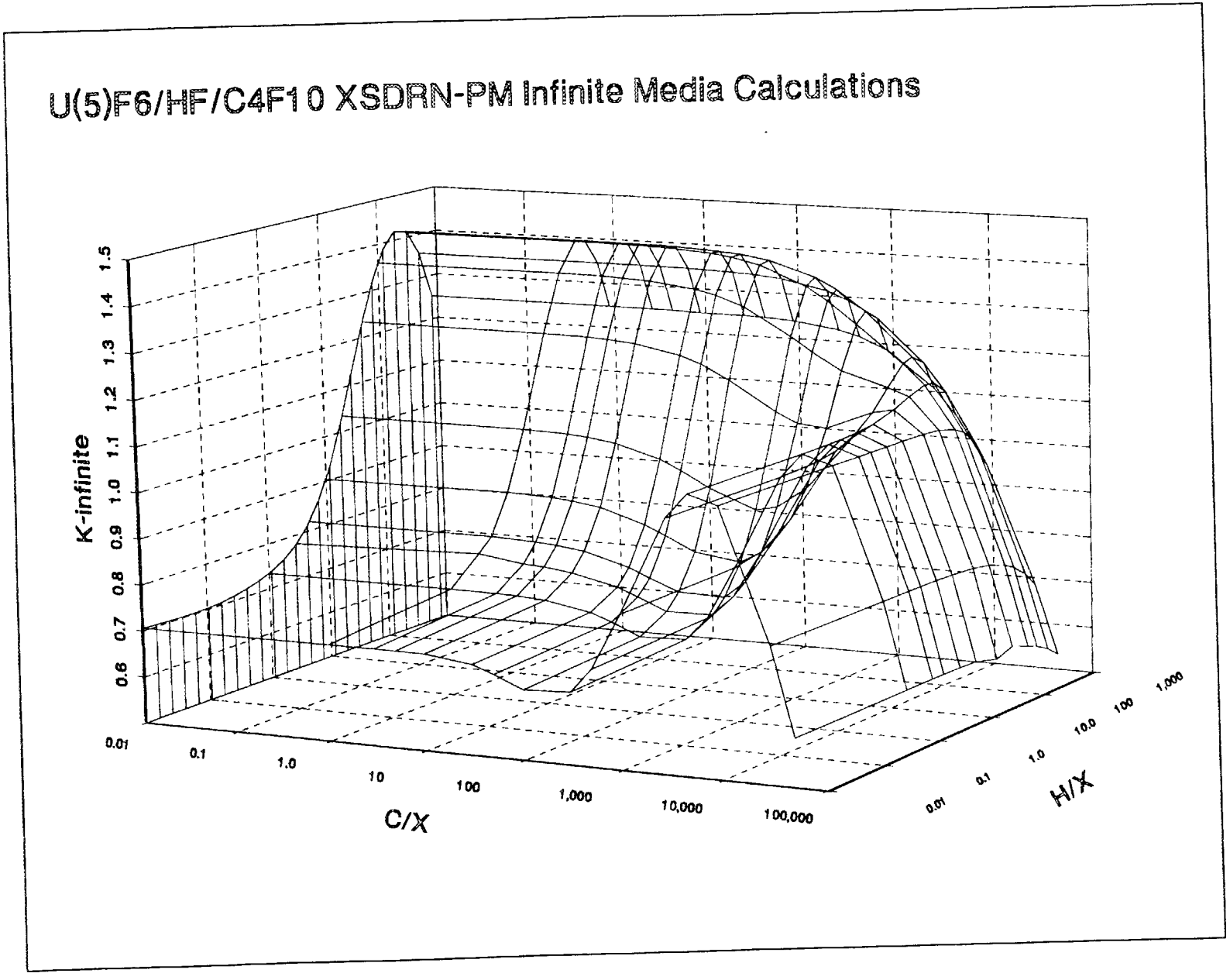

Fig. 2. k_∞ vs H/X and C/X for $UF_6/HF/C_4F_{10}$ mixtures.

Table 4. Critical spherical geometries

C/X	H/X	Critical Radius (cm)							
		0	20	50	100	200	300	500	800
1000 (170 gUF_6/L)[a]	U[b]	-[d]	-	334	186	135	118	111	118
	R[c]	-	-	308	164	117	103	97	105
3000 (58 gUF_6/L)	U	703	446	339	273	226	208	200	227
	R	641	414	319	252	206	190	-	217
5000 (35 gUF_6/L)	U	440	403	366	330	298	287	296	411
	R	410	386	344	308	278	268	280	398
10000 (17 gUF_6/L)	U	(582)[e]	605	579	608	660	(786)	3890	-
	R	556	569	555	-	-	716	3690	-

[a] The values of density are approximate and are based on an H/X = 0.
[b] Unreflected.
[c] Reflected with 90-cm concrete.
[d] These values were not estimated.
[e] Values in parentheses are considered less reliable due to convergence problems in the calculation.

quantities of UF_6 dissolved in the coolant. The solubility of UF_6 in the coolant and the possibility of UF_6 migration into the coolant (for example, through leaky coolers) should be evaluated. Another factor that should be considered is the solubility of HF in the coolant. Even though the fluorocarbon coolants are moderators, the size of a critical system is quite large. The presence of hydrogen will significantly reduce the size of a critical system.

The presence of hydrogen, and particularly the possibility of dissolved HF, is a concern in fluorocarbon-moderated systems. A relatively small hydrogen content in the fluorocarbon gives a substantial moderating effect for very small uranium concentrations. For example, at a hydrogen impurity level of 0.017%, the effective H/X is approximately 100 at a C/X of 10,000.

In the event that coolant leaks into the cascade, the temperature and pressure are such that the coolant should vaporize. In this case, the coolant could not moderate an existing UF_6 freeze-out or other uranium-containing deposit. Similarly, the operating temperature and pressure of the surge drums should maintain the coolant in the vapor phase. An evaluation should be performed to determine if there is a possibility that large quantities of coolant could condense if the surge drums were used to freeze out UF_6.

3.2 FREEZER/SUBLIMER CALCULATIONAL COMPARISON

The freezer/sublimers (F/S) are unique in the operating cascade in that they are large geometry and are intended to contain large quantities of solid-phase UF_6.[12] A single boundary separates the UF_6 and coolant media. For these reasons, several calculations were performed to verify that the conditions considered in the evaluation of the F/S are still adequately subcritical with the

alternative coolants. Similar calculations were performed by R. L. Newvahner at the Portsmouth plant when the alternative coolants were initially identified in 1991.[13]

A model developed in a previous analysis of a 10-MW F/S was chosen for analysis.[14] Case II02C in Table 13 of ref. 14 for 3.5% enrichment at H/U = 0.088 was used as a single-point comparison calculation. The result is given in Table 5. The original calculated k_{eff} using a validated version of SCALE-4.0 on the IBM 3090 computer at ORNL was 0.8728 ± 0.0024. The calculated k_{eff} using SCALE-4.2 on the work station gave a value of 0.8684 ± 0.0023. These values are within 2σ and are considered adequate to demonstrate that the two versions of SCALE are substantially the same and either could be used for these scoping calculations.

Table 5. 10-MW F/S calculational comparison

Case	Description	k_{eff}	Dev.
10mii02c	Fully loaded, 3.5% enriched, water in the tubes, H/U = 0.088 (from ref. 13)	0.8728	0.0024
10mii02c	Fully loaded, 3.5% enriched, water in the tubes, H/U = 0.088	0.8684	0.0023
10mii12a	Fully loaded, 3.5% enriched, R-114 in the tubes, H/U = 0.15	0.5379	0.0017
10mii12b	Fully loaded, 3.5% enriched, void in the tubes, H/U = 0.15	0.5473	0.0020
10mii12c	Fully loaded, 3.5% enriched, water in the tubes, H/U = 0.15	0.8831	0.0024
10mii12d	Fully loaded, 3.5% enriched, C_4F_{10} in the tubes, H/U = 0.15	0.5540	0.0015
10mii12e	Fully loaded, 3.5% enriched, C_4F_8 in the tubes, H/U = 0.15	0.5572	0.0016
10mi12d	Nominally loaded, 3.5% enriched, C_4F_{10} in the tubes, H/U = 0.15	0.4118	0.0020
10mif12d	Nominally loaded, 3.5% enriched, C_4F_{10} in the tubes, H/U = 0.15, vapor region flooded w/C_4F_{10}	0.4991	0.0018

The material specifications of the F/S model were modified to represent an intermixed H/U = 0.15 at an enrichment of 3.5%, which correspond to conditions upon which approval of F/S operation are based. Table 5 presents the results for a 10-MW F/S fully loaded with 3.5% enriched

UF_6 at H/U = 0.15 with R-114, void, water, C_4F_{10}, and C_4F_8 in the coolant tubes. The results show that greatest reactivity is obtained with water in the tubes with $k_{eff} = 0.8831 \pm 0.0024$. The results also indicate that the F/S is more reactive with the fluorocarbon coolants than with R-114 in the tubes, but that this reactivity is only slightly greater than that with void in the tubes.

Additional calculations were performed for a nominally loaded F/S. Case 10mi12d represents the nominal operating condition of the F/S, and Case 10mif12d represents a hypothetical case where the coolant floods the vapor region in a nominally loaded F/S. This condition should not be realizable in the operating cascade because the vapor pressure of the coolant significantly exceeds the pressure of the cascade at operating temperatures. The calculated k_{eff} is small but is significantly larger than that calculated for the nominal conditions.

If flooding the vapor region in the F/S with liquid coolant is a credible event, additional information on the amount of UF_6 and/or HF possibly dissolved in the coolant would be needed, since criticality would be possible. This possibility was not considered in the earlier F/S evaluation because R-114 coolant acts as a neutron absorber.

These calculations indicate that the alternative fluorocarbon coolants are more reactive than R-114 but that the reactivity of the F/S remains significantly below that where water is in the tubes. Based on these results, it appears that the accident conditions used in the evaluation of the F/S are still adequately subcritical and the alternative coolants are acceptable in the F/S system. This conclusion is the same as the conclusion reached in ref. 13.

As an aside, the evaluation in ref. 13 considered a third alternative coolant, C_4F_9H, in the F/S calculations. The reactivity of the F/S was not significantly different than with the alternative fluorocarbon coolants. Even though C_4F_9H appears acceptable in the tubes of the F/S, it may not be acceptable under single failure conditions in the F/S or the cascade due to its large hydrogen content. It is suggested that hydrogen-containing fluorocarbons not be considered or used as cascade coolant media. In the event that the use of hydrogen-containing fluorocarbons is dictated, an extensive criticality safety evaluation will be required.

4. CONCLUSIONS AND RECOMMENDATIONS

Infinite media multiplication calculations performed for UF_6/HF/R-114 and UF_6/HF/C_4F_{10} systems demonstrate that R-114 is a neutron absorber due to the chlorine content and that C_4F_{10} is a neutron moderator. Several calculations were performed to estimate the critical spherical radius of unreflected and concrete-reflected systems. The results indicate that critical C_4F_{10}- moderated UF_6 systems will be large compared with water-moderated systems. These data suggest that equipment which is safe geometry for water-moderated uranium systems will be safe for fluorocarbon-moderated systems and will not require reevaluation.

An equipment survey should be performed to identify unsafe geometry equipment that could contain liquid C_4F_{10}. This equipment can be subdivided into three categories: (1) equipment designed to handle liquid coolant, where uranium is not supposed to be present, such as RCW heat exchangers (which have an additional source of external moderation in the RCW tubes), coolant makeup and storage tanks, etc.; (2) equipment designed to handle UF_6, where liquid coolant is used for direct cooling, such as F/S, the freon removal system, gas coolers, etc.; (3) equipment designed to handle principally UF_6, where liquid coolant should not exist, such as surge drums, accumulators, the shell side of the F/S, etc. The controls or process conditions that prevent UF_6 and/or liquid coolant from being present in these systems should be identified. The solubility of UF_6 and/or HF in the fluorocarbon coolant may be a factor in establishing the safety of the system.

F/S calculations indicate that the replacement coolants C_4F_{10} and C_4F_8 are both more reactive than R-114 when in the F/S tubes. However, the reactivity is significantly less than when water is in the tubes. It appears that the accident conditions considered in the evaluation of the F/S are still adequately subcritical. If flooding of the vapor region of the F/S with liquid coolant is a credible event, additional information on the amount of UF_6 and/or HF that could be dissolved in the coolant will be required. In light of the effects on critical size when hydrogen is present in the fluorocarbon coolants, it is recommended that hydrofluorocarbons, such as C_4F_9H, *not* be considered or used as coolants in the cascade.

Because of peculiarities related to reflector effectiveness, which exist in low-density uranium systems, an evaluation should be performed for the surge drums, Horntonspheres, etc., where enriched UF_6 might be frozen out as a shell surrounding a low-density (gas-phase) UF_6/HF/coolant mixture. The gas mixture in these systems will be enriched in any HF/coolant content as the UF_6 is frozen out. The moderating characteristics in combination with the large geometry may be sufficient to cause concern in these low-density systems.

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APPENDIX A

UF_6/HF/COOLANT MIXTURE DENSITIES

The densities for the mixtures of $UF_6/HF/C_4F_{10}$ and UF_6/HF/R-114 are based on a theoretical volume additive formulation. The theoretical densities for solid UF_6 and liquid HF were based on a temperature of 23°C. The volume additive formulations for uranium density as a function of H/X and C/X moderation ratio are given in Eq. (A.1) for $UF_6/HF/C_4F_{10}$ and in Eq. (A.2) for UF_6/HF/R-114. The data sheets used to generate the input for the infinite media calculations presented in Sect. 3.1 are given in Tables A.1 and A.2. In both Eqs. (A.1) and (A.2) and in Tables A.1 and A.2 densities are given in *g/cc*.

$$\rho_U = \frac{\textit{molecular weight of uranium}}{69.36140 + H/U * 21.02320 + C/U * 39.56344} \tag{A.1}$$

$$\rho_U = \frac{\textit{molecular weight of uranium}}{69.36140 + H/U * 21.02320 + C/U * 58.31502} \tag{A.2}$$

Table A.1. $UF_6/HF/C_4F_{10}$ density

Component densities for theoretical mixtures of uf6/hf/c4f10

```
u-235 enrichment =  5.000            molecular wt of uranium =  237.89880
temperature of mixture = 23.00000deg. c
theoretical  uf6  density =  5.07325 molecular wt of   uf6    =  351.88800
theoretical   hf  density =   .95162 molecular wt of   hf     =   20.00600
theoretical c4f10 density =  1.50380 molecular wt of  c4f10   =  237.98200
specific molar volume of   uf6 =   69.36140
specific molar volume of    hf =   21.02320
specific molar volume of c4f10 =   39.56344
density of components in a theoretical mixture
```

h/x = .000
h/u = .000

c/x	c/u	uranium	uf6	hf	c4f10	kinf
.00	.000	3.42984	5.07325	.00000	.00000	0.7063
1.00	.051	3.33362	4.93092	.00000	.04219	0.7062
3.00	.152	3.15650	4.66893	.00000	.11985	0.7064
5.00	.253	2.99725	4.43338	.00000	.18967	0.7063
10.00	.506	2.66156	3.93684	.00000	.33685	0.7050
30.00	1.518	1.83809	2.71881	.00000	.69790	0.6921
50.00	2.530	1.40377	2.07639	.00000	.88832	0.6754
100.00	5.061	.88248	1.30531	.00000	1.11688	0.6485
300.00	15.182	.35506	.52519	.00000	1.34812	0.6531
500.00	25.304	.22224	.32873	.00000	1.40636	0.7052
1000.00	50.607	.11484	.16987	.00000	1.45345	0.8242
3000.00	151.822	.03915	.05791	.00000	1.48663	1.0315
5000.00	253.036	.02360	.03491	.00000	1.49345	1.0858
10000.00	506.073	.01184	.01751	.00000	1.49861	1.0658
30000.00	1518.218	.00396	.00585	.00000	1.50207	0.7863
50000.00	2530.363	.00237	.00351	.00000	1.50276	0.6018

h/x = 1.000
h/u = .051

c/x	c/u	uranium	uf6	hf	c4f10	kinf
.00	.000	3.37803	4.99661	.01438	.00000	0.7346
1.00	.051	3.28465	4.85849	.01398	.04157	0.7337
3.00	.152	3.11256	4.60394	.01325	.11818	0.7326
5.00	.253	2.95761	4.37474	.01259	.18716	0.7311
10.00	.506	2.63025	3.89053	.01119	.33289	0.7266
30.00	1.518	1.82310	2.69664	.00776	.69221	0.7083
50.00	2.530	1.39501	2.06343	.00594	.88278	0.6919
100.00	5.061	.87901	1.30018	.00374	1.11249	0.6646
300.00	15.182	.35450	.52436	.00151	1.34599	0.6686
500.00	25.304	.22202	.32840	.00094	1.40496	0.7176
1000.00	50.607	.11478	.16978	.00049	1.45270	0.8316
3000.00	151.822	.03915	.05790	.00017	1.48637	1.0335
5000.00	253.036	.02360	.03490	.00010	1.49329	1.0864
10000.00	506.073	.01184	.01751	.00005	1.49853	1.0658
30000.00	1518.218	.00396	.00585	.00002	1.50204	0.7862
50000.00	2530.363	.00237	.00351	.00001	1.50274	0.6017

h/x = 3.000
h/u = .152

c/x	c/u	uranium	uf6	hf	c4f10	kinf
.00	.000	3.27896	4.85007	.04186	.00000	0.7807
1.00	.051	3.19090	4.71982	.04074	.04038	0.7910
3.00	.152	3.02825	4.47924	.03866	.11498	0.7759
5.00	.253	2.88138	4.26200	.03679	.18234	0.7728
10.00	.506	2.56979	3.80111	.03281	.32524	0.7653
30.00	1.518	1.79385	2.65337	.02290	.68110	0.7419
50.00	2.530	1.37782	2.03800	.01759	.87190	0.7241
100.00	5.061	.87215	1.29004	.01114	1.10381	0.6976
300.00	15.182	.35338	.52270	.00451	1.34173	0.6985
500.00	25.304	.22158	.32775	.00283	1.40218	0.7416
1000.00	50.607	.11466	.16961	.00146	1.45121	0.8456
3000.00	151.822	.03913	.05788	.00050	1.48585	1.0371
5000.00	253.036	.02359	.03490	.00030	1.49298	1.0878
10000.00	506.073	.01184	.01751	.00015	1.49837	1.0658
30000.00	1518.218	.00396	.00585	.00005	1.50199	0.7859
50000.00	2530.363	.00237	.00351	.00003	1.50271	0.6016

h/x = 5.000
h/u = .253

c/x	c/u	uranium	uf6	hf	c4f10	kinf
.00	.000	3.18553	4.71188	.06778	.00000	0.8208
1.00	.051	3.10236	4.58885	.06602	.03926	0.8188
3.00	.152	2.94839	4.36112	.06274	.11195	0.8149
5.00	.253	2.80899	4.15491	.05977	.17776	0.8111
10.00	.506	2.51205	3.71570	.05345	.31793	0.8023
30.00	1.518	1.76552	2.61147	.03757	.67035	0.7748
50.00	2.530	1.36105	2.01319	.02896	.86129	0.7554
100.00	5.061	.86540	1.28006	.01841	1.09527	0.7302
300.00	15.182	.35227	.52105	.00750	1.33751	0.7267
500.00	25.304	.22114	.32710	.00471	1.39941	0.7642
1000.00	50.607	.11455	.16943	.00244	1.44973	0.8595
3000.00	151.822	.03912	.05786	.00083	1.48533	1.0408
5000.00	253.036	.02359	.03489	.00050	1.49266	1.0891
10000.00	506.073	.01184	.01751	.00025	1.49821	1.0657
30000.00	1518.218	.00396	.00585	.00008	1.50193	0.7857
50000.00	2530.363	.00237	.00351	.00005	1.50268	0.6014

Table A.1 (continued)

h/x = 10.000
h/u = .506

a/x	a/u	uranium	uf6	hf	c4f10	kinf
.00	.000	2.97371	4.39856	.12656	.00000	0.9037
1.00	.051	2.90110	4.29117	.12347	.03672	0.9051
3.00	.152	2.76603	4.09138	.11772	.10502	0.9008
5.00	.253	2.64298	3.90936	.11248	.16725	0.8966
10.00	.506	2.37845	3.51808	.10122	.30102	0.8871
30.00	1.518	1.69847	2.51229	.07228	.64489	0.8565
50.00	2.530	1.32085	1.95373	.05621	.83585	0.8356
100.00	5.061	.84897	1.25575	.03613	1.07448	0.8043
300.00	15.182	.34951	.51698	.01487	1.32705	0.7907
500.00	25.304	.22005	.32549	.00936	1.39252	0.8158
1000.00	50.607	.11425	.16900	.00486	1.44602	0.8913
3000.00	151.822	.03909	.05781	.00166	1.48403	1.0496
5000.00	253.036	.02358	.03487	.00100	1.49188	1.0924
10000.00	506.073	.01183	.01751	.00050	1.49782	1.0658
30000.00	1518.218	.00396	.00585	.00017	1.50180	0.7850
50000.00	2530.363	.00237	.00351	.00010	1.50260	0.6010

h/x = 20.000
h/u = 1.012

a/x	a/u	uranium	uf6	hf	c4f10	kinf
.00	.000	2.62466	3.88226	.22340	.00000	1.0360
1.00	.051	2.56793	3.79836	.21857	.03250	1.0341
3.00	.152	2.46154	3.64098	.20952	.09346	1.0303
5.00	.253	2.36360	3.49612	.20118	.14957	1.0265
10.00	.506	2.14978	3.17985	.18298	.27208	1.0178
30.00	1.518	1.57856	2.33493	.13436	.59936	0.9889
50.00	2.530	1.24718	1.84476	.10615	.78923	0.9671
100.00	5.061	.81792	1.20982	.06962	1.03517	0.9319
300.00	15.182	.34413	.50902	.02929	1.30663	0.8925
500.00	25.304	.21791	.32232	.01855	1.37895	0.9023
1000.00	50.607	.11367	.16814	.00968	1.43867	0.9468
3000.00	151.822	.03902	.05771	.00332	1.48144	1.0656
5000.00	253.036	.02355	.03483	.00200	1.49031	1.0986
10000.00	506.073	.01183	.01750	.00101	1.49702	1.0658
30000.00	1518.218	.00395	.00585	.00034	1.50153	0.7837
50000.00	2530.363	.00237	.00351	.00020	1.50244	0.6002

h/x = 50.000
h/u = 2.530

a/x	a/u	uranium	uf6	hf	c4f10	kinf
.00	.000	1.94112	2.87120	.41305	.00000	1.2354
1.00	.051	1.90992	2.82505	.40641	.02417	1.2343
3.00	.152	1.85043	2.73706	.39375	.07026	1.2319
5.00	.253	1.79453	2.65438	.38186	.11356	1.2295
10.00	.506	1.66853	2.46801	.35505	.21117	1.2240
30.00	1.518	1.30267	1.92685	.27720	.49461	1.2044
50.00	2.530	1.06840	1.58033	.22735	.67610	1.1878
100.00	5.061	.73704	1.09019	.15683	.93281	1.1558
300.00	15.182	.32895	.48656	.07000	1.24896	1.0930
500.00	25.304	.21172	.31316	.04505	1.33978	1.0705
1000.00	50.607	.11197	.16561	.02383	1.41706	1.0644
3000.00	151.822	.03881	.05741	.00826	1.47373	1.1049
5000.00	253.036	.02348	.03473	.00500	1.48561	1.1143
10000.00	506.073	.01181	.01747	.00251	1.49465	1.0649
30000.00	1518.218	.00395	.00585	.00084	1.50074	0.7800
50000.00	2530.363	.00237	.00351	.00051	1.50196	0.5858

h/x = 100.000
h/u = 5.061

a/x	a/u	uranium	uf6	hf	c4f10	kinf
.00	.000	1.35359	2.00216	.57606	.00000	1.3589
1.00	.051	1.33834	1.97961	.56957	.01694	1.3582
3.00	.152	1.30886	1.93600	.55702	.04970	1.3568
5.00	.253	1.28064	1.89426	.54502	.08104	1.3555
10.00	.506	1.21516	1.79740	.51715	.15379	1.3522
30.00	1.518	1.00882	1.49219	.42933	.38303	1.3402
50.00	2.530	.86238	1.27559	.36701	.54572	1.3295
100.00	5.061	.63275	.93594	.26929	.80083	1.3067
300.00	15.182	.30641	.45322	.13040	1.16339	1.2485
500.00	25.304	.20215	.29901	.08603	1.27922	1.2162
1000.00	50.607	.10923	.16157	.04649	1.38245	1.1784
3000.00	151.822	.03848	.05692	.01638	1.46105	1.1486
5000.00	253.036	.02335	.03454	.00994	1.47785	1.1316
10000.00	506.073	.01178	.01742	.00501	1.49071	1.0621
30000.00	1518.218	.00395	.00584	.00168	1.49941	0.7731
50000.00	2530.363	.00237	.00351	.00101	1.50116	0.5997

Table A.1 (continued)

h/x = 200.000
h/u = 10.121

c/x	c/u	uranium	uf6	hf	c4f10	kinf
.00	.000	.84317	1.24718	.71768	.00000	1.4196
1.00	.051	.83723	1.23839	.71262	.01060	1.4193
3.00	.152	.82560	1.22118	.70272	.03135	1.4185
5.00	.253	.81428	1.20445	.69308	.05153	1.4178
10.00	.506	.78730	1.16454	.67012	.09964	1.4162
30.00	1.518	.69518	1.02827	.59171	.26395	1.4096
50.00	2.530	.62235	.92055	.52972	.39383	1.4036
100.00	5.061	.49319	.72950	.41978	.62419	1.3897
300.00	15.182	.26948	.39860	.22937	1.02318	1.3481
500.00	25.304	.18539	.27422	.15780	1.17316	1.3186
1000.00	50.607	.10414	.15404	.08864	1.31806	1.2701
3000.00	151.822	.03783	.05596	.03220	1.43633	1.1889
5000.00	253.036	.02311	.03419	.01967	1.46258	1.1455
10000.00	506.073	.01172	.01733	.00997	1.48290	1.0521
30000.00	1518.218	.00394	.00583	.00336	1.49677	0.7601
50000.00	2530.363	.00237	.00351	.00202	1.49957	0.5858

h/x = 300.000
h/u = 15.182

c/x	c/u	uranium	uf6	hf	c4f10	kinf
.00	.000	.61229	.90567	.78173	.00000	1.4149
1.00	.051	.60915	.90103	.77773	.00771	1.4147
3.00	.152	.60297	.89188	.76983	.02289	1.4142
5.00	.253	.59691	.88292	.76210	.03777	1.4137
10.00	.506	.58228	.86129	.74343	.07370	1.4126
30.00	1.518	.53031	.78440	.67706	.20135	1.4081
50.00	2.530	.48685	.72012	.62158	.30808	1.4039
100.00	5.061	.40407	.59768	.51589	.51140	1.3941
300.00	15.182	.24050	.35573	.30705	.91313	1.3621
500.00	25.304	.17119	.25322	.21857	1.08334	1.3373
1000.00	50.607	.09951	.14719	.12705	1.25940	1.2923
3000.00	151.822	.03720	.05502	.04749	1.41244	1.1980
5000.00	253.036	.02288	.03384	.02921	1.44762	1.1429
10000.00	506.073	.01166	.01724	.01488	1.47517	1.0381
30000.00	1518.218	.00394	.00582	.00502	1.49414	0.7475
50000.00	2530.363	.00237	.00350	.00302	1.49799	0.5771

h/x = 500.000
h/u = 25.304

c/x	c/u	uranium	uf6	hf	c4f10	kinf
.00	.000	.39562	.58519	.84185	.00000	1.3582
1.00	.051	.39431	.58325	.83906	.00499	1.3580
3.00	.152	.39171	.57940	.83352	.01487	1.3577
5.00	.253	.38915	.57561	.82806	.02463	1.3575
10.00	.506	.38288	.56633	.81472	.04846	1.3568
30.00	1.518	.35970	.53204	.76539	.13657	1.3542
50.00	2.530	.33916	.50167	.72170	.21462	1.3515
100.00	5.061	.29680	.43901	.63156	.37564	1.3454
300.00	15.182	.19792	.29276	.42116	.75148	1.3239
500.00	25.304	.14846	.21960	.31591	.93948	1.3058
1000.00	50.607	.09138	.13516	.19444	1.15647	1.2694
3000.00	151.822	.03600	.05325	.07661	1.36695	1.1769
5000.00	253.036	.02242	.03316	.04770	1.41859	1.1161
10000.00	506.073	.01154	.01706	.02455	1.45995	1.0040
30000.00	1518.218	.00392	.00580	.00834	1.48889	0.7230
50000.00	2530.363	.00236	.00349	.00503	1.49482	0.5612

h/x = 800.000
h/u = 40.486

c/x	c/u	uranium	uf6	hf	c4f10	kinf
.00	.000	.25844	.38228	.87991	.00000	1.2531
1.00	.051	.25788	.38145	.87800	.00326	1.2524
3.00	.152	.25677	.37980	.87421	.00975	1.2522
5.00	.253	.25566	.37817	.87044	.01618	1.2520
10.00	.506	.25294	.37414	.86118	.03201	1.2500
30.00	1.518	.24261	.35886	.82601	.09212	1.2500
50.00	2.530	.23309	.34478	.79360	.14750	1.2483
100.00	5.061	.21227	.31398	.72271	.26866	1.2444
300.00	15.182	.15639	.23133	.53246	.59380	1.2302
500.00	25.304	.12380	.18312	.42150	.78344	1.2175
1000.00	50.607	.08140	.12040	.27713	1.03018	1.1902
3000.00	151.822	.03434	.05080	.11693	1.30397	1.1118
5000.00	253.036	.02176	.03219	.07409	1.37717	1.0551
10000.00	506.073	.01136	.01680	.03868	1.43770	0.9485
30000.00	1518.218	.00390	.00577	.01328	1.48110	0.6883
50000.00	2530.363	.00235	.00348	.00802	1.49010	0.5393

Table A.2. UF_6/HF/R-114 density

Component densities for theoretical mixtures of uf6/hf/r114

```
u-235 enrichment =  5.000            molecular wt of uranium =  237.89880
temperature of mixture = 23.00000deg. c
theoretical uf6 density  =  5.07325  molecular wt of uf6     =  351.88800
theoretical  hf density  =   .95162  molecular wt of  hf     =   20.00600
theoretical r114 density =  1.46530  molecular wt of  r114   =  170.89800
specific molar volume of  uf6 =   69.36140
specific molar volume of   hf =   21.02320
specific molar volume of r114 =   58.31502
density of components in a theoretical mixture

h/x =      .000
h/u =      .000
```

c/x	c/u	uranium	uf6	hf	r114	kinf
.00	.000	3.42984	5.07325	.00000	.00000	0.7063
1.00	.051	3.28987	4.86621	.00000	.05980	0.7026
3.00	.152	3.04161	4.49899	.00000	.16586	0.6954
5.00	.253	2.82818	4.18331	.00000	.25704	0.6881
10.00	.506	2.40610	3.55899	.00000	.43736	0.6696
30.00	1.518	1.50668	2.22860	.00000	.82162	0.5992
50.00	2.530	1.09671	1.62221	.00000	.99676	0.5395
100.00	5.061	.65271	.96546	.00000	1.18645	0.4311
300.00	15.182	.24918	.36858	.00000	1.35884	0.2428
500.00	25.304	.15399	.22777	.00000	1.39951	0.1713
1000.00	50.607	.07876	.11650	.00000	1.43165	0.1000
3000.00	151.822	.02666	.03944	.00000	1.45391	-
5000.00	253.036	.01605	.02374	.00000	1.45844	-
10000.00	506.073	.00804	.01190	.00000	1.46186	-

```
h/x =  300.000
h/u =   15.182
```

c/x	c/u	uranium	uf6	hf	r114	kinf
.00	.000	.61229	.90567	.78173	.00000	1.4149
1.00	.051	.60767	.89884	.77584	.01105	1.3599
3.00	.152	.59865	.88549	.76432	.03265	1.2620
5.00	.253	.58989	.87253	.75313	.05361	1.1775
10.00	.506	.56907	.84173	.72655	.10344	1.0094
30.00	1.518	.49866	.73760	.63666	.27193	0.6465
50.00	2.530	.44376	.65639	.56657	.40332	0.4795
100.00	5.061	.34798	.51472	.44428	.63253	0.2981
300.00	15.182	.18675	.27623	.23843	1.01838	0.1331
500.00	25.304	.12762	.18877	.16294	1.15989	0.0930
1000.00	50.607	.07123	.10537	.09095	1.29483	-
3000.00	151.822	.02574	.03807	.03286	1.40370	-
5000.00	253.036	.01571	.02324	.02006	1.42771	-
10000.00	506.073	.00796	.01177	.01016	1.44626	-

APPENDIX B

INPUT EXAMPLES

Sample input for the infinite media calculations, critical spherical radius searches, and F/S calculations are included in this appendix. The modifications required for the other calculations primarily involve changes to the fissile mixtures and titles of the cases.

Infinite media calculations for UF_6 /HF/C_4F_{10} systems at H/X = 0.

```
=csas1x
kinf calc for uf6/hf/c4f10 system. h/x=0., c/x=0., 5% enrichment
27gr infh
uf6        1 den=5.07325 1. 293. 92235 5. 92238 95. end
hfacid     1 den=0.00000 1. 293. end
arbmc4f10        0.00000 2 0 1 1  6012  4
                                  9019  10
          1 1. 293. end
end comp
end
=csas1x
kinf calc for uf6/hf/c4f10 system. h/x=0., c/x=1., 5% enrichment
27gr infh
uf6       1 den=4.93092 1. 293. 92235 5. 92238 95. end
hfacid    1 den=0.00000 1. 293. end
arbmc4f10       0.04219 2 0 1 1  6012  4
                                  9019  10
          1 1. 293. end
end comp
end
=csas1x
kinf calc for uf6/hf/c4f10 system. h/x=0., c/x=3. 5% enrichment
27gr infh
uf6       1 den=4.66893 1. 293. 92235 5. 92238 95. end
hfacid    1 den=0.00000 1. 293. end
arbmc4f10       0.11985 2 0 1 1  6012  4
                                  9019  10
          1 1. 293. end
end comp
end
=csas1x
kinf calc for uf6/hf/c4f10 system. h/x=0., c/x=5.5% enrichment
27gr infh
uf6       1 den=4.43338 1. 293. 92235 5. 92238 95. end
hfacid    1 den=0.00000 1. 293. end
arbmc4f10       0.18967 2 0 1 1  6012  4
                                  9019  10
          1 1. 293. end
end comp
end
=csas1x
kinf calc for uf6/hf/c4f10 system. h/x=0., c/x=10. 5% enrichment
27gr infh
uf6       1 den=3.93684 1. 293. 92235 5. 92238 95. end
hfacid    1 den=0.00000 1. 293. end
arbmc4f10       0.33685 2 0 1 1  6012  4
                                  9019  10
          1 1. 293. end
end comp
end
=csas1x
kinf calc for uf6/hf/c4f10 system. h/x=0., c/x=30. 5% enrichment
27gr infh
uf6       1 den=2.71881 1. 293. 92235 5. 92238 95. end
hfacid    1 den=0.00000 1. 293. end
arbmc4f10       0.69790 2 0 1 1  6012  4
                                  9019  10
          1 1. 293. end
end comp
end
=csas1x
kinf calc for uf6/hf/c4f10 system. h/x=0., c/x=50. 5% enrichment
27gr infh
uf6       1 den=2.07639 1. 293. 92235 5. 92238 95. end
hfacid    1 den=0.00000 1. 293. end
arbmc4f10       0.88832 2 0 1 1  6012  4
                                  9019  10
          1 1. 293. end
end comp
end
=csas1x
kinf calc for uf6/hf/c4f10 system. h/x=0., c/x=100. 5% enrichment
27gr infh
uf6       1 den=1.30531 1. 293. 92235 5. 92238 95. end
hfacid    1 den=0.00000 1. 293. end
arbmc4f10       1.11688 2 0 1 1  6012  4
                                  9019  10
          1 1. 293. end
end comp
end
```

```
=csas1x
kinf calc for uf6/hf/c4f10 system. h/x=0., c/x=300. 5% enrichment
27gr infh
uf6       1 den=0.52519 1. 293. 92235 5. 92238 95. end
hfacid    1 den=0.00000 1. 293. end
arbmc4f10       1.34812 2 0 1 1  6012  4
                                 9019  10
          1 1. 293. end
end comp
end
=csas1x
kinf calc for uf6/hf/c4f10 system. h/x=0., c/x=500. 5% enrichment
27gr infh
uf6       1 den=0.32873 1. 293. 92235 5. 92238 95. end
hfacid    1 den=0.00000 1. 293. end
arbmc4f10       1.40636 2 0 1 1  6012  4
                                 9019  10
          1 1. 293. end
end comp
end
=csas1x
kinf calc for uf6/hf/c4f10 system. h/x=0., c/x=1000. 5% enrichment
27gr infh
uf6       1 den=0.16987 1. 293. 92235 5. 92238 95. end
hfacid    1 den=0.00000 1. 293. end
arbmc4f10       1.45345 2 0 1 1  6012  4
                                 9019  10
          1 1. 293. end
end comp
end
=csas1x
kinf calc for uf6/hf/c4f10 system. h/x=0., c/x=3000. 5% enrichment
27gr infh
uf6       1 den=0.05791 1. 293. 92235 5. 92238 95. end
hfacid    1 den=0.00000 1. 293. end
arbmc4f10       1.48663 2 0 1 1  6012  4
                                 9019  10
          1 1. 293. end
end comp
end
=csas1x
kinf calc for uf6/hf/c4f10 system. h/x=0., c/x=5000. 5% enrichment
27gr infh
uf6       1 den=0.03491 1. 293. 92235 5. 92238 95. end
hfacid    1 den=0.00000 1. 293. end
arbmc4f10       1.49345 2 0 1 1  6012  4
                                 9019  10
          1 1. 293. end
end comp
end
=csas1x
kinf calc for uf6/hf/c4f10 system. h/x=0., c/x=10000. 5% enrichment
27gr infh
uf6       1 den=0.01751 1. 293. 92235 5. 92238 95. end
hfacid    1 den=0.00000 1. 293. end
arbmc4f10       1.49861 2 0 1 1  6012  4
                                 9019  10
          1 1. 293. end
end comp
end
=csas1x
kinf calc for uf6/hf/c4f10 system. h/x=0., c/x=30000., 5% enrichment
27gr infh
uf6        1 den=0.00585 1. 293. 92235 5. 92238 95. end
hfacid     1 den=0.00000 1. 293. end
arbmc4f10        1.50207 2 0 1 1  6012  4
                                   9019  10
          1 1. 293. end
end comp
end
=csas1x
kinf calc for uf6/hf/c4f10 system. h/x=0., c/x=1., 5% enrichment  <= note error in title - WCJ
27gr infh
uf6       1 den=0.00351 1. 293. 92235 5. 92238 95. end
hfacid    1 den=0.00000 1. 293. end
arbmc4f10       1.50276 2 0 1 1  6012  4
                                 9019  10
          1 1. 293. end
end comp
end
```

Critical spherical radius search calculations for UF_6 /HF/C_4F_{10} systems at H/X = 0.

```
=csasi
uf6/hf/c4f10 system. h/x=0., c/x=3000. 5% enrichment
27gr infh
uf6       1 den=0.05791 1. 293. 92235 5. 92238 95. end
hfacid    1 den=0.00000 1. 293. end
arbmc4f10       1.48663 2 0 1 1  6012  4
                                 9019  10
          1 1. 293. end
rfconcrete 2 1. end
end comp
end
=xsdrn
unreflected uf6/hf/c4f10 system. h/x=0., c/x=3000. 5% enrichment
0$$ a3 2 e
1$$ 3 1 210 1 0 1 1 8 3 4 a12 300 e 2$$ -2 -1 e
5** a4 0 -1 a10 1. e                1t
13$$ 1  14$$ 1  15** f1.            2t
33$$ f1.                            4t
35** 209i0.  1200.
36$$  210r1
39$$    1
41**   0.8                          5t
end
=xsdrn
concrete reflected uf6/hf/c4f10 system. h/x=0., c/x=3000. 5% enrichment
0$$ a3 2 e
1$$ 3 2 210 1 0 2 2 8 3 4 a12 300 e 2$$ -2 -1 e
5** a4 0 -1 a10 1. e                1t
13$$ 1 2 14$$ 1 2 15** f1.            2t
33$$ f1.                              4t
35** 179i0. 29i400. 490.
36$$  180r1  30r2
39$$    1     2
41**   0.8    0                      5t
end
=csasi
uf6/hf/c4f10 system. h/x=0., c/x=5000. 5% enrichment
27gr infh
uf6       1 den=0.03491 1. 293. 92235 5. 92238 95. end
hfacid    1 den=0.00000 1. 293. end
arbmc4f10       1.49345 2 0 1 1  6012  4
                                 9019  10
          1 1. 293. end
rfconcrete 2 1. end
end comp
end
=xsdrn
unreflected uf6/hf/c4f10 system. h/x=0., c/x=5000. 5% enrichment
0$$ a3 2 e
1$$ 3 1 210 1 0 1 1 8 3 4 a12 300 e 2$$ -2 -1 e
5** a4 0 -1 a10 1. e                1t
13$$ 1  14$$ 1  15** f1.            2t
33$$ f1.                            4t
35** 209i0.  900.
36$$  210r1
39$$    1
41**   0.8                          5t
end
=xsdrn
concrete reflected uf6/hf/c4f10 system. h/x=0., c/x=5000. 5% enrichment
0$$ a3 2 e
1$$ 3 2 210 1 0 2 2 8 3 4 a12 300 e 2$$ -2 -1 e
5** a4 0 -1 a10 1. e                1t
13$$ 1 2 14$$ 1 2 15** f1.            2t
33$$ f1.                              4t
35** 179i0. 29i300. 390.
36$$  180r1  30r2
39$$    1     2
41**   0.8    0                      5t
end
```

```
=csasi
uf6/hf/c4f10 system. h/x=0., c/x=10000. 5% enrichment
27gr infh
uf6       1 den=0.01751 1. 293. 92235 5. 92238 95. end
hfacid    1 den=0.00000 1. 293. end
arbmc4f10       1.49861 2 0 1 1  6012  4
                                 9019  10
          1 1. 293. end
rfconcrete 2 1. end
end comp
end
=xsdrn
unreflected uf6/hf/c4f10 system. h/x=0., c/x=10000. 5% enrichment
0$$ a3 2 e
1$$ 3 1 210 1 0 1 1 8 3 4 a12 300 e 2$$ -2 -1 e
5** a4 0 -1 a10 1. e                1t
13$$ 1  14$$ 1  15** f1.            2t
33$$ f1.                            4t
35** 209i0.  900.
36$$  210r1
39$$    1
41**   0.8                          5t
end
=xsdrn
concrete reflected uf6/hf/c4f10 system. h/x=0., c/x=10000. 5% enrichment
0$$ a3 2 e
1$$ 3 2 210 1 0 2 2 8 3 4 a12 300 e 2$$ -2 -1 e
5** a4 0 -1 a10 1. e                1t
13$$ 1 2 14$$ 1 2 15** f1.            2t
33$$ f1.                              4t
35** 179i0. 29i400. 490.
36$$  180r1  30r2
39$$    1     2
41**   0.8    0                      5t
end
```

10-MW F/S calculational input for 3.5% enrichment, H/U = 0.15, C_4F_{10} on the tube side.

```
=csas25
freezer/sublimer 10mw. full loading, 3.5, h/u=0.15, c4f10 on tubeside.
27gr latt
'matl 1 is r-114, void, c4f10, or water
'arbmr114   1.455 3 0 1 0  6012 2
'                           9019 4
'                          17000 2 1 1. 288. end
'arbmvoid    1.-15 3 0 1 0  6012 2
'                           9019 4
'                          17000 2 1 1. 288. end
arbmc4f10   1.5352 2 0 1 1  6012  4
                            9019 10 1 1. 293. end
'h2o     1 1. end
'matl 2 is cupro-nickle
arbmc71500  8.94  4 0 0 1 29000 67.80
                          28000 31.00
                          26000  0.70
                          25055  0.50  2 .5 288. end
'matl 3 is al
al      3 .5 end
'matl4 is uf6-hf/al volume weighted mixture
' 0.8650 vol fraction uf6, 0.1350 vol fraction al
uf6     4 den=4.89486 0.8650 288. 92235 3.5 92238 96.5 end
hfacid  4 den=0.04174 0.8650 288. end
al      4             0.0675 288. end
'matl 5 is uf6-hf mixture  in overloaded region
uf6     5 den=4.89486 1.000  288. 92235 3.5 92238 96.5 end
hfacid  5 den=0.04174 1.000  288. end
'matl 6 is sa-516, gr-55 steel
arbmsa516   7.85  4 0 0 1 26000 98.855
                          25055  0.765
                          14000  0.290
                           6012  0.900 6 1. 288. end
'matl 7 is h2o reflector
h2o     7 1. end
rfconcrete 8 1. end
end comp
'note: interchange definition of fuel and moderator regions for
'      cross section processing.
squarepitch 6.9850 2.2606 1 4 2.54 2 end
freezer/sublimer 10mw. full loading, 3.5%, h/u=0.15, c4f10 on tubeside.
read parm nubmyes npg=600 pltmyes tme=45 end parm
read geom
unit 1
'simplified model of finned tube w/ uf6-hf/al volume homogenized.
cylinder  1 1  1.1303  2p99.06
cylinder  2 1  1.2700  2p99.06
cylinder  3 1  1.3589  2p99.06
cylinder  4 1  2.8575  2p99.06
cylinder  5 1  2.8575  2p99.06
unit 4
'cuboid for interior 12x12 array
'note: a full array of finned tubes is modeled. the interior region
'      of the f/s actually has 4 tubes removed leaving an open area.
cuboid    5 1  4p3.4925  2p99.06
hole    1   0.        0.       0.
unit 10
'base model for 10mw f/s.
array 1  -41.9100 -41.9100 -99.06
cylinder  5 1 60.0098  2p99.06
hole    1   3.4925  52.3875  0.
hole    1   3.4925  45.4025  0.
hole    1  10.4775  52.3875  0.
hole    1  10.4775  45.4025  0.
hole    1  17.4625  52.3875  0.
hole    1  17.4625  45.4025  0.
hole    1  24.4475  45.4025  0.
hole    1  31.4325  45.4025  0.
hole    1  45.4025   3.4925  0.
hole    1  45.4025  10.4775  0.
hole    1  45.4025  17.4625  0.
hole    1  45.4025  24.4475  0.
hole    1  45.4025  31.4325  0.
hole    1  52.3875   3.4925  0.
hole    1  52.3875  10.4775  0.
hole    1  52.3875  17.4625  0.
hole    1  -3.4925  52.3875  0.
hole    1  -3.4925  45.4025  0.
hole    1 -10.4775  52.3875  0.
hole    1 -10.4775  45.4025  0.
hole    1 -17.4625  52.3875  0.
hole    1 -17.4625  45.4025  0.
hole    1 -24.4475  45.4025  0.
hole    1 -31.4325  45.4025  0.
hole    1 -45.4025   3.4925  0.
```

```
hole     1 -45.4025  10.4775  0.
hole     1 -45.4025  17.4625  0.
hole     1 -45.4025  24.4475  0.
hole     1 -45.4025  31.4325  0.
hole     1 -52.3875   3.4925  0.
hole     1 -52.3875  10.4775  0.
hole     1 -52.3875  17.4625  0.
hole     1   3.4925 -52.3875  0.
hole     1   3.4925 -45.4025  0.
hole     1  10.4775 -52.3875  0.
hole     1  10.4775 -45.4025  0.
hole     1  17.4625 -52.3875  0.
hole     1  17.4625 -45.4025  0.
hole     1  24.4475 -45.4025  0.
hole     1  31.4325 -45.4025  0.
hole     1  45.4025  -3.4925  0.
hole     1  45.4025 -10.4775  0.
hole     1  45.4025 -17.4625  0.
hole     1  45.4025 -24.4475  0.
hole     1  45.4025 -31.4325  0.
hole     1  52.3875  -3.4925  0.
hole     1  52.3875 -10.4775  0.
hole     1  52.3875 -17.4625  0.
hole     1  -3.4925 -52.3875  0.
hole     1  -3.4925 -45.4025  0.
hole     1 -10.4775 -52.3875  0.
hole     1 -10.4775 -45.4025  0.
hole     1 -17.4625 -52.3875  0.
hole     1 -17.4625 -45.4025  0.
hole     1 -24.4475 -45.4025  0.
hole     1 -31.4325 -45.4025  0.
hole     1 -45.4025  -3.4925  0.
hole     1 -45.4025 -10.4775  0.
hole     1 -45.4025 -17.4625  0.
hole     1 -45.4025 -24.4475  0.
hole     1 -45.4025 -31.4325  0.
hole     1 -52.3875  -3.4925  0.
hole     1 -52.3875 -10.4775  0.
hole     1 -52.3875 -17.4625  0.
cylinder  6 1  60.9600  2p105.6640
cuboid    7 1  4p90.96  2p105.6640
unit 5
hemisphe+z 1 1 81.5775       chord  -55.6330
hemisphe+z 6 1 82.5290       chord  -55.6330
cuboid       7 1 4p90.96     113.0000 55.6330
unit 6
cylinder     1 1 60.0088     2.948  0.0
cylinder     6 1 60.9600     2.948  0.0
cuboid       7 1 4p90.96     2.948  0.0
unit 7
hemisphe-z 1 1 81.5775      chord -55.6330
hemisphe-z 6 1 82.5290      chord -55.6330
cylinder     0 1 60.9600  -55.6330 -82.5290
cuboid       7 1 4p90.96  -55.6330 -82.5290
unit 8
cuboid       8 1 4p90.96   60.48      0.0
global unit 20
array 2 2r-90.96  -190.0850
end geom
read array
 ara=1 nux=12 nuy=12 nuz=1 fill f4 end fill
 ara=2 nux=1  nuy=1  nuz=6 fill 8 7 6 10 6 5 end fill
end array
read plot
xul=-75 yul=75 zul=0 xlr=75 ylr=-75 zlr=0 uax=1 vdn=-1 nax=130
nch=' wua  swr' end
xul=-91 yul=0 zul=170 xlr=91 ylr=0 zlr=-200 uax=1 vdn=-1 nax=130
end plot
end data
end
```

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