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Calculational Criticality Analyses of 10- and 20-MW UF_6 Freezer/Sublimer Vessels

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MANAGED BY
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FOR THE UNITED STATES
DEPARTMENT OF ENERGY

ORNL/CSD/TM-288

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CALCULATIONAL CRITICALITY ANALYSES OF 10- AND 20-MW UF_6 FREEZER/SUBLIMER VESSELS

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Date Published — February 1993

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MARTIN MARIETTA ENERGY SYSTEMS, INC.
managing the
Oak Ridge National Laboratory Oak Ridge Y-12 Plant
Oak Ridge K-25 Plant Paducah Gaseous Diffusion Plant
under Contract No. DE-AC05-84OR21400
for the
U.S. DEPARTMENT OF ENERGY

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ABSTRACT

Calculational criticality analyses have been performed for 10- and 20-MW UF_6 freezer/sublimer vessels. The freezer/sublimers have been analyzed over a range of conditions that encompass normal operation and abnormal conditions. The effects of HF moderation of the UF_6 in each vessel have been considered for uranium enriched between 2 and 5 wt % ^{235}U. The results indicate that the nuclearly safe enrichments originally established for the operation of a 10-MW freezer/sublimer, based on a hydrogen-to-uranium moderation ratio of 0.33, are acceptable. If strict moderation control can be demonstrated for hydrogen-to-uranium moderation ratios that are less than 0.33, then the enrichment limits for the 10-MW freezer/sublimer may be increased slightly. The calculations performed also allow safe enrichment limits to be established for a 20-MW freezer/sublimer under moderation control.

1. INTRODUCTION

The purpose of this report is to present calculational criticality analyses of 10- and 20-MW freezer/sublimer (F/S) vessels. A 10-MW F/S has been previously analyzed by Taylor.[1,2] This report has three goals: (1) to reconfirm the results of the previous analysis using current computer codes and neutron cross-section libraries; (2) to provide analyses that can be used to establish safe operating limits for the 20-MW F/S; and (3) to provide a discussion of the assumptions used in this analysis, why they were made, and how they affect the calculated results.

The original Taylor reports were written primarily for use by the criticality safety group and criticality engineers directly responsible for the review and approval of the operation of the F/S vessels at Oak Ridge Gaseous Diffusion Plant (ORGDP). The analyses were comprehensive, and considerable detail was given of intermediate results used to reach conclusions on the nuclearly safe ^{235}U enrichment for an F/S. Over a period of several years the documents were referenced in a number of safety analysis reports. Some attempts have been made to redefine the acceptable operation of the F/S based on intermediate results presented in Taylor's reports. It is hoped that the discussion presented here will clarify the criticality control parameters for the F/S and identify assumptions that should be made when certain parameters are not controlled.

This report presents a calculational criticality analysis of a F/S vessel; it does not represent a complete criticality safety evaluation and does not constitute nuclear criticality safety approval for operation. The calculated reactivity or multiplication factor of an F/S for specific conditions of loading, including UF_6 mass, ^{235}U enrichment, and moderation level, are given. No attempt is made to specify the safe enrichment or conditions of operation (and related control parameters) for the system. The values of the control parameters will need to be established elsewhere, and the criticality engineers responsible for the approval of operations of the F/S system will need to determine acceptable conditions of operation.

Section 2 of this report gives a brief review of the F/S system. The modes of operation of the F/S are discussed, and a general description of the F/S vessel is presented.

Section 3 gives a discussion of general concepts of criticality safety and the F/S. A comparison is made between the F/S equipment and operations of the cascade and product withdrawal.

Section 4 gives the details of the codes and cross sections used in this calculational analysis. Detailed geometric models are presented for both 10- and 20-MW F/S vessels.

Section 5 gives calculational results. Discussions of code validation and applicability to the F/S are given in Sect. 6.

2. FREEZER/SUBLIMER

2.1 SYSTEM DESCRIPTION

The F/S system is designed to allow rapid control of in-process UF_6 inventory in a diffusion plant. A 10-MW F/S is capable of removing (freezing, desubliming) or replacing (subliming) about 4000 kg of UF_6 in 1 h. The 20-MW unit has twice the capacity of a 10-MW unit and is capable of freezing or subliming about 8000 kg of UF_6 in 1 h.

The F/S system consists of an F/S vessel, a condenser/reboiler (C/R), and interconnecting piping pumps and instrumentation. A schematic of an F/S system is shown in Fig. 1. Both the F/S vessel and the C/R are large-geometry heat exchangers. The F/S vessel is a single-pass, finned-tube heat exchanger. The C/R is a U-tube heat exchanger. Heat is removed or supplied to the primary side of the C/R by the recirculating cooling water (RCW) system. The refrigerant R-114 (dichlorotetrafluoroethane) is used on the secondary side to move heat between the C/R and the F/S vessel. The R-114 loop is required to provide dual wall isolation between the UF_6 in the F/S vessel and water in the C/R. The R-114 is chemically inert to UF_6 and is not considered a moderating material. On the other hand, water reacts vigorously with UF_6 and is a good moderator. Water entry into the F/S vessel would have significant impact on cascade operation and the criticality safety of the vessel.

The F/S system has five modes of operation: freeze, cold standby, sublime, hot standby, and modified hot standby. A brief description of these modes extracted from the Gaseous Diffusion Plant Safety Analysis Report (GDP SAR)[3] is given below for reference purposes.

The freeze mode allows UF_6 from the "B" line to enter the F/S at a controlled rate and to be stored in a solid phase. The UF_6 is frozen on the outside of the finned tubes in the F/S by passing cold R-114 through the tubes. The fins on the tubes project horizontally from the vertical tubes, such that the fins serve as trays to hold the solid UF_6. Any noncondensible gases entering the F/S are returned to the cascade cell "A" bypass through a vent line. During the freeze mode, R-114 is cooled by flowing supply-side (cold) RCW through the C/R. The cool R-114 enters the F/S vessel from the bottom. As the heat of desublimation is absorbed, the R-114 boils. The R-114 vapors flow to the elevated C/R where they are condensed, and the heat is passed to the RCW system. The condensed R-114 then flows back to the F/S. The mass of UF_6 entering the vessel is monitored by weight-load cells.

Cold standby mode maintains UF_6 in the frozen state and is the standby condition when the F/S is not in the freeze or sublime mode. In cold standby, the F/S is isolated from the cascade by closing valves to the A and B lines and the vent. The R-114 in the system is maintained in the condensed state by flowing supply-side RCW through the C/R. The R-114 flows by gravity to the F/S, where it removes the normal cell heat and vaporizes back to the C/R in an essentially steady-state operation.

In the sublime mode, UF_6 is returned to the cascade from the F/S vessel at a controlled rate. The heat of sublimation is supplied by pumping return-side (hot) RCW through the C/R causing the R-114 to vaporize. As the R-114 vapor passes through the F/S, it condenses, passing heat into the UF_6. The condensed R-114 liquid is pumped back to the C/R. The UF_6 process gas is returned to the cascade through the A line. The rate of return to the cascade is monitored using the F/S load cells.

The hot-standby mode consists of heating the R-114 in the C/R using return-side RCW with the R-114 pump off and the UF_6 lines and vent closed. Hot standby is used if there is a low RCW temperature, low R-114 temperature, or low R-114/RCW differential pressure.

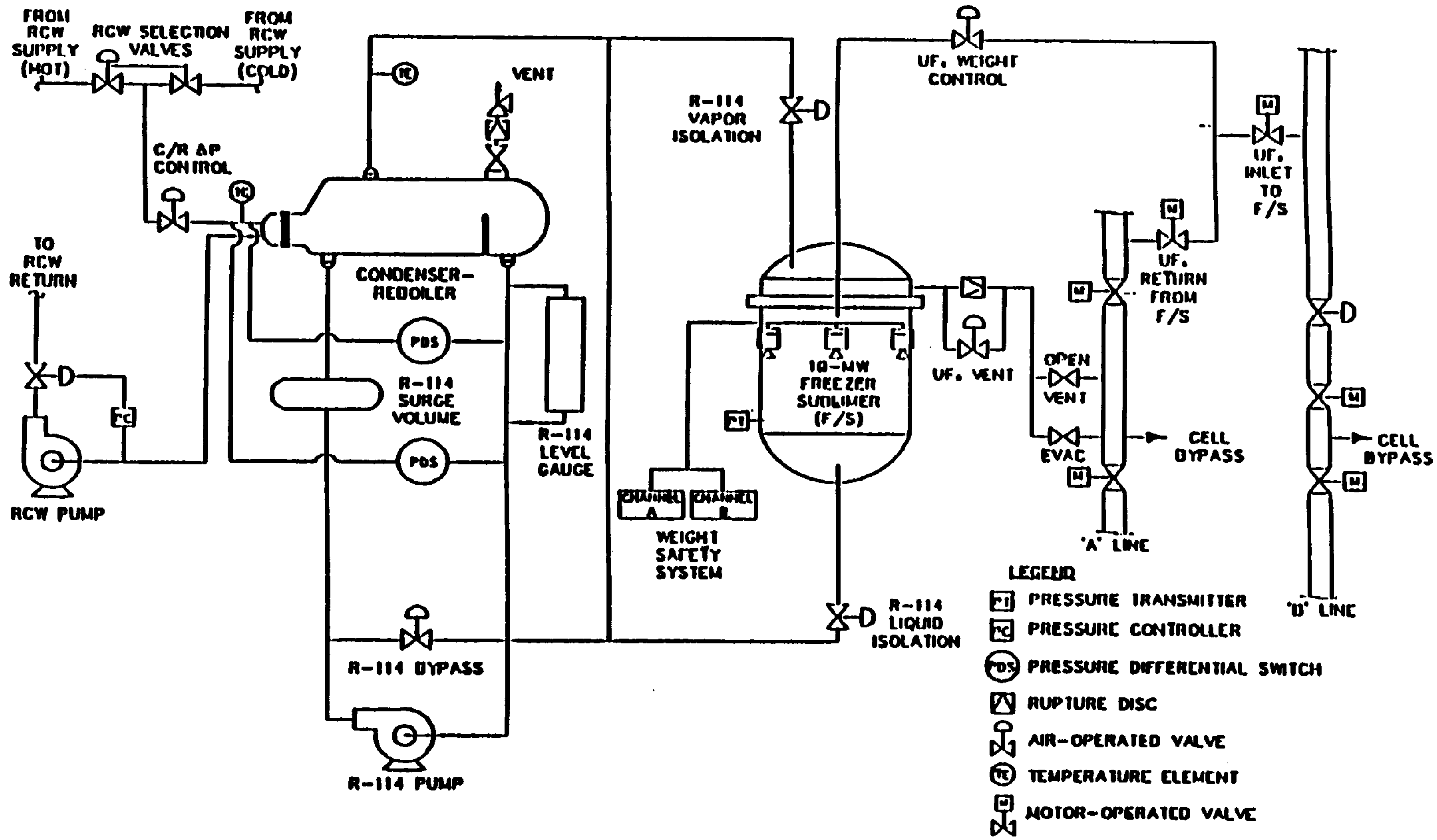

Fig. 1. Typical single-unit F/S.

The modified hot-standby mode occurs only when there are indications of excess UF_6 in the F/S vessel. It is the same as the hot-standby mode, except that the UF_6 return line and vent are open.

Table 1 gives the range of normal operating conditions for the F/S system.

Table 1. F/S operating conditions

Mode	RCW temp. (°F)	RCW press. (psig)	R-114 temp. (°F)	R-114 press. (psig)
Freeze	80–95	25–45	80–107	17-36
Sublime	120–160	0–10	112–160	40–94
Cold standby	80–95	25–45	80–100	17–31
Hot standby	120–160	0–10	112–160	40–94
Modified hot standby	120–160	0–10	112–160	40–94

2.2 F/S VESSEL DESCRIPTION

An F/S is a finned-tube heat exchanger. The 10-MW F/S vessel is 4 ft in diameter with an overall height of approximately 9.5 ft. The tube bundle consists of 204 cupronickel finned tubes mounted vertically between two fixed tube sheets. The tubes consist of a 1-in. outside diameter (OD) cupronickel base to which 2.25-in.-OD aluminum fins have been bonded. The tubes are 7 ft in length, with a finned length of 6.5 ft. Process gas is admitted to the center of the tube bundle through a 6-in. pipe connection that penetrates the top tube sheet, allowing the UF_6 to flow radially outward. The R-114 is admitted to the vessel through either a 4-in.-diam pipe connection located in the bottom dished head or a 6-in. off-center pipe nozzle at the top of the vessel. A 2-in. vent line located just below the top tube sheet is provided to remove noncondensibles. A double-ply expansion joint is installed in the shell to compensate for differential thermal expansion. The vessel is supported on three dual bridge load cells, which are used to measure and control UF_6 inventory within the F/S.

The 20-MW F/S vessel is 4.75 ft in diameter, with an overall height of 13 ft. Its tube bundle consists of 288 tubes of the same outside diameter (OD) and construction as used in the 10-MW unit. The tubes are 10 ft in length with a finned exposure of 9.42 ft. The UF_6 and R-114 connections are dimensionally the same as for the smaller vessel.

Figure 2 shows a cutaway drawing of a typical F/S vessel. Figure 3 shows a schematic of a typical finned-tube section.

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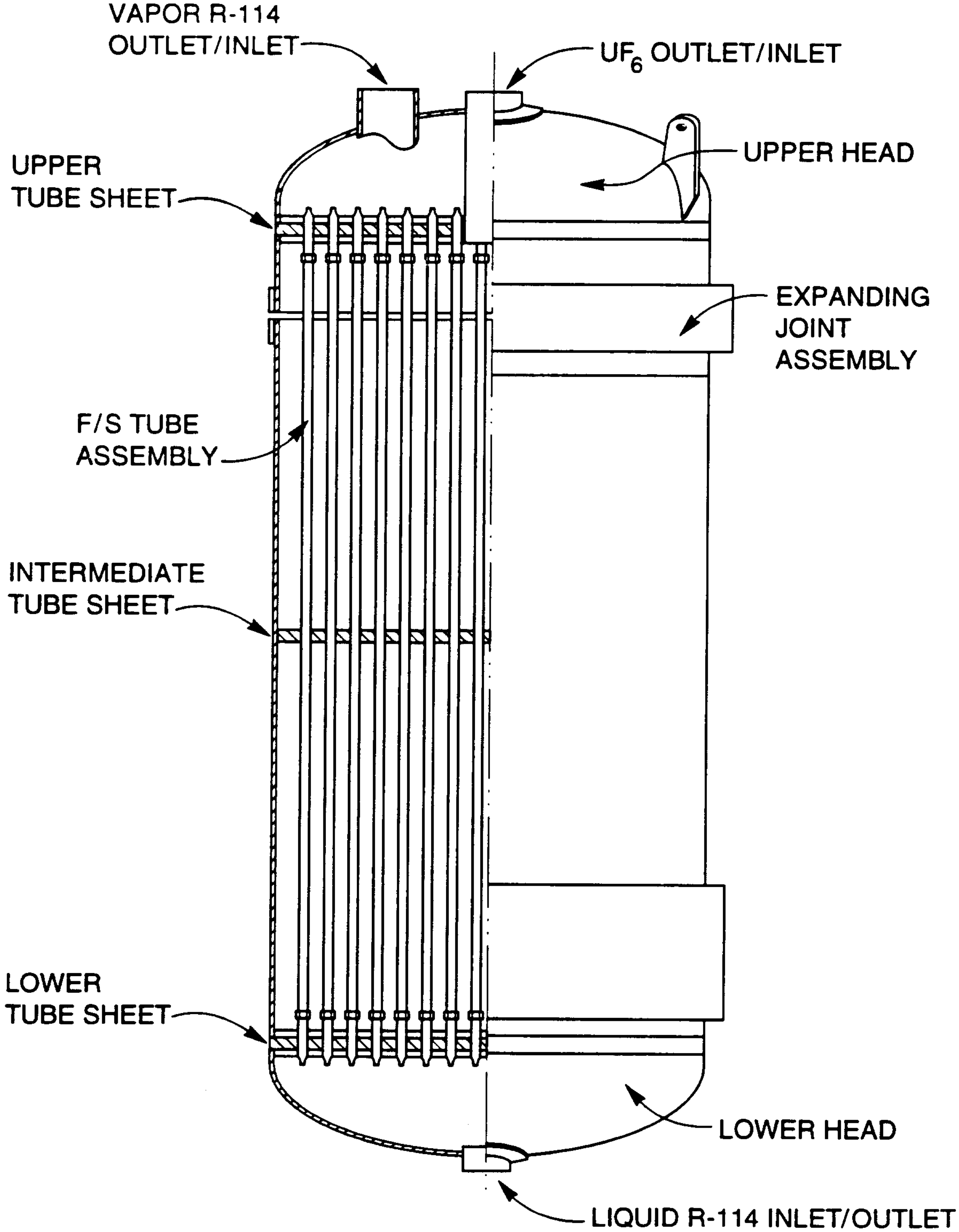
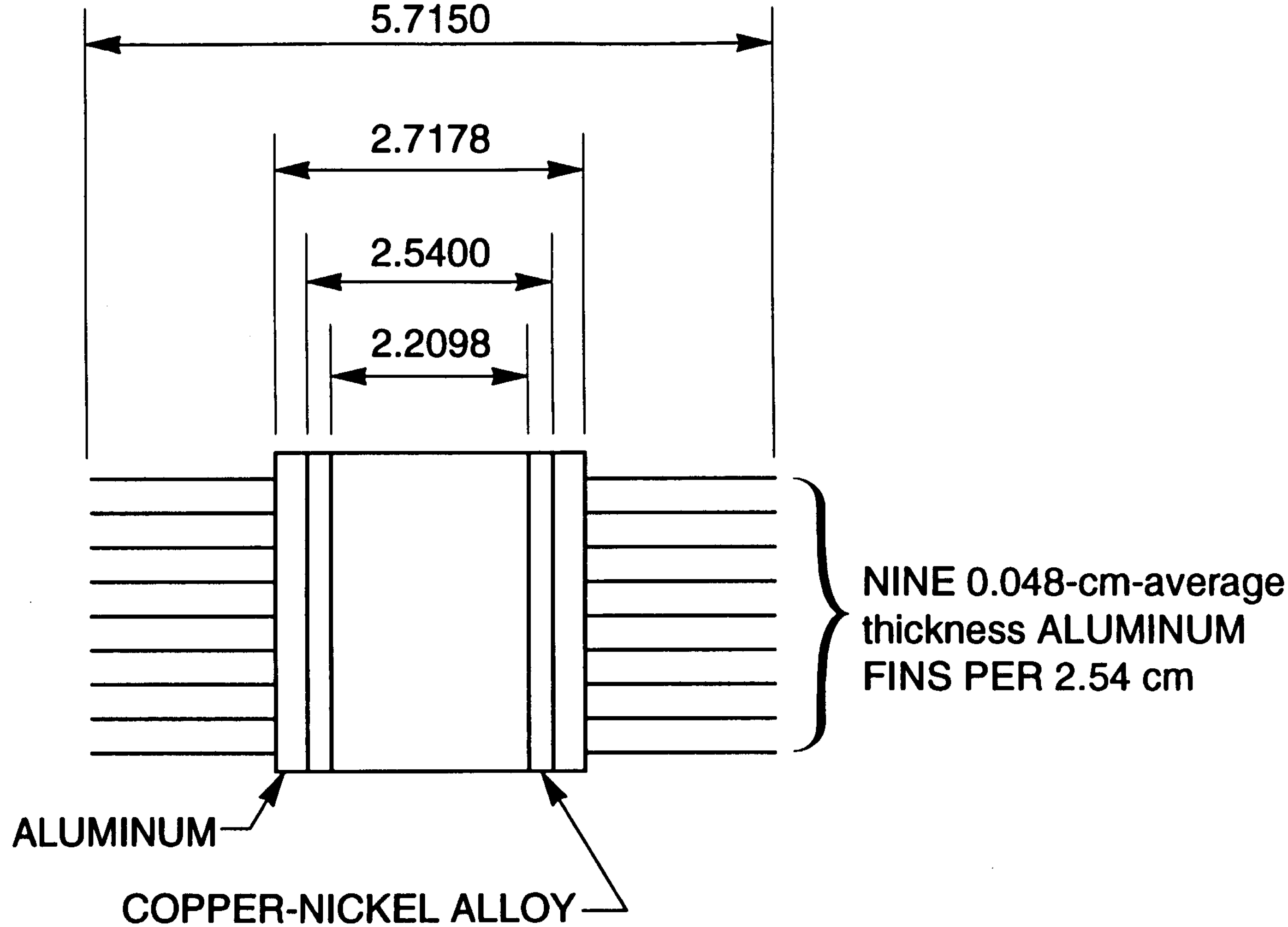


Fig. 2. Cutaway drawing of a typical F/S.

ORNL-DWG 93M-5368



NOTE: All dimensions in centimeters

Fig. 3. Typical F/S tube.

3. CRITICALITY SAFETY CONSIDERATIONS

The F/S vessel and the operation of the F/S system in the cascade are unique in that the F/S vessel is large geometry and is designed to contain large quantities of solid-phase UF_6. The purpose of this section is to give a brief overview of criticality safety nomenclature and its application to the F/S. A comparison is made between the F/S system, the cascade, and UF_6-withdrawal equipment and operations.

Where practicable, the nuclear safety of equipment or operations that involve fissile material are based on single-parameter limits, such as safe mass or geometry for a specific enrichment. For purposes of this discussion, nuclearly safe geometry may be defined as that geometry which, for a given enrichment and fissile material, is subcritical at optimum moderation and full water reflection. Similarly, nuclearly safe mass may be defined as the mass of fissile material which, for a given enrichment, is subcritical at optimum moderation in spherical geometry and is fully water reflected. The only other controls required for these individually safe units controlled to a single parameter limit are those related to neutronic interaction and placement relative to other individually safe units.

Design fundamentals for the gaseous diffusion plant state that with the exception of cascade equipment that handles uranium in the gaseous state, all uranium-containing equipment should meet the requirements of a geometrically safe system wherever feasible.[4,5] Where it is impractical to design a system of safe geometry, equipment of unsafe geometry should generally be designed to operate on positive control of the ^{235}U mass or concentration.

The double-contingency principle is used to evaluate the criticality safety of equipment and operations involving fissile material.[6] Double contingency requires that two unlikely, independent, and concurrent changes in conditions essential to the nuclear safety of the operation must occur before criticality is possible. Criticality controls are the physical and/or administrative limitations imposed on one or more processes or nuclear variables of a given system such that criticality is not possible as long as these limitations are maintained. An important concept in a diffusion plant is that certain "controlled" nuclear variables are process limited, and the true nature of the controls are the administrative controls of the existing process system and operations.

The F/S is considered unsafe geometry. For uranium enriched to greater than 1%, the F/S vessel is large enough in diameter to sustain criticality if sufficiently moderated. The term "sufficiently moderated" is important in the criticality safety of the F/S. The F/S is designed to contain large quantities of UF_6 and, therefore, a mass of ^{235}U, which represents multiple safe masses for enrichments above 1%. In order for an F/S to be demonstrated to be adequately subcritical for enrichments greater than 1%, the moderation level of the uranium in the vessel must be controlled to a sufficiently small value.

Low-enriched uranium has a useful property related to neutron moderation in that uranium enriched to less than 5 wt % ^{235}U cannot be made critical in the absence of a moderator, where hydrogen is the most common moderator considered. The subcriticality of low-enriched uranium may be achieved by controlling the moderation. For the purpose of this report, moderation control is defined as the strict limitation of the level of moderator present such that the effective neutron multiplication factor of the F/S is less than a subcritical acceptance value under all credible conditions. Moderation control has been widely recognized as a primary criticality safety control in the area of transport and storage of low-enriched UF_6 (ref. 7).

In the strictest sense, moderation control implies (1) the ability to measure the moderation level and (2) the means to prevent a specified level from being exceeded. In application, no device is available that measures moderation levels. Instead, controls are put in place to prevent or limit the addition of a moderator to a system.

Moderation by water or other hydrogenous compounds (e.g., oil) is prevented by using barriers such as the wall of the container or eliminating their use in a system. Another hydrogenous moderating compound that is present in a diffusion cascade and which must be considered in UF_6 processing is HF. UF_6 is stable in HF. The primary source of HF as an impurity in a diffusion plant is the result of wet-air inleakage into the cascade. Moisture in the air reacts with UF_6 to form UO_2F_2 and HF. The UO_2F_2 deposits as a solid at or near the site of the reaction; HF gas mixes with the UF_6 and passes through the cascade. HF gas, as an impurity in the UF_6, is always present at some level in an operating cascade. Historically, because the level of HF in the UF_6 gas stream is not known or monitored, and because all the events that could lead to HF in the process gas stream were not known or not specifically identified, it was assumed in criticality safety evaluations that there was an unlimited supply of HF in the process gas as a binary UF_6-HF mixture. HF moderation is of great concern in an operating F/S.

HF moderation control may be accomplished by controlling the pressure and temperature simultaneously to prevent condensation of liquid HF or surface sorption of HF. Several ancillary concepts and criteria are related to moderation control. One of these is that the diffusion plant equipment is sufficiently small such that criticality is not possible for gaseous UF_6 independent of the moderation level of HF in the gas mixture. This equipment includes compressors, converters, coolers, and surge drums. The density of the UF_6 (i.e., UF_6 in the gas phase as opposed to a liquid or a solid phase) is a primary criticality control for cascade equipment. The moderation level of HF in the gas phase is unknown and assumed to be at a worst-case condition for criticality safety analysis.

A principal difference between the F/S criticality safety and the safety of the operating cascade is the density of the UF_6 under normal operating conditions. A primary control for the cascade is that the uranium is in the gas phase and not frozen out or deposited in the equipment. Before criticality is possible in operating diffusion equipment, an abnormal condition must occur, resulting in a deposit of solid uranium. In the F/S, the presence of solid UF_6 is a normal mode of operation.

A possibility does exist in diffusion equipment that UF_6 will not remain in the gas phase but "freeze out" into the solid phase. This situation can and has occurred at cold spots in the cascade. The diffusion plant equipment is not safe geometry for solid-phase UF_6. Freezeouts are considered an abnormal condition of operation which is protected against by maintaining temperatures and pressures for normal cascade operation. Administrative controls and procedures, along with a deposit monitoring program, are used to help minimize the possibility of a freezeout and/or to detect the freezeout and allow corrective action to minimize the mass of uranium involved and the length of time that the condition exists. However, freezeouts have occurred in the past at a frequency such that it is marginal that they should be considered unlikely events.

The safety of the cascade must be demonstrated when the condition of UF_6 freezeout occurs. Historically, this has been addressed by evaluating freezeout locations and assuming an upper bound on the moderation level in the freezeout. Gas coolers in the cascade are one location where UF_6 freezeout is considered more likely to occur. The safety of gas coolers containing UF_6 has been evaluated based on an assumed hydrogen-to-uranium (H/U) = 0.33

(ref. 5).* Cascade operating conditions and the physical characteristics of UF_6 and HF are used to justify the moderation control presumption in the event of a freezeout. Two conditions must occur before criticality is possible: (1) a deposit of uranium must occur or exist, and (2) a moderator must be introduced or be present such that an H/U = 0.33 is exceeded. These considerations have led to criticality safety acceptance of cascade operation.

UF_6 withdrawal by compression liquefaction is another operation that has criticality safety concerns and controls which are similar to those related to F/S operation. Gas-phase UF_6 is compressed and condensed to a liquid and drained into unsafe geometry product cylinders. The safety of the withdrawal operation is based on a combination of safe geometry and moderation control. The pressure/temperature of the liquid UF_6 is monitored and controlled to demonstrate that HF is not present in quantities that could result in criticality. Moderation control is demonstrated in safe geometry equipment before the UF_6 is allowed to drain into unsafe geometry. At the Portsmouth and Oak Ridge diffusion plants, moderation control is/was demonstrated in safe geometry accumulators before being drained into unsafe geometry cylinders. Because the accumulator at the Paducah plant is unsafe geometry, moderation control must be demonstrated at the condenser prior to draining into the accumulator.

Moderation from other sources such as oil from compressors or pumps has been addressed by limiting the size of the pumps and the oil volume available, or by isolating the pumps from the UF_6 by traps or automatic valves which prevent backflow of oil into the UF_6 system. Moderation from external sources, such as fire sprinklers, requires that the UF_6 containment boundary be breached. Because the withdrawal system operates above atmospheric pressure, any breach in the UF_6 boundary, at least initially, results in a UF_6 release, not an introduction of a moderator into equipment containing solid or liquid UF_6. The nuclear safety of the withdrawal system is based on demonstration of moderation control before UF_6 is drained into unsafe geometry and on equipment design and operating characteristics making it improbable that water or oil will enter the system.

UF_6 withdrawal and F/S operations are similar in that both operations take gas-phase UF_6 to a more compact solid or liquid state. Both operations rely on moderation control as the primary (only) control after some point in the process. The operations are different in several respects. The F/S takes gas-phase UF_6 and freezes it directly into unsafe geometry. The F/S operates below atmospheric pressure, and there are different controls required to prevent introduction of water or oil. The F/S handles UF_6 in the solid phase as opposed to a liquid. These and other differences result in a different set of controls and considerations for operation of the F/S than those used for cascade operation and UF_6 withdrawal. Some of these controls are discussed below.

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*There have been several values of H/U moderation level used as an assumed upper bound over the years at the various diffusion plants. The value of H/U = 0.33 is more widely documented, although little background information is available to suggest the technical basis on which it was established. The evaluations of cascade equipment are based on the hydrogen being supplied by HF, as opposed to water or oil. A H/U = 0.33 is assumed in evaluation of cascade freezeouts, but generally not in the evaluation of cascade deposits of UO_2F_2 or UF_4 caused, for example, by wet-air inleakage or equipment failure. The moderation level of deposits caused by wet-air or oil inleakage to the cascade may significantly exceed a H/U = 0.33, depending on the nature and location of the deposit. Deposits of this type are generally analyzed on a case-by-case basis and have not been generically studied.

Two requirements in place for the F/S are that positive R-114/RCW and R-114/UF_6 pressure differentials exist during all modes of operation. The purpose of these controls is to prevent inadvertent water entry or UF_6 entry into the R-114 tubes. These controls do not directly monitor the integrity of the R-114 boundary in that small leaks, especially in the C/R, could exist for long periods of time before differential pressure equalizes. However, they do indicate when the possibility exists for water entry into the R-114 system. At the point differential pressure is lost, it has been assumed that water has entered the R-114 tubes and a single boundary is all that is preventing water entry into a moderation-controlled vessel. Observe that the pressure and temperature ranges for normal operation given in Table 1 indicate a range of conditions that may not satisfy the differential pressure requirements. For the freeze mode and cold standby mode, normal operation could allow the R-114 pressure (17-36 PSIG) to be below the RCW pressure (25-45 PSIG). There is a direct correlation between R-114 pressure and temperature, and the R-114 and RCW temperatures are coupled through the C/R. The minimum RCW temperature must be increased and/or the maximum RCW pressure in the C/R must be decreased from the values in Table 1 in order to satisfy the differential pressure requirements.

Moderation control of HF must also be demonstrated during both normal and abnormal operation of the cascade and the F/S. In the early 1980s at ORGDP, it was shown that HF moderation control could be lost even though the pressure/temperature conditions were such that liquid HF could not condense because of the possibility of surface sorption or monolayer deposition of HF onto UF_6 surfaces. Both condensed-phase and surface-sorbed HF must be controlled such that acceptable moderating levels are not exceeded. It was suggested that controls be placed on the temperature of the RCW system and the pressure of the UF_6 in the F/S vessel such that pressure/temperature conditions inside the F/S could not exceed two-thirds of the condensation pressure/temperature of pure HF. This procedure allowed demonstration of moderation control independent of the composition of UF_6, lights, and HF entering the F/S.

In the operation of the F/S, a cascade upset that breaches the integrity of the F/S vessel and triggers the fire sprinklers could result in criticality even though this may be a single unlikely event or a series of events which are not independent. For low-enriched uranium, there are random factors that affect the likelihood of criticality related to the moderation level and the length of time required to supply this moderation. These random factors may have to be used to judge the acceptability of the F/S systems and operation. Procedures for cascade treatment and for emergency response to breach of the cascade (e.g., because of exothermic, explosive reactions, etc.) need to be scrutinized with respect to the location and operational status of the F/S systems.

4. FREEZER/SUBLIMER PHYSICS MODEL

The F/S is a complex geometric assembly. The neutronics model is also complex. Multiple levels of heterogeneity must be addressed in cross-section processing for the model. The purpose of this section is to describe the computer codes, computational methodology, and background calculations that were used to establish an acceptable F/S model.

A brief description of the computer program modules used in this analysis are given in Sect. 4.1. SCALE-4.0 was chosen for the calculational analysis of the F/S. This version has several enhancements over previous versions that allow more appropriate cross-section processing.

The finned-tube assembly model is discussed in Sect. 4.2. A series of calculations were performed to examine the sensitivity of k_{eff} to approximations required to model the F/S. The results of these calculations indicate that the reactivity effects of the aluminum fins with solid UF_6–HF in between could be approximated as a homogeneous mixture of UF_6–HF–Al without introducing any nonconservatism into the final results.

The detailed models used to determine the k_{eff} of the F/S under various conditions are given in Sect. 4.3. It is not possible to model all possible loading conditions in the F/S vessel. A set of calculational models were chosen such that the calculated k_{eff} encompasses the range of conditions which could exist in a F/S.

A discussion of the assumptions and limitations of the physics model are given in Sect. 4.4.

4.1 CALCULATIONAL METHOD

The SCALE-4.0 computer program modules used in the criticality evaluations are part of the Standardized Computer Analysis for Licensing Evaluation (SCALE) code system.[8] The CSAS25 control sequence or the CSAS1X control sequence of the CSAS4[9] control module of SCALE were used for all computations. The CSAS25 control sequence activates the functional modules BONAMI-S,[10] NITAWL-S,[11] and KENO V.a.[12] The CSAS1X control sequence activates the functional modules BONAMI-S, NITAWL-S, and XSDRNPM-S.[13] The control sequence and functional modules are summarized in the following paragraphs. The 27-group ENDF/B-IV cross-section library in SCALE-4.0 was used for all calculations.

One of the more important enhancements in SCALE-4.0 over previous versions is the implementation of the annular treatment in the LATTICECELL option of the code. In previous versions of SCALE, interchanging the location of the fissile material and moderator regions in the LATTICECELL description resulted in incorrect cross-section processing that could create a bias in the calculations (positive or negative, depending on the specific systems). With the annular treatment, all radial regions in the LATTICECELL description are treated rigorously. This feature of the code is important in the F/S analysis. The control sequences and functional models used in this evaluation are described below.

The CSAS25 control sequence reads user-specified input data, which include the required cross-section library, specification for mixtures, information for resonance processing of nuclides (size, geometry, and temperature), and a detailed geometry model for KENO V.a. Physical and neutronics information not supplied explicitly but required by the functional modules (such as theoretical density, molecular weights, average resonance region background cross sections) is supplied by the Standard Composition Library[14] or calculated by the Materials Information Processor.[15] The Standard Composition Library consists of a standard composition directory and table, an isotopic distribution directory and table, and a nuclide information table. These data were used to set up the input for BONAMI-S, NITAWL-S, and KENO V.a.

The 27-group ENDF/B-IV master cross-section library in SCALE[16] is activated in the CSAS25 control sequence by specifying 27GROUPNDF4 (27GR) as the cross-section library name. The 27-group library is the broad-group companion library to the 218-group Criticality Safety Reference Library. The Criticality Safety Reference Library master library, which is based on ENDF/B-IV data, was generated as a pseudo-problem-independent fine-group structure library for use in general criticality safety analysis and shipping cask calculations. The 27-group library was collapsed from the 218-group library using a characteristic fission-(1/E)-Maxwellian spectral flux shape. Explicit ENDF/B-IV resonance parameters are carried for resonance nuclides in both the 27- and 218-group master libraries. These resonance parameters are used by NITAWL-S in the CSAS25 control sequence for calculating problem-dependent, self-shielded resonance region cross sections.

BONAMI-S performs resonance shielding through the application of the Bondarenko shielding factor method. BONAMI-S reads the master format library and applies the Bondarenko correction to all nuclides that have Bondarenko data. Input data to BONAMI-S, set up by the CSAS25 control sequence, include information relating to the physical characteristics (composition of material, size, geometry, temperature) of the system being calculated. BONAMI-S produces a Bondarenko-corrected master format library which is read by NITAWL-S.

For the 27-group master cross-section library used in this study, the primary purpose of the BONAMI functional module is to select the required material cross sections and to create a smaller master cross-section library to be processed by NITAWL. No data processing is performed in BONAMI for the 27-group cross-section library.

NITAWL-S applies the Nordheim Integral Treatment to perform neutron cross-section processing in the resonance energy range for nuclides that have ENDF/B resonance parameter data. This technique involves the numerical integration of ENDF/B resonance parameters using a calculated flux distribution which is based on the calculated collision density across each resonance and subsequent weighting of the reaction cross section to the desired broad group structure. Input data to NITAWL-S, automatically set up by the CSAS25 control sequence, include information relating to the physical and neutronic characteristics of the system being calculated. NITAWL-S uses these data to complete the processing of the problem-dependent master library from BONAMI-S. In the SCALE sequence, NITAWL-S assembles the group-to-group transfer arrays from the elastic and inelastic scattering components, and performs other tasks to produce a problem-dependent, working cross-section library that can be used by KENO V.a.

KENO V.a, a multigroup Monte Carlo computer code, is used to determine k_{eff} for multidimensional systems. The geometrical bodies allowed in KENO V.a for defining models include cuboids, spheres, and cylinders. KENO V.a has an enhanced geometry package that (1) allows arrays to be defined and positioned throughout the model, (2) includes a P_n-scattering treatment, (3) has an extended use of differential albedo reflection, (4) generates printer plots for checking the input model, (5) allows supergrouping of energy-dependent data, (6) has a restart capability, and (7) defines origin specifications for cuboids, spheres, cylinders, hemicylinders, and hemispheres.

XSDRNPM-S is a one-dimensional (1-D) discrete-ordinates multigroup transport code used to determine k_{eff} for 1-D systems or infinite media systems. The geometric capabilities of XSDRNPM-S include spherical geometry, infinite-length cylinders, and infinite slabs. Options for buckling corrections allow approximation of finite-length two-dimensional (2-D) cylinders and finite three-dimensional (3-D) slabs. XSDRNPM-S calculations are useful in evaluating the effects of small changes in cross-section processing or modeling for a system that might be hidden in the statistics of a Monte Carlo code. Default SCALE values for convergence (1×10^{-4}), quadrature order (S_8), and Legendre cross-section expansion (P_3) were used. XSDRNPM-S results were used only for sensitivity analysis, with detailed KENO V.a calculations used for all safety evaluations.

4.2 FINNED-TUBE ASSEMBLY MODEL

The F/S has multiple levels of heterogeneity. The first level of heterogeneity is that of the UF_6-HF fissile mixture and the aluminum fins. A second level of heterogeneity is the UF_6-HF-Al and the cupronickel tube lattice. The computer codes used in this analysis do not allow explicit cross-section processing for this double heterogeneity. A complicating factor is that the magnitude of heterogeneous effects is dependent on the physical characteristics of the system. The purpose of this section is to identify the possible sources of moderation and heterogeneity in the F/S and to establish a calculational model that acceptably accounts for their effects.

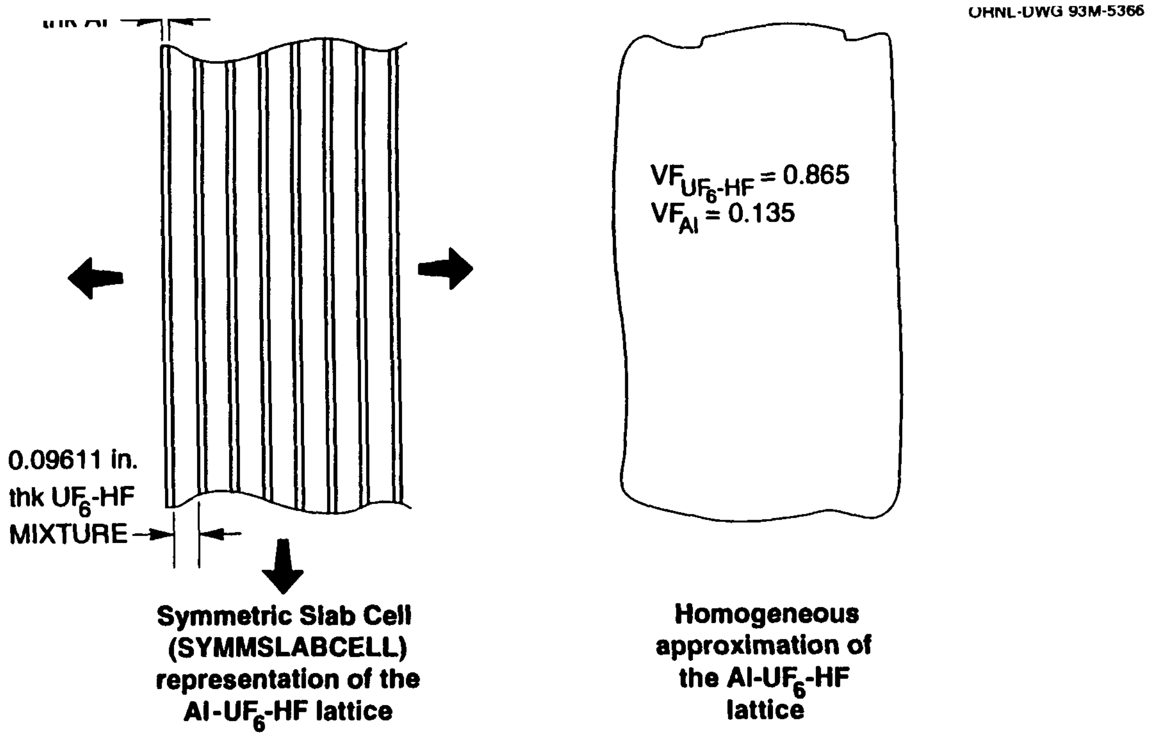
Heterogenous effects may exist when the fissile material is separated from a moderating material. The magnitude of the effects depends on several parameters, including the thickness of the fissile region, the density of the fissile material, the type of moderating material, the thickness of the moderating material region, and the enrichment of the uranium. Hydrogen is a good moderator and is generally of greatest concern. Aluminum is not a good moderating material; however, a significant quantity of aluminum is latticed with the fissile material. The heterogeneity presented by the aluminum fins and the UF_6-HF must be evaluated. The effects are expected to be minor with respect to that of the UF_6-HF-Al and the cupronickel tube lattice with the tubes flooded with water. If the heterogeneous effects of aluminum can be demonstrated, then the use of a volume-homogenized UF_6-HF-Al mixture will allow explicit treatment of tube lattice effects.

Hydrogen moderation of the UF_6 in the F/S can be from several sources. During otherwise normal operation, HF, either as a condensed liquid or adsorbed to the surface of the UF_6, is a moderator. In the analyses performed here, reference to the H/U moderation ratio specifically relates to an assumed quantity of HF intermixed with the UF_6.

The level of moderation of the UF_6 in the F/S may also be increased if water enters the freon side of the tubes. During normal operation either freon R-114 or R-114 vapor (void) is present on the tube side. In one possible accident scenario, water could flood the freon tubes. This case is specifically addressed in the F/S calculational models. The possibility of water entering the UF_6 side of the F/S vessel has not been analyzed here because it is accepted *a priori* that if water is introduced directly into the F/S vessel containing enriched UF_6, criticality is likely.

A series of infinite media multiplication (k_∞) calculations were performed to investigate the heterogeneous and moderating effects of the aluminum fins. This procedure was accomplished by performing calculations for lattices of UF_6-HF and aluminum with explicit treatment of the geometric effects, and then comparing the results with calculations in which the aluminum was volume homogenized into the UF_6-HF mixture. Several uranium enrichments and H/U atomic ratios were considered. These calculations were performed using the CSAS1X control sequence of SCALE-4.0, described in Sect. 4.1.

The lattice of UF_6-HF and aluminum was modeled using the *SYMMSLABCELL* option of the *LATTICECELL*-type calculation. Figure 4 gives a schematic representation of the



SCALE input example

```
=CSAS1X
C510L H/U=0  5.0% ENR.
27GROUPNDF4  LATTICECELL

URANIUM    1 DEN=3.4578    1.0 293   92235 5.0   92238 95.0    END
F          1 DEN=1.6568    1.0                                 END
HFACID     1 DEN=0.0       1.0                                 END

' AL @ 2.6989G/CC
AL         2               1.0                                 END

END COMP
'               PITCH      FUEL OD  FUEL  MMOD
SYMMSLABCELL    0.28222    0.24412   1     2                   END
END
```

```
=CSAS1X
C510 H/U=0  5.0% ENR.
27GROUPNDF4 INFHOMMEDIUM

URANIUM  1 DEN=3.4578  .8650 293  92235 5.0  92238 95.0  END
F        1 DEN=1.6568  .8650                             END
HFACID   1 DEN=0.0     .8650                             END
AL       1             .1350                             END
END COMP
END
```

Fig. 4. LATTICECELL and INFHOMMEDIUM approximations of the fin assembly.

geometry model used to process the cross sections when using this option. The model approximates the horizontal surfaces of the aluminum fins as infinite plates in a configuration of nine 0.015-in.-thick plates of aluminum per inch. In this model, the minimum fin thickness of 0.015 in. was used instead of the average thickness given in Fig. 3. This maximizes the volume of UF_6 and minimizes the volume of aluminum in the model. Three enrichments of uranium were considered in the fuel region: 2, 3, and 5 wt % ^{235}U. The H/U in the fuel region was varied from 0 to about 16 for each enrichment. The results are given in Table 2.

Comparison of the LATTICECELL and INFHOMMEDIUM calculational results in Table 2 indicates that the two models are nearly equivalent and that heterogenous effects of the aluminum in the UF_6-HF-Al lattice are negligible. A slight amount of conservatism is present for the volume-homogenized cases, which is considered acceptable. Also shown in Table 2 are the calculational results for the homogeneous 5% enrichment cases with no aluminum. These results indicate that the presence of the aluminum has a small effect on the infinite media multiplication at moderation levels below an H/U = 1.0. As the moderation level is increased, the absence of the aluminum increases the infinite media multiplication by about 3%.

Table 2. Finned-tube modeling effects

		Infinite media multiplication (k_∞)		
Case	H/U	l)LATTICECELL	h)INFHOMMEDIUM	w/o Al INFHOMMEDIUM
5.0% Enriched				
c510 {l or h}	0.0	0.69594	0.69554	0.70574
c511	0.33	0.83408	0.83313	0.84693
c512	1.0	1.01520	1.01561	1.03144
c513	2.0	1.16497	1.16554	1.18373
c514	4.0	1.29810	1.29874	1.32153
c515	8.0	1.37475	1.37508	1.40762
c516	10.0	1.38185	1.38214	1.41915
c517	12.0	1.38025	1.38044	1.42173
c518	14.0	1.37326	1.37343	1.41866
c519	16.0	1.36289	1.36304	1.41193
3.0% Enriched				
c313	2.0	1.07933	1.08013	
c314	4.0	1.20252	1.20308	
c315	8.0	1.24870	1.24908	
c316	10.0	1.24238	1.24270	
c317	14.0	1.21098	1.21125	
c318	6.0	1.24090	1.24134	
2.0% Enriched				
c213	2.0	0.99799	0.99861	
c214	4.0	1.10334	1.10386	
c215	8.0	1.12037	1.12071	
c216	10.0	1.10312	1.10342	
c217	14.0	1.05519	1.05541	
c218	6.0	1.12577	1.12618	

Case c515, 5% enrichment at an H/U = 8, was arbitrarily chosen to further study the effects of the aluminum in the system. The results of these calculations are presented in Table 3. In the first set of calculations presented in Table 3, the volume fraction of UF_6 was reduced by factors of 0.7, 0.5, and 0.3 from the initial value to simulate various UF_6 loadings. Comparison of the results indicates that as the relative amount of UF_6 is reduced, the conservatism introduced by the homogenized (INFHOMMEDIUM) model increases slightly. In the second set of calculations, the volume fraction of aluminum was varied by factors ranging from 0.0 to 2.0. Increasing the volume fraction of aluminum above 1.0 simulates conditions where the fin thickness and/or the aluminum density are greater than that used in the model. The homogenized model exhibits a small amount of conservatism over the lattice model for each of the calculations. In addition, the calculated infinite media multiplication decreases as the relative amount of aluminum is increased. The aluminum is acting as a neutron absorber and not as a moderator for the systems considered.

The results of these calculations indicate that volume homogenization of the UF_6-Al lattice introduces minor conservatism into the model and is considered acceptable. Approximation of the UF_6-Al lattice in this manner allows for explicit modeling of the F/S tube lattice.

Table 3. Reactivity effects of aluminum

Case	H/U	UF_6 volume fraction	Infinite media multiplication k_∞ l)LATTICECELL	h)INFHOMMEDIUM
c515 {l or h}	8.0	1.0	1.37475	1.37508
c525		0.7	1.36133	1.36763
c525		0.5	1.34339	1.35239
c525		0.3	1.30376	1.31779

Case	H/U	Al volume fraction	l)LATTICECELL	h)INFHOMMEDIUM
al0 {l or h}	8.0	0.0	1.40761	1.40762
al1		0.2	1.40090	1.40093
al2		0.5	1.39097	1.39116
al3		0.7	1.38444	1.38469
al4		1.0	1.37475	1.37508
al5		1.2	1.36838	1.36875
al6		1.5	1.35893	1.35949
al7		1.7	1.35270	1.35331
al8		2.0	1.34347	1.34401

4.3 FREEZER/SUBLIMER CALCULATIONAL MODEL

Because it is impossible to analyze all possible UF_6 loading conditions in the F/S, an extensive series of calculations were performed for a 20-MW F/S with 5% enriched uranium to determine a subset of calculations which could be used as a bounding set for analysis of the 10- and 20-MW F/S. The subset of calculations, performed for each size F/S unit over a range of enrichments and moderation levels, bounds conditions which could exist in the F/S.

The F/S model was constructed to minimize the changes that would have to be made in the model for the parametric calculations performed. This was accomplished by building a generic geometry model for the 10- and 20-MW vessels and changing the material compositions in the regions to model various conditions, such as freon in the tubes, void in the tubes, water in the tubes, nominal UF_6 loading, and complete UF_6 loading. Modeling in this manner helps reduce errors inadvertently introduced when the model is changed.

Section 4.3.1 describes the generic geometry models used for the 10- and 20-MW F/S vessels. Section 4.3.2 gives the material specifications used in the calculation model. Calculational results for a 20-MW F/S with 5% enriched UF_6 are given in Sect. 4.3.3. These results were used to establish the subset of calculations used as bounding calculations for the 10- and 20-MW F/S. The results presented in Sect. 4.3.3 allow a "feel" for the reactivity effects of changes in the model.

An error was inadvertently introduced into the resonance processing for the F/S calculations in Sect. 4.3.3, where the vessel was modeled as filled with UF_6. The error was introduced when two regions that contained the same resonance material were modeled adjacent to each other. The SCALE cross-section processing routines are not designed to treat resonance overlap from within a region or between regions. This subtle modeling error introduced a nonconservative bias in the calculated k_{eff}. The geometric corrections applied by the code caused the resonance absorption in ^{238}U to be high. The modeling error was corrected for the calculations presented in Sect. 5.

4.3.1 Freezer/sublimer geometry model

A sketch of the F/S geometry model showing the KENO V.a geometry units is given in Fig. 5. Tables 4 and 5 give the dimensions of the 10- and 20-MW geometry models, respectively. The geometry models for the 10- and 20-MW F/S calculations were constructed in a similar manner; the differences were in the diameter and length of the vessel.

Each model consists of a lattice of finned tubes surrounded by a cylindrical steel shell. Solid 2.6-in.(6.604-cm)-thick steel tube sheets were modeled at each end of the finned tube region. The heads were modeled as a segment of a spherical shell which approximates the curvature, thickness, and depth of the actual ellipsoidal heads. A minimum of 30 cm of water was modeled outside the sides and top of the F/S to account for reflective effects of adjacent equipment, structures, or housings which might exist. Sixty centimeters of concrete was modeled as the bottom reflector.

The 0.5-in. nominal wall thickness F/S vessel was modeled with a reduced wall thickness of about 0.375 in. This adjustment was made to account for any undertolerance in the wall of the vessel and to add a slight amount of conservatism to the model because of the increased effectiveness of the external water reflector.

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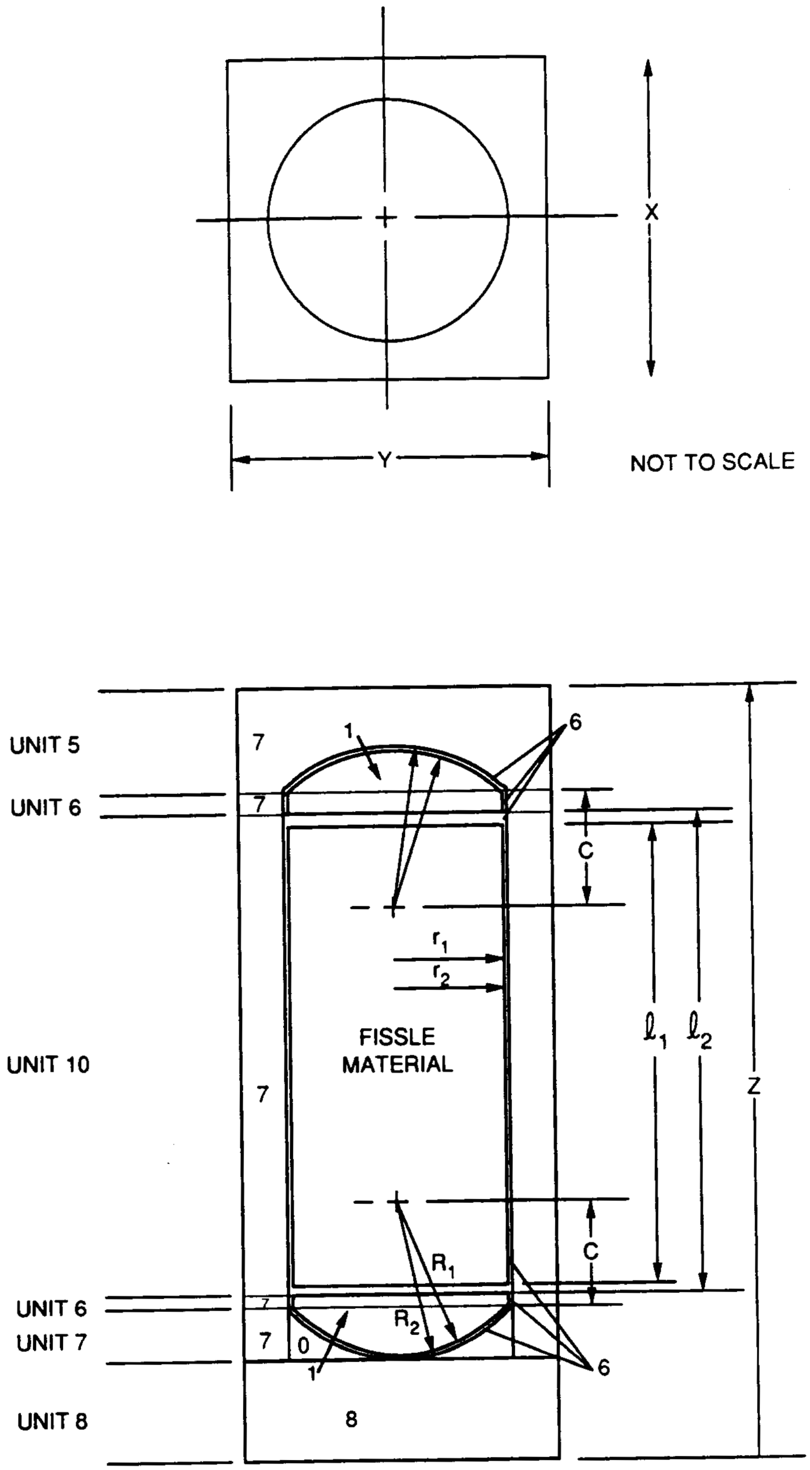

Fig. 5. F/S geometry model.

Table 4. 10-MW F/S geometry model

Unit	Description	Geometry (all dimensions in cm)	Material region	Material
8	Lower concrete reflector	Cuboid x=y=181.92, z=60.48	8	Reg. concrete
7	Lower head	Spheroidal segment R_1=81.5775, C=55.633	1	Void/freon/water
		Spheroidal segment R_2=82.5290, C=55.633	6	Steel; SA-516 GR55
		Cylinder r=60.9600, Z=26.896	0	Void
		Cuboid x=y=181.92, Z=26.896	7	Water reflector
6	Head straight flange	Cylinder r_1=60.0088, z=2.948	1	Void/freon/water
		Cylinder r_2=60.9600, z=2.948	6	Steel; SA-516 GR55
		Cuboid x=y=181.92, z=2.948	7	Water reflector
10	Finned-tube region and upper and lower tube sheets	Cylinder r_1=60.0088, l_1=198.12	-	Fissile material region
		Cylinder r_2=60.9600, l_2=211.3280	6	Steel; SA-516 GR55
		Cuboid x=y=181.92, z=211.3280	7	Water reflector
5	Upper head	Spheroidal segment R_1=81.5775, C=55.633	1	Void/freon/water
		Spheroidal segment R_2=82.5290, C=55.633	6	Steel; SA-516 GR55
		Cuboid x=y=181.92, z=57.367	7	Water reflector

Reference Drawings

M5E17202 R Rev D Freezer/Sublimer 10 MW[17]
M5E17202 T Rev C Head - 10 MW upper and lower[18]
M5E17202 V Rev A Tube sheet, 10 MW upper and lower[19]

Table 5. 20-MW F/S geometry model

Unit	Description	Geometry (all dimensions in cm)	Material region	Material
8	Lower concrete reflector	Cuboid x=y=204.78, z=60.48	8	Reg. concrete
7	Lower head	Spheroidal segment R_1=97.0475, C=66.058	1	Void/freon/water
		Spheroidal segment R_2=98.0000, C=66.058	6	Steel; SA-516 GR55
		Cylinder r=72.39, z=31.942	0	Void
		Cuboid x=y=204.78, z=31.942	7	Water reflector
6	Head straight flange	Cylinder r_1=71.4375, z=4.253	1	Void/freon/water
		Cylinder r_2=72.3900, z=4.253	6	Steel; SA-516 GR55
		Cuboid x=y=204.78, z=4.253	7	Water reflector
10	Finned-tube region and upper and lower tube sheets	Cylinder r_1=71.4375, l_1=289.56	-	Fissile material region
		Cylinder r_2=72.3900, l_2=302.768	6	Steel; SA-516 GR55
		Cuboid x=y=204.78, z=302.768	7	Water reflector
5	Upper head	Spheroidal segment R_1=97.0475, C=66.058	1	Void/freon/water
		Spheroidal segment R_1=98.0000, C=66.058	6	Steel; SA-516 GR55
		Cuboid x=y=204.78, z=61.9417	7	Water reflector

Reference Drawings

M5E17202 B Rev C Freezer/Sublimer 20 MW[20]
M5E17202 E Rev D Head - 20 MW upper and lower[21]
M5E17202 G Rev A Tube Sheet, 20 MW upper and lower[22]

The interior region of the F/S contains the fissile material. The model of this region was constructed by first modeling the finned tubes and then constructing a "base array." The base array was the largest square array of tubes that could be modeled within the F/S shell. Finned tube positions outside of the base array were modeled using the KENO V.a HOLE feature.

The Wolverine[23] finned-tube assembly was modeled radially as a 1.0-in. OD by 0.055-in. wall thickness (1.1303-cm inside radius × 1.27-cm outside radius) cupronickel tube with an integral contact 1.07-in. OD (1.3589-cm outside radius) aluminum tube. The finned region was modeled with an OD of 2.25 in. (2.8575-cm outside radius). A homogeneous mixture of UF_6–HF–Al was modeled. The volume fraction of UF_6–HF and Al were 0.865 and 0.135, respectively. This corresponds to a finned-tube assembly with 9 uniform 0.015-in.-thick fins per inch. The tubes were modeled on a 2.75-in.(6.9850 cm)-center-to-center pitch. The region external to the finned region was modeled as a void or filled with UF_6–HF. Figure 6 shows a sketch of the finned-tube geometry model. The dimensions for the F/S finned tube model are given in Table 6.

The 0.065-in. minimum wall thickness of the cupronickel tube was modeled with a reduced wall thickness of 0.055 in. This adjustment was made to account for corrosion which might reduce the wall thickness. This modeling increases the volume available for water in the tubes and reduces the amount of absorbing material in the vessel model. The aluminum fin thickness and diameter were taken to be the minimum specification values. This modeling increased the volume available for UF_6–HF and decreased the amount of absorbing material in the vessel model.

4.3.2 Material compositions used in the F/S analysis

The material compositions used in the F/S analysis are described in this section. Nominal material compositions and nominal material densities were specified initially. Subsequently, the volume fractions for the aluminum and cupronickel were reduced to build a degree of conservatism into the model. The material composition descriptions presented in this section include this built-in conservatism. These modeling optimizations are discussed in detail in Sect. 4.4.

A description of the SCALE standard compositions used in the calculations are given in Table 7. These standard compositions were used in the specification of the mixtures used in the calculational models. The standard composition volume fraction was used to adjust the relative amounts of materials in mixtures containing more than one standard composition. The mixture compositions used in the calculations are given in Table 8.

Mixture 1 in the F/S is the material inside the cupronickel tube. This mixture could be freon, a void, or water, depending on the specific case being modeled. In order to facilitate simple modifications of the model, all three of these materials were included in the material description of each case.

For cases in which R-114 was considered in the tubes, the physical and chemical properties of 1,1 dichloro 1,2,2,2 tetraflouroethane were used. The chemical formulation can be expressed in simplest form as $C_2Cl_2F_4$. R-114 was modeled in SCALE using the arbitrary material option for a compound. A theoretical density of 1.455 g/cc was used, corresponding to the density of R-114 at 25°C and atmospheric pressure.

A void inside the tube was modeled as R-114 at a density of 1×10^{-15}. Even though this is not a true void, calculationally it is an insignificant density.

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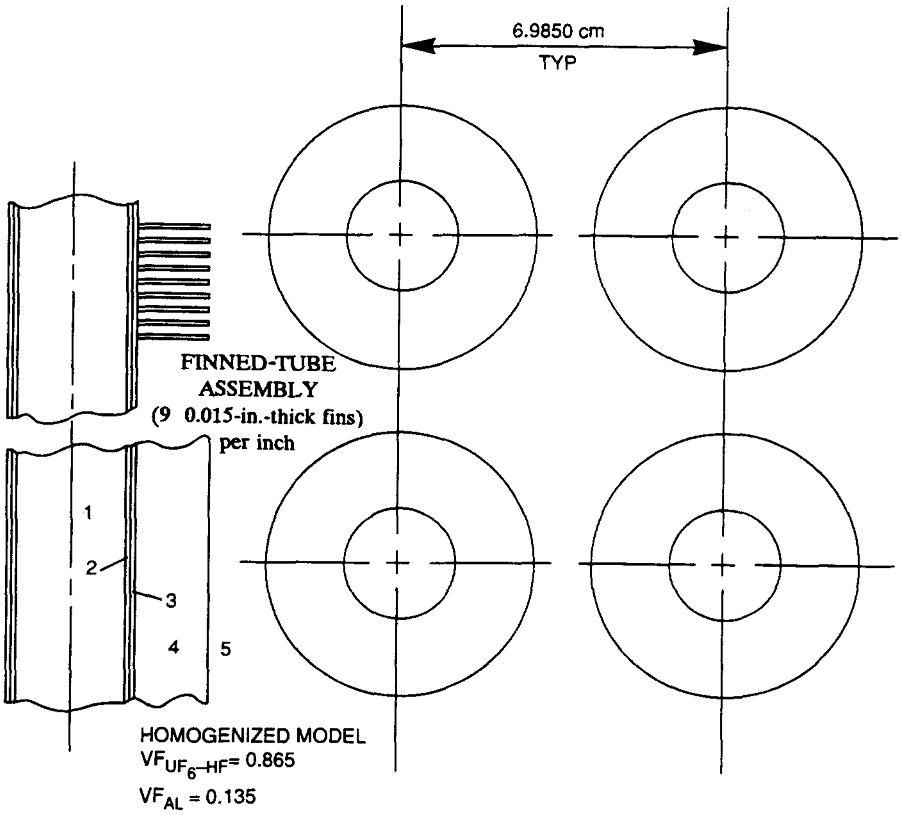

Fig. 6. Finned-tube assembly model.

Table 6. Finned-tube assembly model

Unit	Description	Geometry[a] (all dimensions in cm)	Material region	Material
1	Finned-tube assembly "HOLE" model	Cylinder r=1.1303	1	Void/freon/water
		Cylinder r=1.2700	2	Cupronickel
		Cylinder r=1.3589	3	Al
		Cylinder r=2.8575	4	UF_6-HF/AL
		Cylinder r=2.8575	5[b]	UF_6 in overloaded region
4	Finned-tube assembly "Base Array" model	Cylinder r=1.1303	1	Void/freon/water
		Cylinder r=1.2700	2	Cupronickel
		Cylinder r=1.3589	3	Al
		Cylinder r=2.8575	4	UF_6-HF/Al
		Cylinder r=2.857	5[b]	UF_6 in overloaded region
		Cuboid x=y=6.9850	5	UF_6 in overloaded region

[a]The length of the finned-tube assembly model is 198.12 cm for the 10-MW F/S and 289.56 cm for the 20-MW F/S.
[b]The model was constructed in a manner that would allow for calculating overloading conditions that were less than "complete filling"; however, this feature was not used in the F/S analysis.
Sources: Dwg. M5E17202 H Rev A Tube, 10 MW and 20 MW finned,[24]
Wolverine Tube INC - Wolverine Trufin type L/C specifications.[23]

Table 7. Standard composition descriptions

Composition name (material)	Material density g/cc	Constituent	wt % in composition (or number of atoms per molecule)
ARBMR114	1.455	C	(2)
(freon R-114)		F	(4)
		Cl	(2)
ARBMVOID	1×10^{-15}	C	(2)
(void)		F	(4)
		Cl	(2)
H_2O	0.9982	H	(2)
(water)		O	(1)
ARBMC71500	8.94	Cu	67.80
(cupronickel)		Ni	31.00
		Fe	0.70
		Mn	0.50
AL	2.6989	Al	100.00
(aluminum)			
UF6	5.11591[a]	U	(1)
(uranium hexafluoride)		F	(6)
HFACID	0.0000[a]	H	(1)
(hydrofluoric acid)		F	(1)
ARBMSA516	7.85	Fe	98.855
(SA-516 GR55 steel)		Mn	0.765
		Si	0.290
		C	0.900
RFCONCRETE		O	48.49
(Rocky Flats concrete)		Ca	23.00
		Si	15.50
		C	5.52
		Al	2.17
		K	1.37
		Mg	1.25
		Fe	1.01
		H	0.75
		Na	0.63
		S	0.19
		Ti	0.10
		N	0.02

[a]The density of UF_6 and HFACID are determined by using a volume additive density formulation given in Appendix B. The density shown is for 2% enriched UF_6 at an H/U = 0.0 and a temperature of 15°C.

Table 8. Mixture compositions used in the calculations

Mixture No.	Compositions used in the mixture	Volume fraction in the mixture	Constituent	Atom density
1	ARBMR114	1.0	C	1.02543-2
			F	2.05086-2
	or		Cl	1.02543-2
	ARBMVOID	1.0	C	7.04764-18
			F	1.40953-17
	or		Cl	7.04764-18
	H2O	1.0	H	6.67514-2
			O	3.33757-2
2	ARBMC71500	0.5[a]	Cu	2.84743-2
			Ni	1.42193-2
			Fe	3.37422-4
			Mn	2.44994-4
3	AL	0.5[a]	Al	3.01187-2
			^{235}U[b]	1.53324-4
4	UF6	0.8650	^{238}U[b]	7.41801-3
	HFACID	0.8650	F	4.5428-2
	AL	0.0675[a]	H	0.00000
			Al	4.06602-3
5	UF6	1.0 (or 1×10^{-5})[c]	^{235}U[b]	1.77253-4
	HFACID	1.0 (or 1×10^{-5})[c]	^{238}U[b]	8.57573-3
			F	5.25179-2
			H	0.00000
6	ARBMSA516	1.0	Fe	8.36829-2
			Mn	6.58277-4
			Si	4.88134-4
			C	3.54553-3
7	H2O	1.0	H	6.67514-2
			O	3.33757-2
8	RFCONCRETE	1.0	O	4.23723-2
			Ca	8.02088-3
			Si	7.71397-2
			C	6.42958-3
			Al	1.12412-3
			K	4.8972-4
			Mg	7.18849-4
			Fe	2.52792-4
			H	1.04019-2
			Na	3.83033-4
			S	8.28260-5
			Ti	2.91932-5
			N	1.99629-5

[a]Scoping calculations were performed at volume fractions of 1.0, 0.7, and 0.5. The results indicated that this material of construction is important to the reactivity of the system. A volume fraction of 0.5 was used in all of the subsequent calculations.

[b]The ^{235}U and ^{238}U atom densities depend on the enrichment and H/U moderation ratio being calculated. These values are for 2% enriched UF_6 at an H/U = 0.0 and at 15°C.

[c]Mixture 5 is the UF_6 modeled in the region between the finned tubes. For the nominal loaded cases, a volume fraction of 1×10^{-5} was used; for fully loaded cases, a volume fraction of 1.0 was used.

The SCALE default specifications corresponding to water at a density of 0.9982 g/cc were used for cases having water inside the tubes.

Mixture 2 is the cupronickel tubing. The nominal composition used for cupronickel was that specified for SB-359 C71500 from ASME Section II, Part B.[25] The material was defined as 67.8 wt % Cu, 31 wt % Ni, with minor quantities of iron and manganese. A density of 8.94 g/cc was used.

Mixture 3 is the aluminum in the tube portion of the Wolverine trufin type L/C finned tube. The SCALE default for Al was used for this material which corresponds to Al at a density of 2.6989 g/cc.

Mixture 4 is the UF_6-HF/Al mixture used to represent the UF_6–HF and Al fins. The mixture was created using SCALE standard compositions for UF_6, HF, and Al. The volume fractions of the UF_6 and HF were specified at 0.8650, and the aluminum was specified at a volume fraction of 0.1350. This maintained the proper proportions of UF_6–HF–Al in the finned region. The density of a mixture of UF_6-HF is a function of the temperature, the H/U atomic ratio of the mixture, and, to a lesser extent, the enrichment of the uranium. The theoretical densities of UF_6 and HF at 15°C were used in a volume additive density formula to determine the densities of UF_6 and HF in a mixture at a given H/U. The density formulation used is given in Appendix A with the calculated UF_6–HF densities for each enrichment and H/U considered in the F/S analysis.

Mixture 5 is the UF_6–HF in the overloaded region of the F/S. Mixture 5 was the same as mixture 4, except the aluminum was omitted and the volume fractions of the UF_6 and HF were changed. For calculations in which nominal UF_6 loading was considered, the volume fraction of mixture 5 was specified as 1×10^{-15}, which represents a near void. For cases in which overloading was considered, a volume fraction of 1 was used.

Mixture 6 is the steel in the F/S steel, tube sheets, and head. The nominal composition for steel was taken to be that specified for SA-516 GR55 from ASME Section II Part A.[26] A density of 7.85 g/cc was used for this material.

4.3.3 Preliminary F/S calculations

The 20-MW F/S model and material compositions described in Sects. 4.3.1 and 4.3.2 were used for preliminary calculations considering 5 wt % enriched UF_6. A range of H/U moderation ratios from 0.0 to 30 have been analyzed. Cases with freon, void, or water on the tube side of the finned tube were calculated for a nominally loaded F/S and for a fully loaded F/S. Several calculations were performed to demonstrate the reactivity effects of the materials of construction.

The model for a nominal loaded F/S was based on UF_6 on the tubes extending radially to the edge of the fin (2.8575 cm). The corresponding mass of UF_6 in the models is dependent on the H/U ratio being considered. The mass of UF_6 at an H/U = 0.0 is 3,619 kg for the 10-MW model and 7,628 kg for the 20-MW model. The fully loaded model was based on the entire free volume of the F/S vessel being filled with UF_6. The corresponding mass of UF_6 at an H/U = 0.0 is 9,676 kg for the 10-MW model and 19,974 kg for the 20-MW model. The mass of UF_6 is about 9% smaller for a H/U = 0.33 than for a H/U = 0.0.

This rather extensive series of calculations demonstrate the reactivity of the F/S for various normal and abnormal operating conditions. The general trends that exist as a function of H/U, tube side material, and loading conditions are expected to be similar for all uranium enrichments and for both the 10- and 20-MW F/S.

The results of these analyses are given in Tables 9 through 12 and presented in Figs. 7 and 8. A consistent naming convention was used for the case names of the F/S calculations. In Tables 9 and 10, the first character of the name defines the loading. Roman numeral "I" designates that nominal loading was modeled. Roman numeral "II" designates that full loading was modeled. A two-digit number corresponds to an H/U value shown in Tables 9 and 10. Case variations for given H/U ratios are presented in Tables 11 and 12. These case names start with a letter and a number designating the type of variation. The nominal loading cases have a two-digit number corresponding to the H/U. The full loading cases have the letter "F" followed by a single-digit number corresponding to the H/U. For example, R201 is a case name for nominal loading, and R2F1 is the corresponding case for full loading. The headings in Tables 9–12 designate which material was considered in the freon tubes. An "a" corresponds to R-114 in the tube, a "b" corresponds to void, and a "c" corresponds to water in the freon tube. The actual case name includes this designation as the last character of the case name. This naming convention was also used in Sect. 5.

The calculational results in Tables 9 and 10 indicate that the R-114 acts as an absorber. The reactivity effects of R-114, as compared to a void increase with H/U moderating ratio varying from about a 6% negative reactivity at H/U = 0.0 to more than 30% negative reactivity at H/U around 5 for the nominally loaded cases. For the fully loaded cases, the reactivity effects of R-114 compared to a void are smaller, varying from abut 2.5% at H/U = 0.33 to about 16% at H/U = 7.

The moderating effects of water in the tube significantly increase the reactivity of both the nominally loaded and fully loaded F/S. The reactivity effects are larger at the lower H/U moderating ratios. The positive reactivity increase is much larger for the nominally loaded F/S than for the fully loaded vessel.

Table 9. Preliminary calculated k_{eff} for 20-MW F/S nominal loading, 5 wt % ^{235}U enrichment[a]

Case	H/U	$k_{eff} \pm \sigma$ (a) R-114	(b) Void	(c) Water
I01 {a, b, or c}	0	0.4354 ± 0.0020	0.4621 ± 0.0023	0.8730 ± 0.0024
I02	0.088	0.4508 ± 0.0018	--	0.8820 ± 0.0025
I03	0.33	0.4861 ± 0.0020	0.5128 ± 0.0023	0.8966 ± 0.0028
I04	1.0	0.5444 ± 0.0019	0.6027 ± 0.0023	0.9269 ± 0.0026
I05	3	0.6067 ± 0.0020	0.7243 ± 0.0023	0.9485 ± 0.0028
I06	5	0.5971 ± 0.0022	0.7659 ± 0.0026	0.9280 ± 0.0026
I07	7	0.5826 ± 0.0017	0.7633 ± 0.0025	0.9019 ± 0.0023
I08	10	0.5398 ± 0.0020	0.7524 ± 0.0023	0.8456 ± 0.0022
I09	15	0.4743 ± 0.0018	0.6942 ± 0.0020	0.7799 ± 0.0021
I10	20	0.4170 ± 0.0013	--	0.7045 ± 0.0021
I11	30	0.3405 ± 0.0012	--	0.8944 ± 0.0017

[a]Calculations performed wtih 100% of nominal aluminum and cupronickel.

Table 10. Preliminary calculated k_{eff} for 20-MW F/S fully loaded, 5 wt % ^{235}U enrichment[a]

Case	H/U	$k_{eff} \pm \sigma$		
		(a) R-114	(b) Void	(c) Water
II01 {a,b, or c}	0	0.5791 ± 0.0015	--	0.9110 ± 0.0027
II02	0.088	0.6120 ± 0.0013	--	0.9300 ±0.0023
II03	0.33	0.6730 ± 0.0018	0.6898 ± 0.0020	0.9586 ± 0.0023
II04	1.0	0.7937 ± 0.0021	0.8346 ± 0.0023	1.0395 ± 0.0027
II05	3	0.9367 ± 0.0022	1.0360 ± 0.0024	1.1417 ± 0.0024
II06	5	0.9793 ± 0.0022	1.1073 ± 0.0027	1.1737 ± 0.0027
II07	7	0.9799 ± 0.0025	1.1375 ± 0.0026	1.1762 ± 0.0028
II08	10	0.9562 ± 0.0019	1.1358 ± 0.0025	1.1629 ± 0.0024
II09	15	0.8946 ± 0.0023	1.1007 ± 0.0026	1.1055 ± 0.0021
II10	20	0.8302 ± 0.0021	--	1.0593 ± 0.0024
II11	30	0.7233 ± 0.0017	--	0.9520 ± 0.0019

[a]Calculations performed with 100% of nominal aluminum and cupronickel.

Table 11. Preliminary calculated k_{eff} for 20-MW F/S nominal loading, 5 wt % ^{235}U enrichment reduced structural density

Case[a]	H/U	$k_{eff} \pm \sigma$	
		(b) Void	(c) Water
R201	0.0	0.4145 ± 0.0023	0.8965 ± 0.0026
R103	0.33	0.5185 ± 0.0023	0.9066 ± 0.0025
R203		0.5240 ± 0.0023	0.9308 ± 0.0028
R303		0.5343 ± 0.0023	0.9678 ± 0.0031
R104	1.0	0.6065 ± 0.0023	0.9390 ± 0.0024
R204		0.6160 ± 0.0023	0.9684 ± 0.0030
R304		0.6310 ± 0.0026	1.0076 ± 0.0027
R105	3.0	0.7346 ± 0.0023	0.9714 ± 0.0025
R205		0.7585 ± 0.0026	0.9971 ± 0.0026
R305		0.7794 ± 0.0029	1.0701 ± 0.0029

[a]Prefix R1 - 80% of nominal aluminum and cupronickel.
R2 - 50% of nominal aluminum and cupronickel.
R3 - 0% of nominal aluminum and cupronickel.

Table 12. Preliminary calculated k_{eff} for 20-MW F/S fully loaded, 5 wt % ^{235}U enrichment reduced structural density

		$k_{eff} \pm \sigma$	
Case[a]	H/U	(b) Void	(c) Water
R2F1	0.0	--	0.9622 ± 0.0024
R1F3	0.33	0.7160 ± 0.0023	1.0037 ± 0.0026
R2F3		0.7250 ± 0.0021	1.0154 ± 0.0025
R3F3		--	1.0362 ± 0.0027
R1F4	1.0	0.8717 ± 0.0023	1.0841 ± 0.0026
R2F4		0.8859 ± 0.0022	1.1005 ± 0.0024
R1F5	3.0	1.0800 ± 0.0024	1.1836 ± 0.0026
R2F5		1.0893 ± 0.0029	1.2090 ± 0.0027

[a]Prefix R1 - 80% of nominal aluminum and cupronickel.
R2 - 50% of nominal aluminum and cupronickel.
R3 - 0% of nominal aluminum and cupronickel.

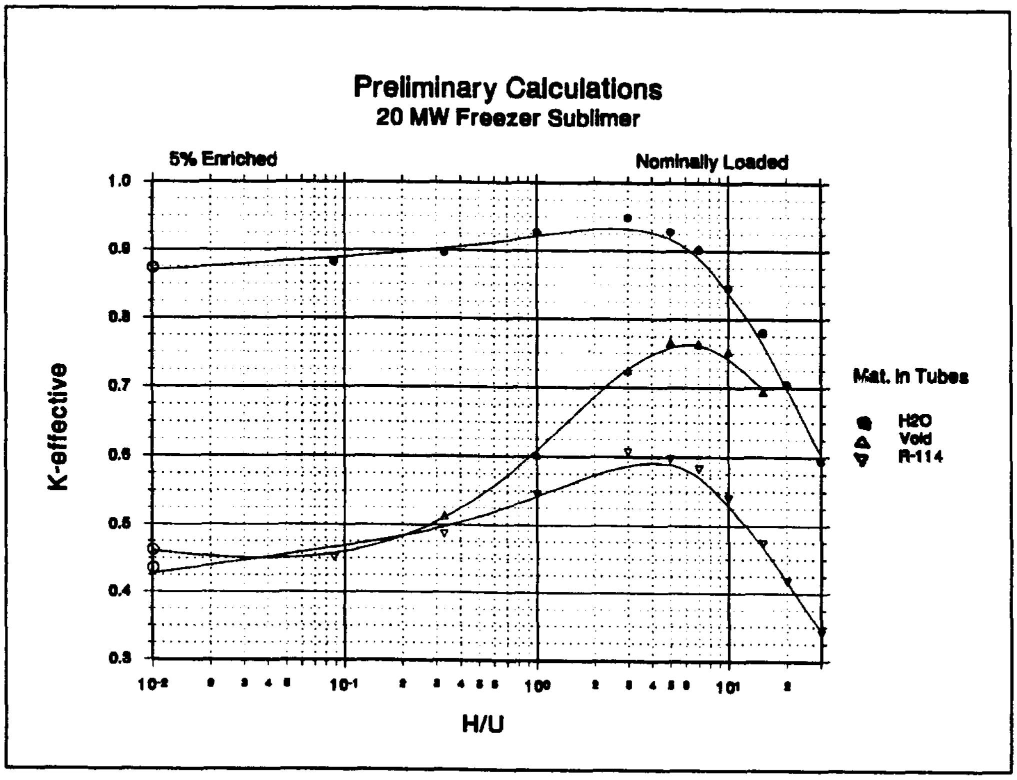

Fig. 7. Preliminary calculations from Table 7 – 20-MW nominally loaded F/S

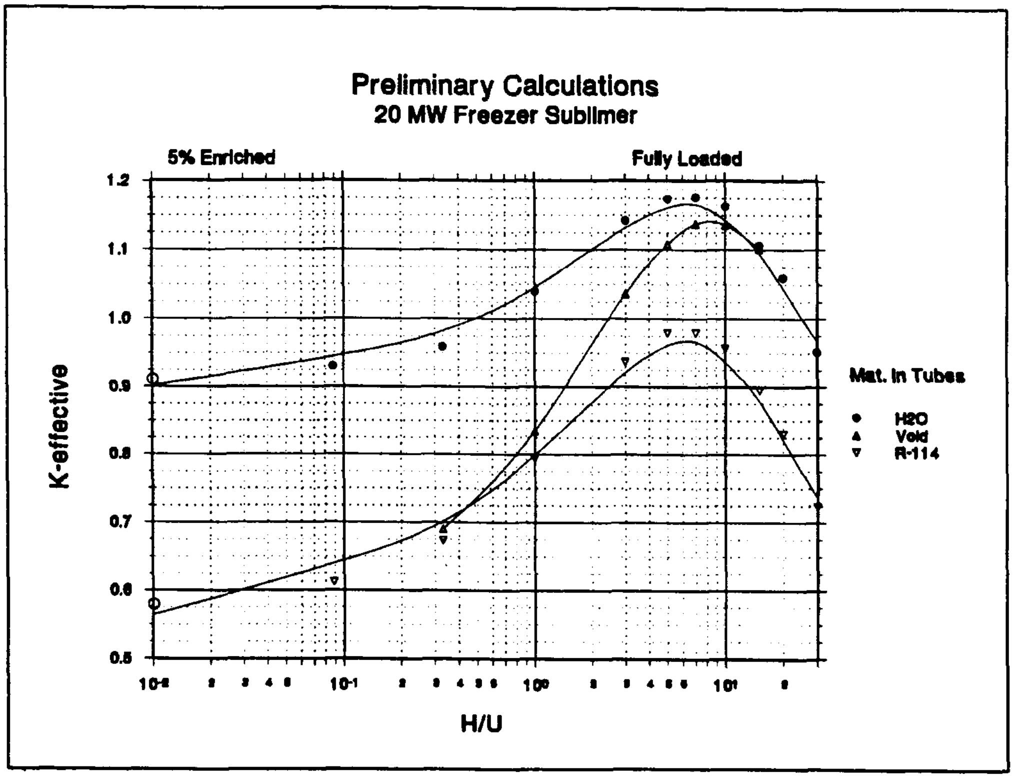

Fig. 8. Preliminary calculations from Table 10 - 20-MW fully loaded F/S

For every case, the k_{eff} calculated for the fully loaded F/S is larger than that for the nominally loaded vessel. The reactivity differences range from about 7% at an H/U = 0.33 to more than 40% at the higher H/U moderating ratios.

The results in Tables 11 and 12 indicate the relative importance of the effect of the structural aluminum and cupronickel on calculated k_{eff}. The results indicate that the reactivity is linearly related to the quantity of structural material modeled. The structural material reduces reactivity by about 8% for an H/U = 0.33 and about 13% for an H/U = 3.0 for both the fully loaded and nominally loaded conditions.

One purpose of the extensive preliminary calculations was to identify a smaller subset of calculations that could be used to evaluate the F/S. The calculations of the fully loaded F/S with water in the tubes yield the highest k_{eff} of the calculations performed. The presence of water in the tubes is one of the accident cases which must be evaluated for the F/S.

The F/S is equipped with load cells to prevent the occurrence of a fully loaded vessel. However, the distribution of UF_6 in the vessel is not directly controlled, and the UF_6 may be unevenly distributed in the vessel.[27] There is a significant increase in k_{eff} for the fully loaded F/S compared with the nominally loaded F/S. The use of the k_{eff} for a nominally loaded vessel to evaluate the safety of the F/S would be nonconservative under conditions of nonuniform loading. The fully loaded condition is one that cannot be exceeded and has the highest calculated k_{eff}.

A fully loaded vessel with water in the tubes would appear to be an appropriate subset for evaluating the safety of the vessel.

The moderating ratios of interest are those in the range 0.0 to 1.0, such that a reasonable subset might be an H/U of 0.0, 0.088, 0.33, 1.0, and 3.0. Extension of the calculations to an H/U = 3.0 allows the trends in reactivity as a function of the moderation ratio to be evaluated. Calculations for a fully loaded F/S at these H/U values with water in the tubes should provide sufficient information for the criticality safety evaluation of the F/S.

The structural aluminum and cupronickel are important in the calculated reactivity of the F/S. Nominal densities were initially used in the material descriptions, and the models were based upon uniform, evenly distributed fins. The use of nominal densities for the structural materials could result in a nonconservative model because of overestimating the quantity of absorbing material in the F/S. In addition, the model does not account for regions where the aluminum fin has been deformed or removed. Reduction of the effective density of the structural material by a few percent would adequately cover the range of variation in material density. The absence or displacement of the fins in a region of the F/S is a localized effect. Applying a reduction in density over the entire model would conservatively address the absence of fins in a region. A volume fraction of 50% for the aluminum and cupronickel was chosen for use in the final calculations. This represents a reduction of the density of these absorbing materials to 50% of their nominal quantities. Modeling in this manner is considered to conservatively account for the possible variations of material density and location in the F/S model.

Several additional cases of interest were chosen to be included in the set of calculations performed for each F/S loading configuration analyzed. These cases were variations of the F/S model with an H/U moderating ratio of 0.33. These included a fully loaded F/S with void in the tubes and a nominally loaded F/S with a void and with water in the tubes. Calculations taking 100% credit and no credit for aluminum and cupronickel were also chosen to be included.

During the review of the preliminary calculations, it was noted that the LATTICECELL specifications for the fully loaded F/S model adjacent regions had been modeled with nearly the same fissile material. Because the SCALE codes do not account for resonance overlap, modeling adjacent regions with the same fissile material would cause both regions to be resonance self-shielded incorrectly and could produce nonconservative results because of excessive ^{238}U resonance absorption. The magnitude of the error is related to the amount of intermixed moderator in the fissile region. It was not expected that the error introduced by this modeling method would be significant for the F/S calculations; however, the magnitude of the effect on k_{eff} is undefined so it was decided to redefine the model for resonance processing.

The LATTICECELL specifications were modified for the calculations performed for Sect. 5 to eliminate any nonconservatism introduced in the resonance processing. Resonance processing for the UF_6–HF–Al was performed by modeling the entire region external to the cupronickel tubes as being filled with this material. The resonance processing of the UF_6–HF in the overfilled region was treated with the lattice effects omitted. This modeling methodology yields cross sections which are slightly over self-shielded and which give slightly conservative results.

4.4. MODELING APPROXIMATIONS

The F/S model is discussed in Sects. 4.2 and 4.3. The purpose of this section is to identify optimizations and approximations used to ensure conservative calculational results. Some optimization is required because of variability in the dimensions and fabrications of the vessel. Other optimizations deal with the cross-section processing; others are related to uncertainties in the actual configuration of the fissile material in the vessel.

The specifications for the finned-tube assembly give a range for the thickness of the fins and nominal and minimum dimensions for the tube materials. The code geometry model used minimum dimensions for the thickness of the aluminum fins and the tube material. This minimizes the absorption by the structural materials and maximizes the volume available for UF_6. No conservatism is claimed for these optimizations in that they reflect a normal range of fabrication that the manufacturer may choose to approach in order to minimize material costs.

A volume additive formulation was used to estimate the density of the UF_6–HF mixture as a function of H/U. The theoretical densities for UF_6 and HF are required parameters. The density of UF_6 and HF are both functions of temperature. The theoretical densities of UF_6 and HF were taken at 15°C for these calculations. This temperature is lower than the operating temperature of the F/S during any normal mode of operation. As a result, the UF_6–HF density is higher for the models than could actually exist in the F/S. This represents a small degree of conservatism in the model.

Calculations in which the F/S was considered completely full of UF_6 with water in the tubes were chosen as the bounding cases. Weight safety systems on the F/S prevent the actual mass in the F/S from reaching this amount. However, the distribution of UF_6 within the F/S is not controlled. UF_6 will tend to preferentially freeze onto surfaces that do not already have a layer of UF_6, but testing with prototype vessels has indicated that there may be significant variations in the distribution of the UF_6 loading of the vessel during freezeout.

The reactivity of the F/S is sensitive to the distribution of UF_6 in the vessel. The reactivity of a nominally loaded F/S is lower if the UF_6 is uniformly distributed than if all of the UF_6 were at full density in one location in the vessel. This is due to the change in neutron migration area and leakage from the fissile system. Modeling the F/S completely full of UF_6 conservatively bounds conditions of nonuniform distribution. No conservatism is claimed for this modeling assumption.

The models that have water in the freon tubes represent an upset condition in which there has been a breach in the condenser/reboiler which has allowed water to displace the freon. The reactivity effect of the water in the freon tubes varies, depending on the intermixed H/U in the UF_6 and the UF_6 loading. Under nominal loading conditions, water in the freon tubes is equivalent to an increase of about 1.76 in the H/U of the UF_6 in the system. Under fully loaded conditions, water in the freon tubes is equivalent to an increase of about 0.76 in the H/U of the UF_6 in the system. The presence of water in the freon tubes results in a larger reactivity effect for the nominally loaded F/S than for the fully loaded F/S. The reactivity of the nominally filled vessel remains lower, however, because of the high neutron leakage from the system.

An infinite variety of loading conditions could exist in the F/S. Under the abnormal condition of water in the freon tubes, the smaller the F/S inventory the greater the positive reactivity effect of the water. The reactivity gain due to the increase in the H/U moderating ratio is countered by a smaller inventory having greater neutron leakage from the vessel. It appears that the neutron leakage effects are of greater importance and drive the overall reactivity of the vessel. As the H/U increases because of intermixed HF, the water in the tubes becomes less important to the overall reactivity of the vessel.

A uniform lattice of finned tubes was used in the model of the F/S. In reality, the central region of the F/S vessel is used as a flow path for UF_6 and does not have finned tubes in this region. Modeling of the F/S in this manner adds some degree of conservatism to the calculations performed with water in the tubes and at low intermixed H/U values. This is due to replacing a central void important to the reactivity of the vessel with fissile material. As the moderating ratio of the intermixed hydrogen increases, the model will become nonconservative because of the decrease in importance of the moderation provided by the water in the tubes and increase in absorption in the structural material in the finned tube assembly. The H/U ratio at which the model becomes nonconservative has not been determined, but is believed to be significantly greater than an H/U = 0.33.

In order to ensure conservatism of the model, the volume fraction of the structural materials of the finned tube were taken to be 50% of their nominal value. The model contains approximately one-half the mass of aluminum and cupronickel that is actually present in the F/S.

5. CALCULATIONAL RESULTS AND CONCLUSIONS

5.1 RESULTS

The results of the calculations performed for 10- and 20-MW F/S vessels are presented in this section. The models were based on the geometry descriptions given in Tables 4 and 5 and the material specifications given in Table 8. Input CSAS25 examples for a 10- and a 20-MW F/S calculation at 5% enrichment and an H/U = 0.0 are given in Appendix B for reference.

The results for the 10- and 20-MW F/S vessels are presented in Tables 13 and 14 respectively. Presented for each calculation are the case identifier, the enrichment, the H/U, the calculation results (k_{eff} and σ), and the average energy group of neutrons causing fission. The results are presented graphically in Figs. 9-11 for a 10-MW F/S and in Figs. 12-14 for a 20-MW F/S.

Figures 9 and 12 show the variation of k_{eff} as a function of H/U for a fully loaded F/S with water in the tubes at four enrichments. The curve represents a smooth spline through the calculated k_{eff}. The reactivity of the F/S is extremely sensitive to even small changes in the amount of hydrogen intermixed with the UF_6.

Figures 10 and 13 show the variation of k_{eff} as a function of enrichment for a fully loaded F/S with water in the tubes for H/U ratios of 0.0, 0.088, and 0.33. The solid curves are a smooth spline through the calculated k_{eff}, and the dashed curves are a smooth spline through the set of points of calculated $k_{eff} + 2\sigma$.

Figures 11 and 14 show k_{eff} as a function of enrichment for a fully loaded and nominally loaded F/S at an H/U = 0.33. The Δk between the fully loaded and nominally loaded calculations is about 0.12 for the 10-MW model and about 0.10 for the 20-MW model. The smaller change for the larger vessel is because of smaller overall neutron leakage from the 20-MW model. No credit for conservatism is taken for the fully loaded model over the nominally loaded model because nonuniform loading (which is known to occur) could result in k_{eff} greater than the nominally loaded values. It is believed that the calculated k_{eff} for the fully loaded vessel is a bounding case for all loading conditions which could occur in the vessel.

Cases IIN3C (no structural material) and IIF3C (full structural material) show the reactivity effects of the aluminum and cupronickel in the model and allow an estimate of the conservatism introduced into the model due to using a volume fraction of 0.5 for these materials. The IIN3C cases may be compared directly with the cases used to establish the acceptable operating criteria in Taylor's report. The ANISN homogenized model used by Taylor appears to be slightly conservative relative to the KENO V.a model for the same loading and moderation conditions. Good agreement is noted between previous KENO IV and KENO V.a calculations. The use of a volume fraction of 0.5 for the structural materials results in a slight reduction ($\sim$2% for the 10-MW F/S and $\sim$3% for the 20-MW F/S) in the amount of conservatism of the current F/S models compared with that used previously for acceptance.

The 10-MW F/S will be used in the cascade in locations that will exceed the enrichment criteria of 2.35 wt % ^{235}U established by Taylor for acceptable operation. Several calculations were performed to allow a more detailed study of the reactivity as a function of H/U for enrichments between 3 and 4% enrichment. The results of these calculations are shown graphically in Figs. 15-20. The H/U at which $k_{eff} + 2\sigma = 0.90$ was read from each of these figures and is plotted graphically as a function of enrichment in Fig. 21. The dashed curve in Fig. 21 is the 95% confidence on the least-squares fit through the data.

Table 13. 10-MW F/S results

Case	5.0 Enrichment				4.0 Enrichment				3.5 Enrichment			
	H/U	k_{eff}	Dev.	AEG	H/U	k_{eff}	Dev.	AEG	H/U	k_{eff}	Dev.	AEG
II01c	0.00	0.9186	0.0028	16.11	0.00	0.8753	0.0024	16.65	0.00	0.8540	0.0022	16.92
II02c	0.088	0.9393	0.0022	16.45	0.088	0.8942	0.0024	16.93	0.088	0.8728	0.0024	17.25
II03c	0.33	0.9824	0.0027	17.32	0.33	0.9503	0.0025	17.85	0.33	0.9161	0.0022	18.11
II04c	1.00	1.0546	0.0028	18.98	1.00	1.0266	0.0024	19.51	1.00	1.0041	0.0024	19.80
II05c	3.00	1.1674	0.0028	21.45	3.00	1.1304	0.0027	21.81	3.00	1.1022	0.0028	22.01
IIN3c	0.33	1.0089	0.0028	17.41	0.33	0.9624	0.0028	17.93	0.33	0.9461	0.0020	18.23
IIF3c	0.33	0.9647	0.0026	17.23	0.33	0.9178	0.0024	17.74	0.33	0.8971	0.0026	18.04
II03b	0.33	0.6404	0.0018	13.06	--	--	--	--	0.33	0.6102	0.0019	13.41
I03b	0.33	0.4694	0.0020	15.46	0.33	0.4339	0.0019	15.72	0.33	0.4178	0.0021	15.91
I03c	0.33	0.8398	0.0028	19.75	0.33	0.8062	0.0031	20.10	0.33	0.7788	0.0024	20.29

Case	3.4 Enrichment				3.3 Enrichment				3.2 Enrichment			
	H/U	k_{eff}	Dev.	AEG	H/U	k_{eff}	Dev.	AEG	H/U	k_{eff}	Dev.	AEG
II01c	0.00	0.8395	0.0023	16.95	0.00	0.8323	0.0025	17.03	0.00	0.8305	0.0025	17.08
II02c	0.088	0.8647	0.0024	17.32	0.088	0.8523	0.0024	17.34	0.088	0.8534	0.0024	17.46
II03c	0.33	0.9065	0.0025	18.15	0.33	0.9072	0.0025	18.26	0.33	0.8967	0.0027	18.27
II04c	1.00	0.9946	0.0027	19.85	1.00	0.9905	0.0026	19.90	1.00	0.9878	0.0029	19.95
II05c	3.00	1.0938	0.0030	22.06	3.00	1.0884	0.0028	22.09	3.00	1.0782	0.0028	22.12

	3.0 Enrichment				2.0 Enrichment			
	H/U	k_{eff}	Dev.	AEG	H/U	k_{eff}	Dev.	AEG
II01c	0.00	0.8192	0.0027	17.24	0.00	0.7321	0.0022	17.88
II02c	0.088	0.8362	0.0025	17.54	0.08	0.7627	0.0020	18.27
II03c	0.33	0.8857	0.0021	18.43	0.33	0.8112	0.0020	19.13
II04c	1.00	0.9713	0.0024	20.07	1.00	0.8882	0.0026	20.69
II05c	3.00	1.0658	0.0025	22.21	3.00	0.9701	0.0022	22.62
IIN3c	0.33	0.9215	0.0025	18.55	0.33	0.8409	0.0027	19.25
IIF3c	0.33	0.8608	0.0024	18.30	0.33	0.7739	0.0023	19.00
II03b	0.33	0.5749	0.0019	13.58	--	--	--	--
I03b	0.33	0.3971	0.0020	16.01	0.33	0.3455	0.0015	16.25
I03c	0.33	0.7563	0.0027	20.51	0.33	0.6729	0.0021	20.89

Table 14. 20-MW F/S results

Case	5.0 Enrichment				4.0 Enrichment				3.0 Enrichment			
	H/U	k_{eff}	Dev.	AEG	H/U	k_{eff}	Dev.	AEG	H/U	k_{eff}	Dev.	AEG
II01c	0.00	0.9570	0.0023	16.06	0.00	0.9078	0.0024	16.58	0.00	0.8535	0.0026	17.18
II02c	0.088	0.9817	0.0021	16.39	0.088	0.9393	0.0023	16.96	0.088	0.8738	0.0022	17.56
II03c	0.33	1.0176	0.0024	17.26	0.33	0.9866	0.0023	17.85	0.33	0.9301	0.0024	18.46
II04c	1.00	1.1002	0.0026	18.99	1.00	1.0618	0.0023	19.52	1.00	1.0132	0.0025	20.11
II05c	3.00	1.2048	0.0025	21.46	3.00	1.1717	0.0026	21.84	3.00	1.1042	0.0025	22.22
IIN3c	0.33	1.0481	0.0023	17.35	0.33	1.0109	0.0028	17.94	0.33	0.9578	0.0024	18.52
IIF3c	0.33	0.9955	0.0023	17.23	0.33	0.9530	0.0026	17.73	0.33	0.8952	0.0022	18.32
I03b	0.33	0.5260	0.0020	14.91	0.33	0.4853	0.0020	15.10	0.33	0.4365	0.0018	15.52
I03c	0.33	0.9326	0.0030	19.76	0.33	0.8899	0.0027	20.12	0.33	0.8347	0.0026	20.55

Case	2.0 Enrichment			
	H/U	k_{eff}	Dev.	AEG
I101c	0.00	0.7734	0.0023	17.91
II02c	0.088	0.7944	0.0023	18.30
II03c	0.33	0.8427	0.0021	19.15
II04c	1.00	0.9282	0.0023	20.72
II05c	3.00	1.0004	0.0022	22.63
IIN3c	0.33	0.8823	0.0022	19.29
IIF3c	0.33	0.8090	0.0022	19.01
I03b	0.33	0.3781	0.0017	15.79
IO3c	0.33	0.7517	0.0024	20.97

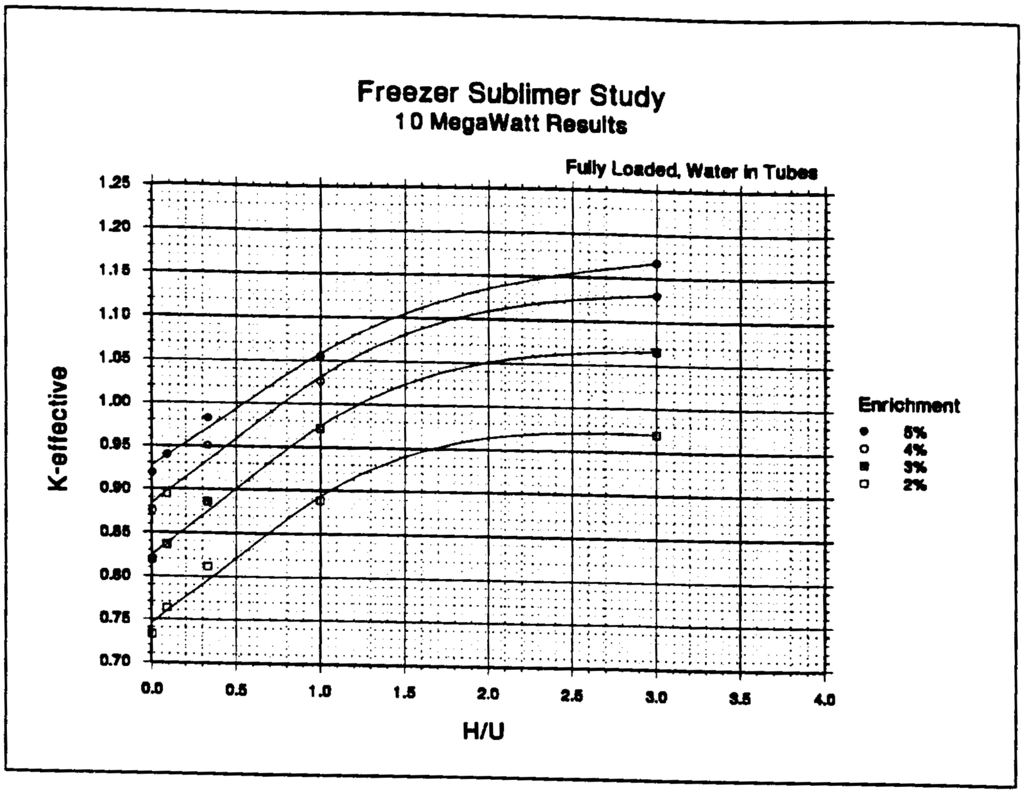

Fig. 9. k_{eff} vs H/U for a 10-MW fully loaded F/S with water in the tubes.

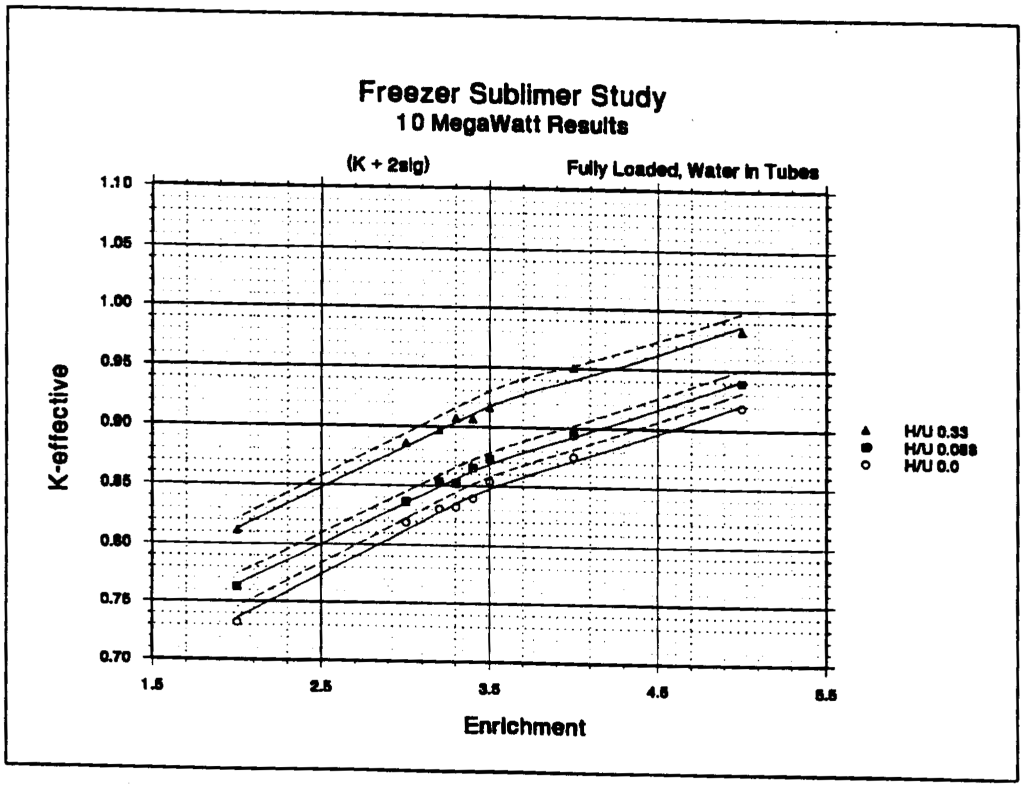

Fig. 10. k_{eff} vs enrichment for a 10-MW fully loaded F/S with water in the tubes.

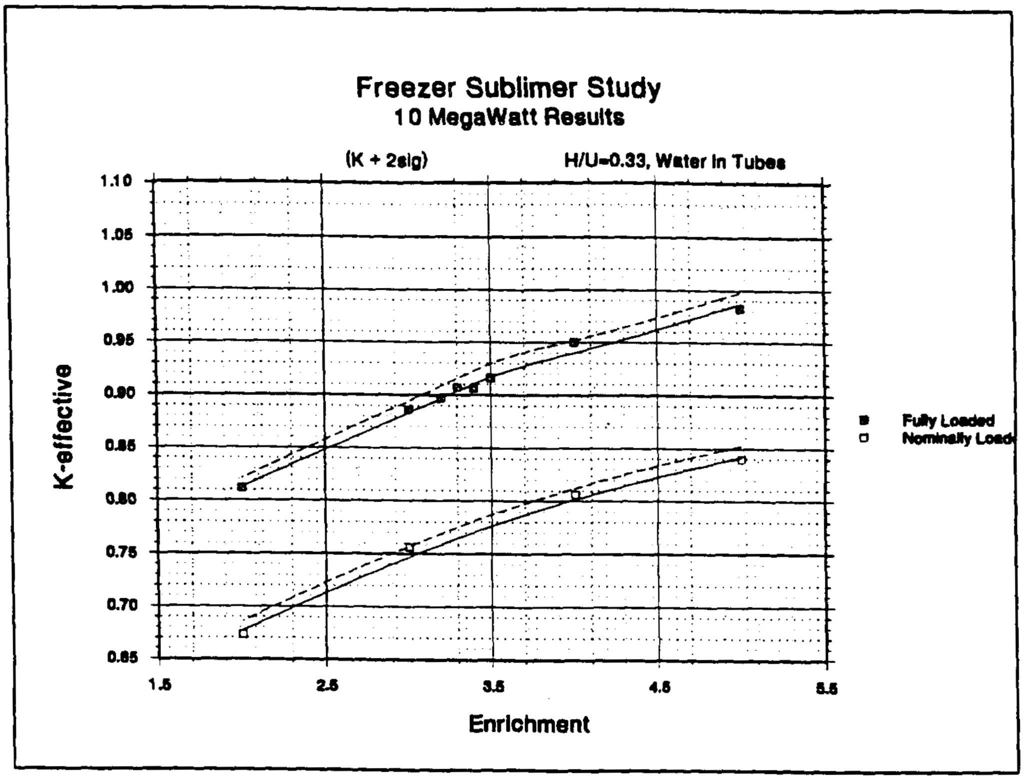

Fig. 11. k_{eff} vs enrichment for a 10-MW F/S fully loaded and nominally loaded.

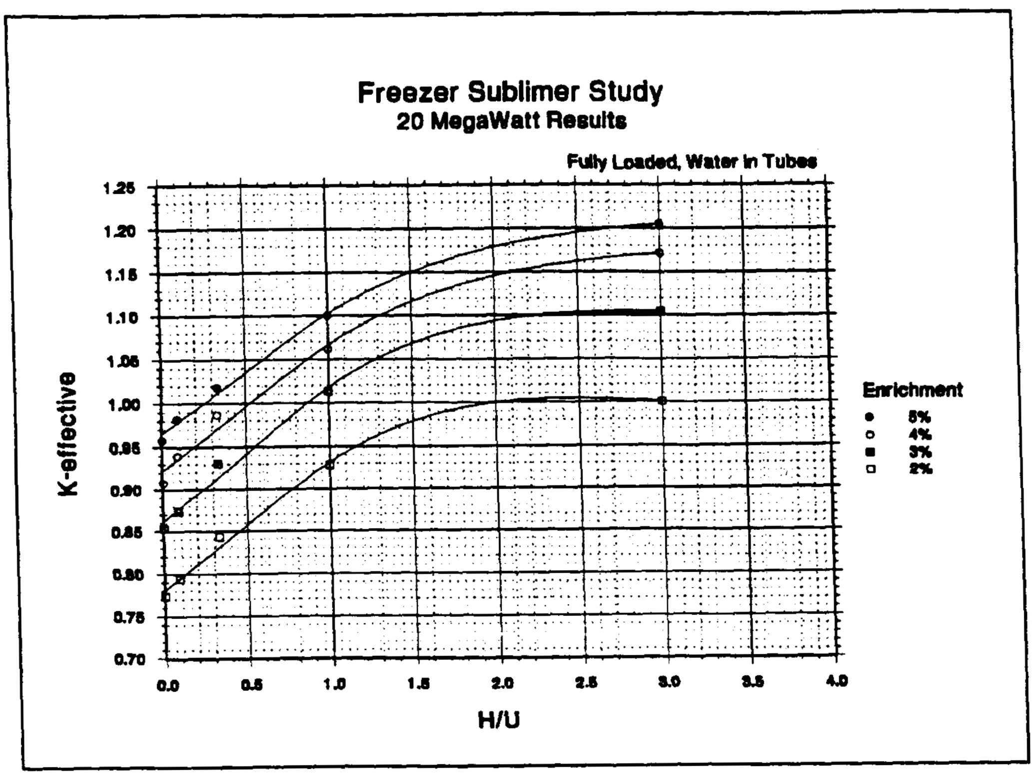

Fig. 12. k_{eff} vs H/U for a 20-MW fully loaded F/S with water in the tubes.

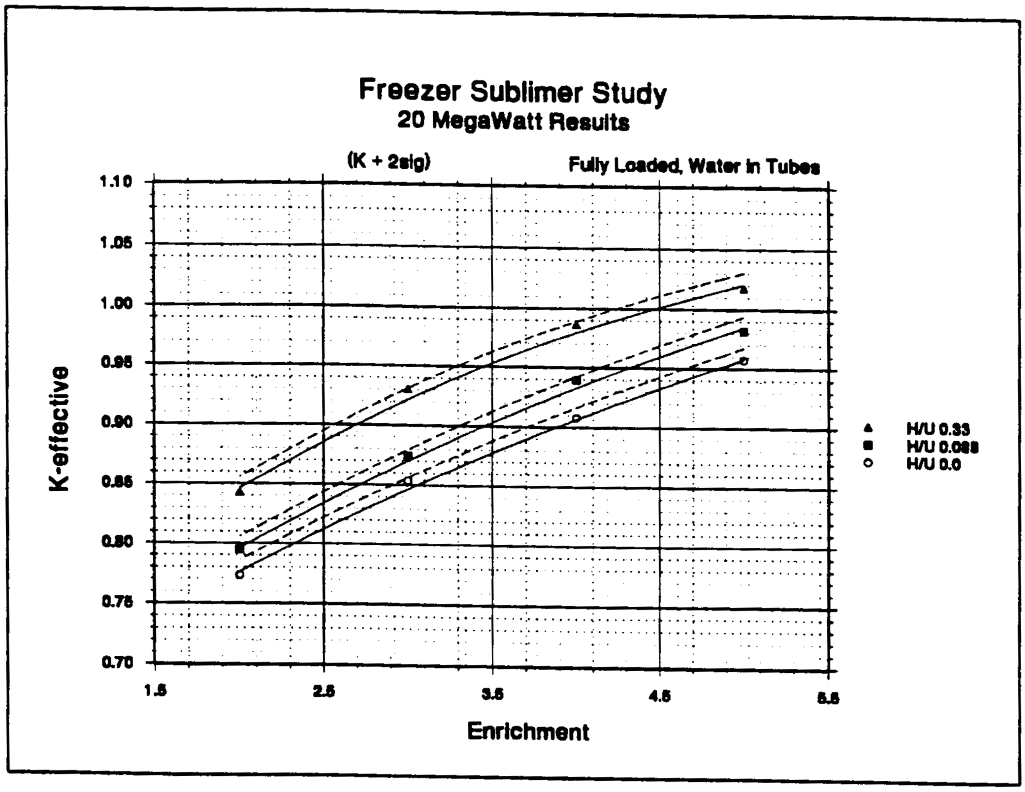

Fig. 13. k_{eff} vs enrichment for a 20-MW fully loaded F/S with water in the tubes.

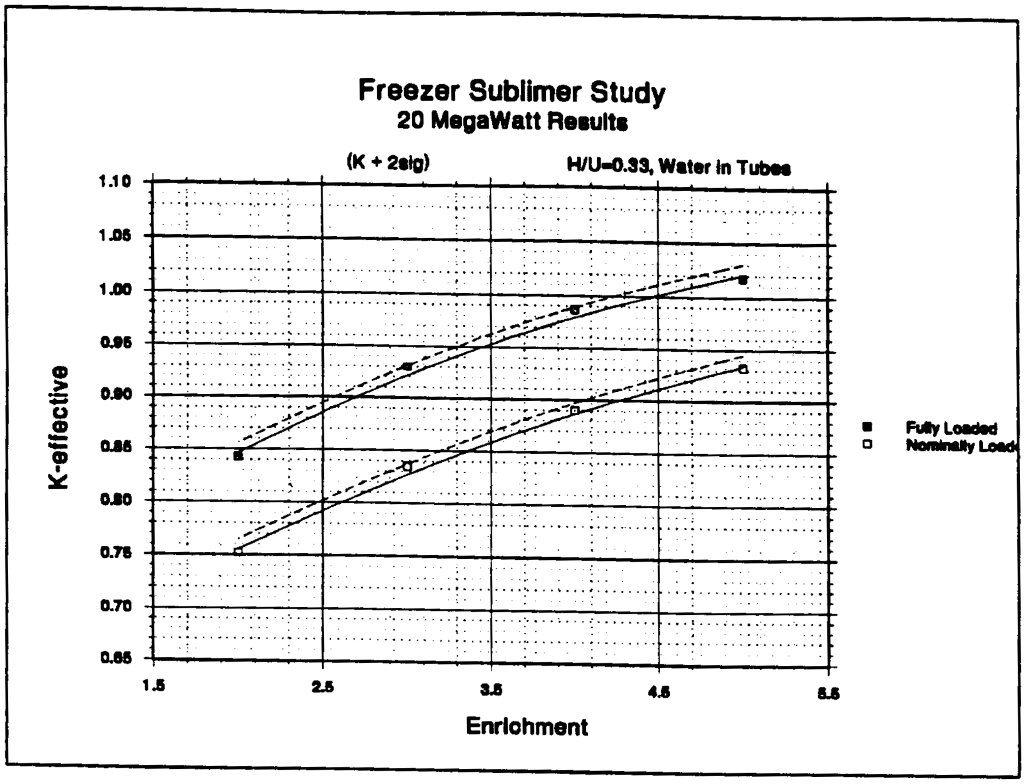

Fig. 14. k_{eff} vs enrichment for a 20-MW F/S fully loaded and nominally loaded.

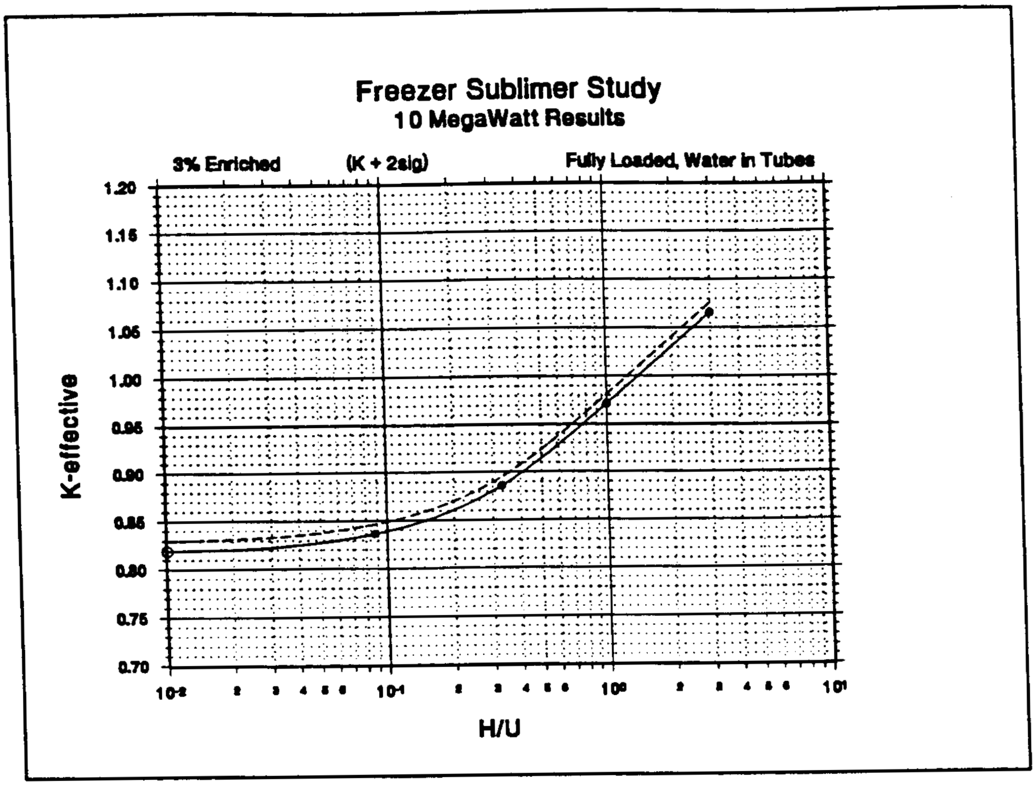

Fig. 15. k_{eff} vs H/U for a 10-MW F/S - 3.0% enrichment.

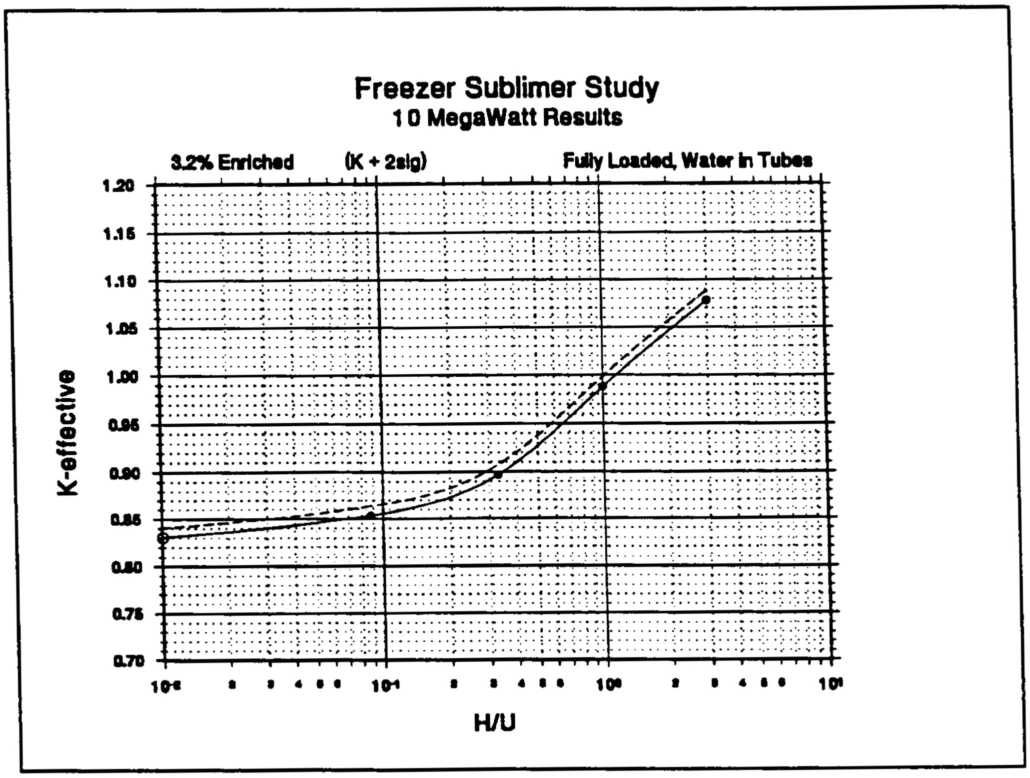

Fig. 16. k_{eff} vs H/U for a 10-MW F/S - 3.2% enrichment.

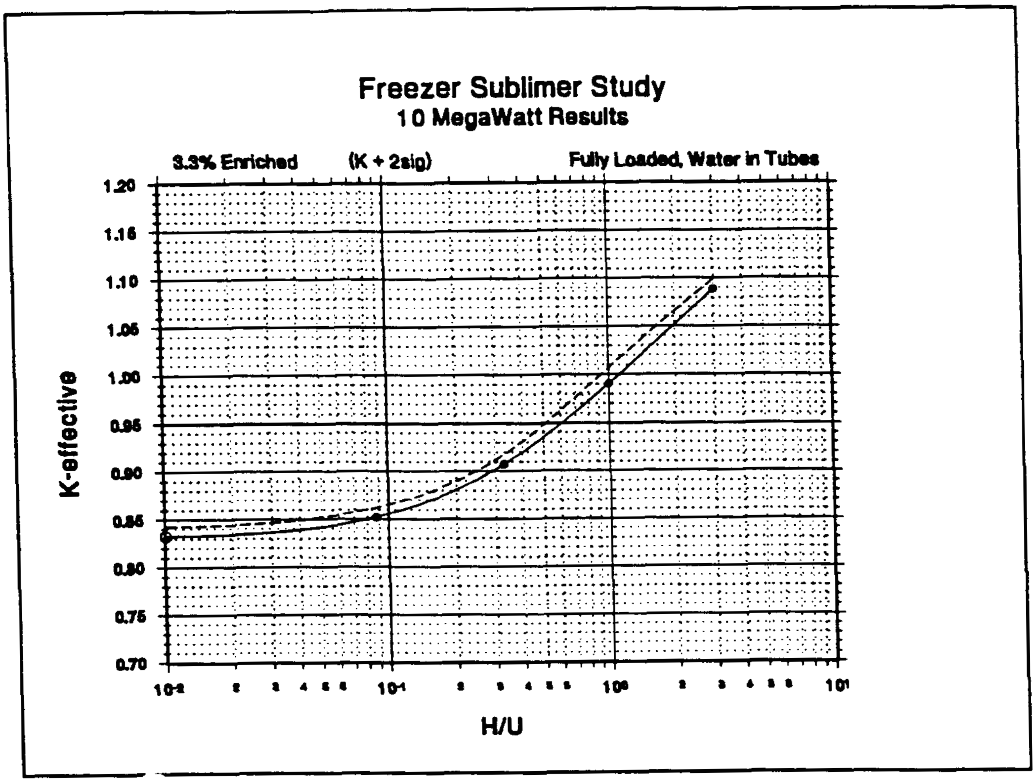

Fig. 17. k_{eff} vs H/U for a 10-MW F/S - 3.3% enrichment.

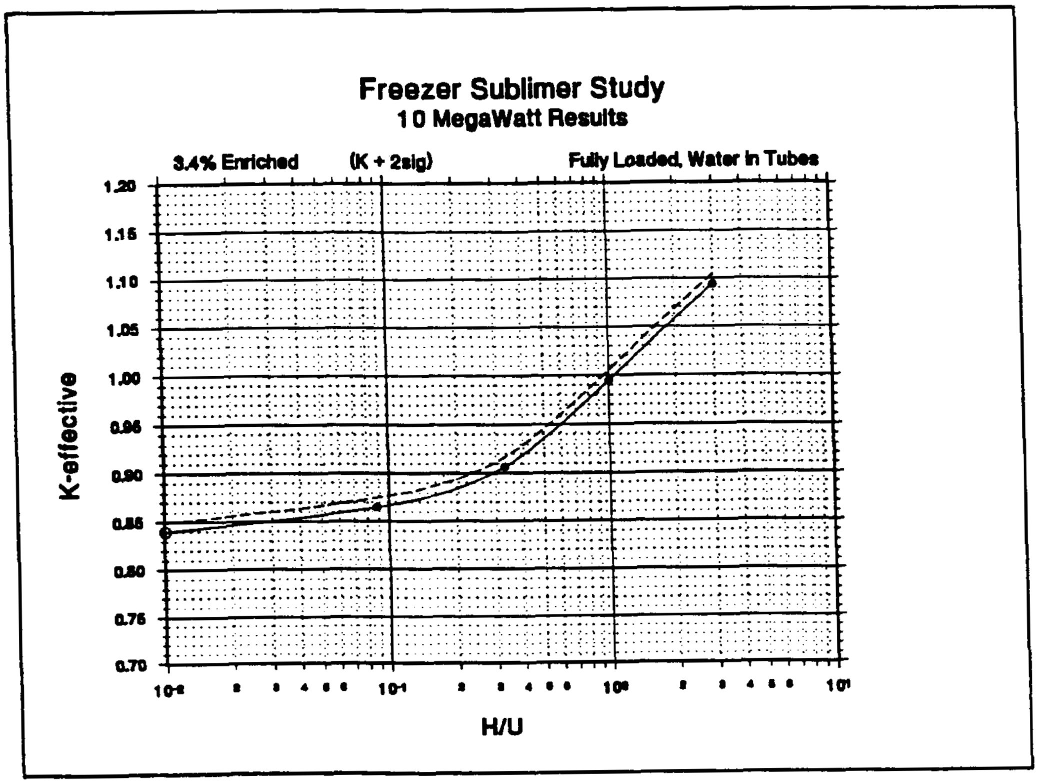

Fig. 18. k_{eff} vs H/U for a 10-MW F/S - 3.4% enrichment.

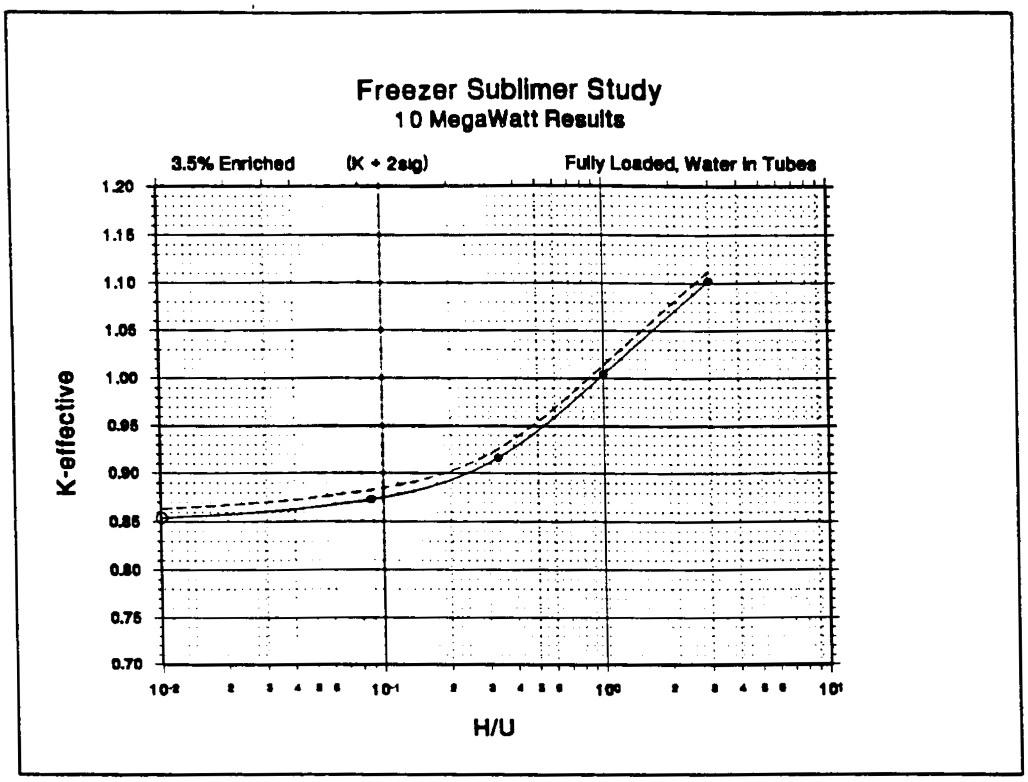

Fig. 19. k_{eff} vs H/U for a 10-MW F/S - 3.5% enrichment.

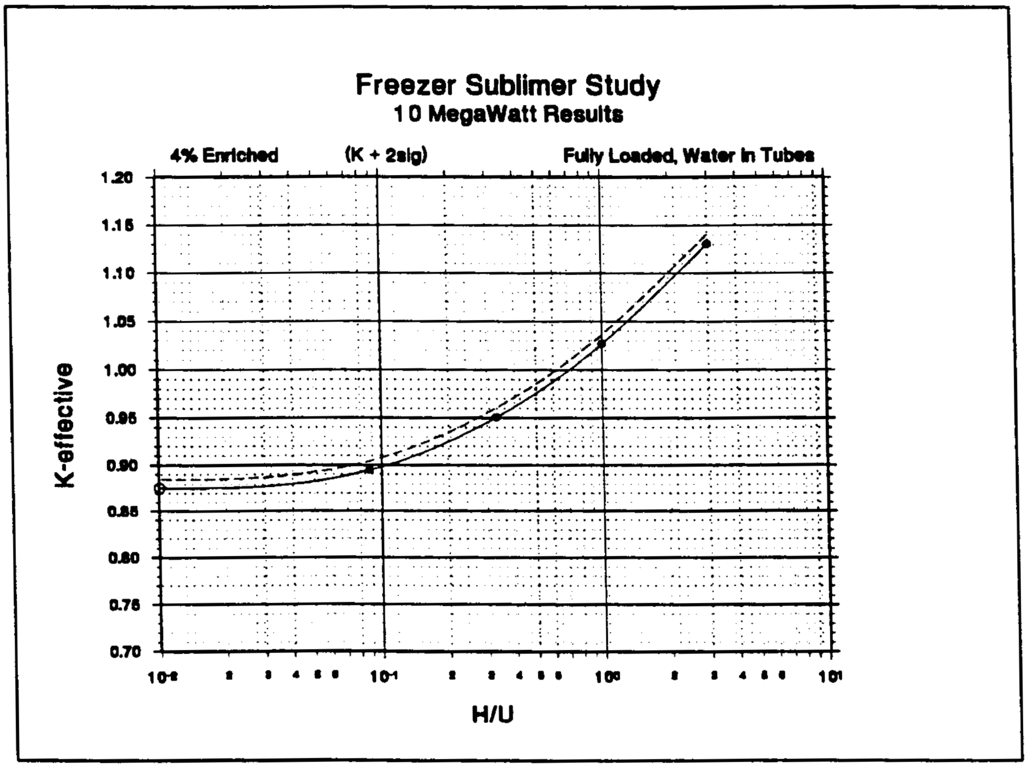

Fig. 20. k_{eff} vs H/U for a 10-MW F/S - 4.0% enrichment.

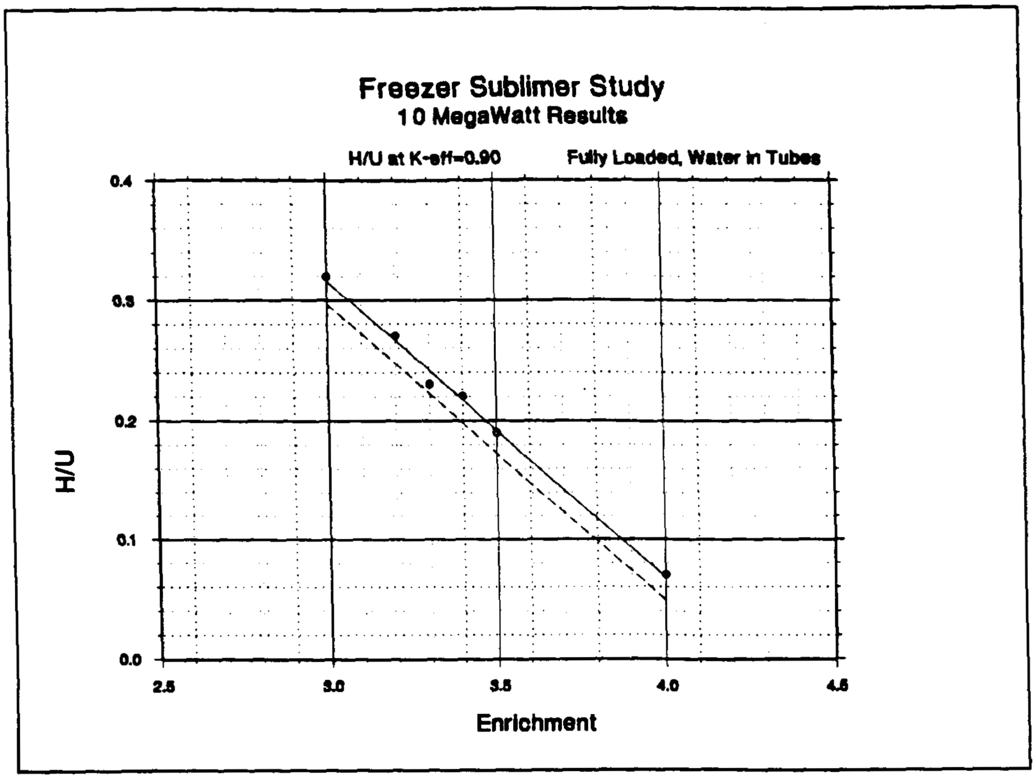

Fig. 21. H/U vs enrichment to yield a $k_{eff} + 2\sigma = 0.90$ (for a 10-MW F/S).

For an F/S that is controlled to H/U = 0.33, Figs. 11 and 14 may be used to establish an acceptable enrichment limit for the 10- and 20-MW F/S, respectively. If these figures are used directly, some allowance should be given for the curve fit of the data.

For a 10-MW F/S controlled to a H/U < 0.33, Fig. 21 may be used to establish the acceptable enrichment limit based on $k_{eff} + 2\sigma = 0.90$ and water in the tubes.

5.2 CONCLUSIONS

Several criticality safety considerations for the operating cascade, the compression liquefaction withdrawal system, and the F/S system have been identified. A comparison of the operations has been presented, identifying important differences and similarities. In each system, the purpose of the criticality safety controls are to prevent the occurrence of a moderated mass of uranium in unsafe geometry. In the cascade, uranium density control is the first criticality control, with moderation control as a second control. In the withdrawal system, geometry control is the primary control at the front of the system, with demonstrated moderation control before the UF_6 is transferred to unsafe geometry. In the F/S, moderation control is the only control and must be demonstrated for every mode of operation because UF_6 is being moved directly from the cascade (which is under density control) into unsafe geometry.

A conservative model of the F/S has been developed. Each of the assumptions used to build the model has been identified, and the justification or reasons leading to these assumptions has been given. The model may be used with confidence to establish the safety of the F/S over the range of enrichments up to 5% and moderation ratios up to H/U = 1.

A set of calculations has been performed for the 10- and 20-MW F/S which covers the range of enrichment and moderation encompassing safe operating conditions. The possibility of water moderation being present in the R-114 tubes has been explicitly addressed in the calculations.

The results demonstrate that the calculations originally performed for the 10-MW F/S are conservative and the enrichment limits established at a H/U = 0.33 are acceptable. The enrichment limits for safe operation may be increased slightly under the same acceptance criteria used previously. The results also allow safe enrichment limits to be established for the 10-MW F/S at different levels of H/U moderation, provided these levels are demonstrated to exist during all modes of operation. The results allow the safe enrichment to be determined for the 20-MW F/S.

6. CODE VALIDATION

A code validation was performed to support the F/S calculation study. Fifty-nine critical experiments were chosen to demonstrate the functionality and ability of the SCALE-4.0 codes and cross sections to accurately calculate critical experiments. The validation is documented in ORNL/CSD/TM-287.[28] Presented here is a brief discussion of the results of this validation and its use and applicability for F/S criticality safety calculational analysis. The CSAS25 sequence and the 27-group library of SCALE-4.0 were validated. The majority of the experiments used in the validation were low-enriched uranium systems. These experiments validate low-enriched uranium at several moderation ratios in spherical, cylindrical, and slab geometry. A series of lattice experiments were included to demonstrate the ability of the CSAS25 sequence to calculate these systems. The uranium materials considered were uranium metal, UO_2, U_3O_8, UF_4, and UO_2F_2.

Several highly enriched uranium experiments were included in the validation, primarily to demonstrate the ability of the codes to properly process resonance cross sections for low-moderated or unmoderated systems.

A statistical analysis of the validation results was performed to establish an upper calculational acceptance criteria. The technique described by Dyer et al.[29] was used to calculate a one-sided, closed-interval, lower tolerance band for the low-enriched experiments as a function of the average energy group of the neutron-causing fission. The results of this analysis are presented graphically in Fig. 22.

Based on the statistical analysis, systems similar to those validated (within the range of validation) may be considered safely subcritical if the calculated k_{eff} plus the uncertainty in the calculation is less than about 0.945.

The application of the validation to the F/S must include consideration of the following four important observations:

1. The F/S geometry is highly unusual in its heterogeneous characteristics. The moderator is inside the tube with near-dry fissile material on the outside. The tubes have a significant negative reactivity effect because of neutron absorption. The calculational analysis is sensitive to the assumption used to describe this unusual lattice.
2. The systems considered in the F/S analysis are highly undermoderated. Even with this low level of moderation, some of the systems analyzed have unacceptably high reactivity. The calculations are especially sensitive to the scattering cross sections and the ^{238}U absorption cross sections. There are no critical experiments using water or HF-moderated, low-enriched UF_6 systems, so the code and cross-section performance cannot be evaluated for these systems. Few experiments of any sort have moderation levels in the region of interest in the F/S analysis.
3. The calculational analysis of the F/S is sensitive to the distribution of the material in the vessel.
4. At nominal loading conditions, with water in the tubes, the uranium in the F/S is significantly undermoderated. As UF_6 is removed from around the tubes, the infinite media multiplication of the F/S tube lattice increases because the uranium becomes more optimumly moderated. The F/S reactivity decreases, however, due to an increase in leakage. Because of this tradeoff in increased leakage versus increased reactivity, the analysis of the F/S is sensitive to the assumed distribution of the UF_6 in the vessel. A

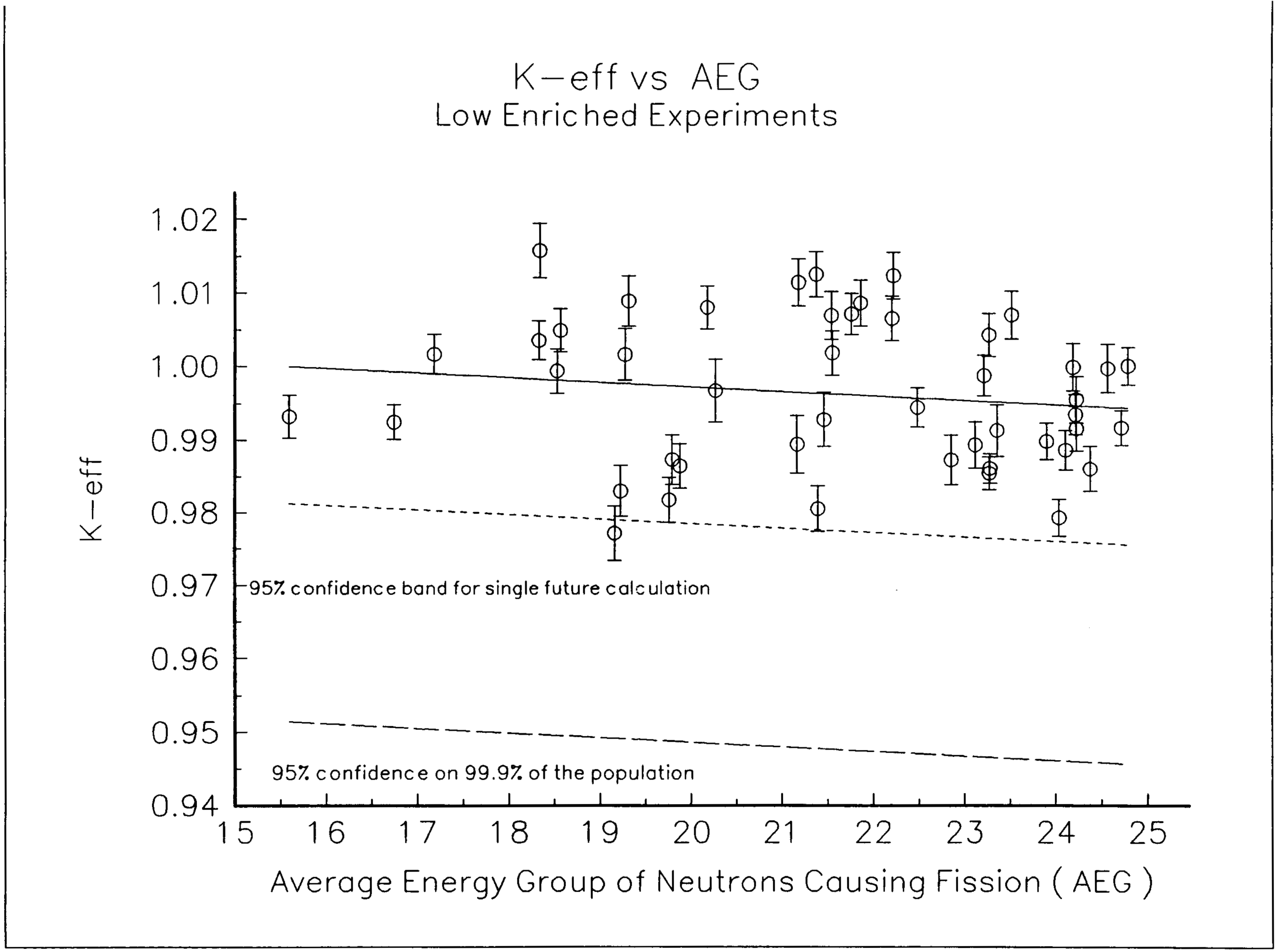

Fig. 22. k_{eff} vs AEG for validation experiments.

vessel with significantly less than nominal inventory with a nonuniform distribution of material in the vessel can approach the k_{eff} calculated for a fully loaded vessel. No attempt has been made in the current analysis to determine optimum loading conditions and the maximum k_{eff}.

In the establishment of an acceptance criteria, one must consider not only the results of the validation but also the system to which the validation is being applied. Because there are several assumptions and limitations in the F/S criticality analysis and the validation, there should be some additional conservatism factored into the acceptance criteria. This level of additional conservatism is quite arbitrary. The value originally established by Taylor of $k + 2\sigma$ less than 0.90 seems reasonable and has been adopted here.

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APPENDIX A

UF_6-HF DENSITIES

The UF_6-HF densities used in the evaluation of the F/S are based on a theoretical volume additive formulation. The theoretical densities for solid UF_6 and liquid HF were calculated from Eqs. (A.1) and (A.2) for a temperature of 15°C. The volume additive formulation for uranium density as a function of H/U moderation ratio is given in Eq. (A.3). The data sheets used to generate the input for the F/S analysis are included in Tables A1 through A8.

$$\rho_{UF_6} = 5.194 - 0.005168 * t \qquad \text{(A.1)}$$

$$\rho_{HF} = 1.0020 - 0.0022625 * t + 3.125 - 6 * t^2 \qquad \text{(A.2)}$$

$$\rho_U = \frac{molecular\ weight\ of\ uranium}{68.80091 + H/U * 20.65102} \qquad \text{(A.3)}$$

Table A.1. UF_6-HF Density - 5.0% Enrichment

^{235}U enrichment = 5.000
Molecular weight of uranium = 237.89880
Temperature of mixture = 15.00°C

Density of components in a theoretical mixture

H/U	Uranium	UF_6	HF
0.00000	3.45779	5.11458	0.00000
0.08800	3.36880	4.98297	0.02493
0.33000	3.14615	4.65363	0.08731
1.00000	2.65952	3.9338	0.2236
3.00000	1.81944	2.6912	0.4590
5.00000	1.38268	2.0451	0.5813
7.00000	1.11502	1.6492	0.6563
10.00000	0.86411	1.2781	0.7266
15.00000	0.62842	0.92953	0.79270
20.00000	0.49375	0.73033	0.83043
30.00000	0.34562	0.51122	0.87193

Table A.2. UF_6-HF Density - 4.0% Enrichment

^{235}U enrichment = 4.000
Molecular weight of uranium = 237.92920
Temperature of mixture = 15.00°C

Density of components in a theoretical mixture

H/U	Uranium	UF_6	HF
0.00000	3.45823	5.11503	0.00000
0.08800	3.36923	4.98340	0.02493
0.33000	3.14656	4.65404	0.08731
1.00000	2.65986	3.93416	0.22365
3.00000	1.81967	2.69145	0.45901
5.00000	1.38286	2.04537	0.58138
7.00000	1.11516	1.64943	0.65637
10.00000	0.86422	1.27826	0.72667
15.00000	0.62850	0.92961	0.79270
20.00000	0.49381	0.73039	0.83043
30.00000	0.34566	0.51126	0.87193

Table A.3. UF_6-HF Density - 3.5% Enrichment

^{235}U enrichment = 3.500
Molecular weight of uranium = 237.94450
Temperature of mixture = 15.00°C

Density of components in a theoretical mixture

H/U	Uranium	UF_6	HF
0.00000	3.45845	5.11525	0.00000
0.08800	3.36945	4.98361	0.02493
0.33000	3.14676	4.65424	0.08731
1.00000	2.66003	3.93433	0.22365
3.00000	1.81979	2.69157	0.45901
5.00000	1.38295	2.04546	0.58138
7.00000	1.11524	1.64950	0.65637
10.00000	0.86427	1.27831	0.72667
15.00000	0.62854	0.92965	0.79270
20.00000	0.49384	0.73042	0.83043
30.00000	0.34568	0.51129	0.87193

Table A.4. UF_6-HF Density - 3.4% Enrichment

^{235}U enrichment = 3.400
Molecular weight of uranium = 237.94750
Temperature of mixture = 15.00°C

Density of components in a theoretical mixture

H/U	Uranium	UF_6	HF
0.00000	3.45849	5.11529	0.00000
0.08800	3.36949	4.98365	0.02493
0.33000	3.14680	4.65428	0.08731
1.00000	2.66006	3.93437	0.22365
3.00000	1.81981	2.69159	0.45901
5.00000	1.38297	2.04548	0.58138
7.00000	1.11525	1.64951	0.65637
10.00000	0.86429	1.27832	0.72667
15.00000	0.62855	0.92966	0.79270
20.00000	0.49385	0.73043	0.83043
30.00000	0.34569	0.51129	0.87193

Table A.5. UF_6-HF Density - 3.3% Enrichment

^{235}U enrichment = 3.300
Molecular weight of uranium = 237.95050
Temperature of mixture = 15.00°C

Density of components in a theoretical mixture

H/U	Uranium	UF_6	HF
0.00000	3.45854	5.11534	0.00000
0.08800	3.36954	4.98370	0.02493
0.33000	3.14684	4.65432	0.08731
1.00000	2.66009	3.93440	0.22365
3.00000	1.81983	2.69162	0.45901
5.00000	1.38298	2.04550	0.58138
7.00000	1.11526	1.64953	0.65637
10.00000	0.86430	1.27833	0.72667
15.00000	0.62856	0.92966	0.79270
20.00000	0.49386	0.73044	0.83043
30.00000	0.34569	0.51129	0.87193

Table A.6. UF_6-HF Density - 3.2% Enrichment

^{235}U enrichment = 3.200
Molecular weight of uranium = 237.95360
Temperature of mixture = 15.00°C

Density of components in a theoretical mixture

H/U	Uranium	UF_6	HF
0.00000	3.45858	5.11538	0.00000
0.08800	3.36958	4.98374	0.02493
0.33000	3.14688	4.65436	0.08731
1.00000	2.66013	3.93443	0.22365
3.00000	1.81986	2.69164	0.45901
5.00000	1.38300	2.04551	0.58138
7.00000	1.11528	1.64954	0.65637
10.00000	0.86431	1.27835	0.72667
15.00000	0.62857	0.92967	0.79270
20.00000	0.49386	0.73044	0.83043
30.00000	0.34570	0.51130	0.87193

Table A.7. UF_6-HF Density - 3.0% Enrichment

^{235}U enrichment = 3.000
Molecular weight of uranium = 237.95970
Temperature of mixture = 15.00°C

Density of components in a theoretical mixture

H/U	Uranium	UF_6	HF
0.00000	3.45867	5.11547	0.00000
0.08800	3.36966	4.98383	0.02493
0.33000	3.14696	4.65444	0.08731
1.00000	2.66020	3.93450	0.22365
3.00000	1.81990	2.69169	0.45901
5.00000	1.38304	2.04555	0.58138
7.00000	1.11531	1.64957	0.65637
10.00000	0.86433	1.27837	0.72667
15.00000	0.62858	0.92969	0.79270
20.00000	0.49388	0.73046	0.83043
30.00000	0.34571	0.51131	0.87193

Table A.8. UF_6-HF Density - 2.0% Enrichment

^{235}U enrichment = 2.000
Molecular weight of uranium = 237.99010
Temperature of mmixture = 15.00°C

Density of components in a theoretical mixture

H/U	Uranium	UF_6	HF
0.00000	3.45911	5.11591	0.00000
0.08800	3.37010	4.98426	0.02493
0.33000	3.14736	4.65484	0.08731
1.00000	2.66054	3.93484	0.22365
3.00000	1.82014	2.69192	0.45901
5.00000	1.38321	2.04573	0.58138
7.00000	1.11545	1.64971	0.65637
10.00000	0.86444	1.27848	0.72667
15.00000	0.62866	0.92977	0.79270
20.00000	0.49394	0.73052	0.83043
30.00000	0.34575	0.51135	0.87193

APPENDIX B

F/S INPUT EXAMPLES

Sample input for the F/S calculations are included in this appendix. The input for the first calculation presented in Tables 13 and 14 is given. The modifications required for the other calculations performed involve changes in the uranium enrichment and component densities in the fissile mixtures and the titles of the cases.

10 MW F/S Calculational Input for 5% Enrichment, H/U=0.

```
//WCJII01C JOB (38823),'6011 MS6370 WCJ',TIME=(45,0),
// MSGCLASS=T,NOTIFY=WCJ
//*MAIN CLASS=WHENEVER
//PROCLIB DD DSN=TZA.PROCLIB.CNTL,DISP=SHR
//STEP EXEC SCALE4
//GO.SYSIN DD *
=CSAS25
FREEZER/SUBLIMER 10MW.FULL LOADING,5.0%,H/U=0.000, WATER ON TUBESIDE.
27GR LATT
'MATL 1 IS R-114, VOID, 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
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=5.11458 0.8650 288. 92235 5.0 92238 95.0 END
HFACID  4 DEN=0.00000 0.8650 288. END
AL      4             0.0675 288. END
'MATL 5 IS UF6-HF MIXTURE  IN OVERLOADED REGION
UF6     5 DEN=5.11458 1.000  288. 92235 5.0 92238 95.0 END
HFACID  5 DEN=0.00000 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,5.0%, H/U=0.000,WATER ON TUBESIDE.
READ PARM NUB=YES NPG=600 PLT=YES 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 60.0088  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=' WCA  SWR' END
XUL=-91 YUL=0 ZUL=170 XLR=91 YLR=0 ZLR=-200 UAX=1 WDN=-1 NAX=130
END PLOT
END DATA
END
```

20 MW F/S Calculational Input for 5% Enrichment, H/U=0.

```
//WCJI101C JOB (38823),'6011 MS6370 WCJ',TIME=(45,0),
// MSGCLASS=T,NOTIFY=WCJ
//PROCLIB DD DSN=TZA.PROCLIB.CNTL,DISP=SHR
//STEP EXEC SCALE4
//GO.SYSIN DD *
=CSAS25
FREEZER/SUBLIMER 20MW.FULL LOADING,5.0%,H/U=0.000, WATER ON TUBESIDE.
27GR LATT
'MATL 1 IS R-114, VOID, 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
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=5.11458 0.8650 288. 92235 5.0 92238 95.0 END
HFACID  4 DEN=0.00000 0.8650 288. END
AL      4             0.0675 288. END
'MATL 5 IS UF6-HF MIXTURE  IN OVERLOADED REGION
UF6     5 DEN=5.11458 1.000  288. 92235 5.0 92238 95.0 END
HFACID  5 DEN=0.00000 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
20MW F/S, FULLY LOADED, 5%, H/U=0.000, WATER ON TUBESIDE
READ PARM NUB=YES NPG=600 PLT=YES TME=45 END PARM
READ GEOM
UNIT 1
'SIMPLIFIED MODEL OF FINNED TUBE W/ UF6-HF/AL VOLUME HOMOGENIZED.
CYLINDER  1 1  1.1303  2P144.78
CYLINDER  2 1  1.2700  2P144.78
CYLINDER  3 1  1.3589  2P144.78
CYLINDER  4 1  2.8575  2P144.78
CYLINDER  5 1  2.8575  2P144.78
UNIT 4
'CUBOID FOR INTERIOR 14X14 ARRAY
'NOTE: A FULL ARRAY OF FINNED TUBES IS MODELED. THE INTERIOR REGION
'      OF THE F/S ACTUALLY HAS 12 TUBES REMOVED LEAVING AN OPEN AREA.
CUBOID    5 1  4P3.4925  2P144.78
HOLE    1  0.        0.       0.
UNIT 10
'BASE MODEL FOR 20MW F/S.
ARRAY 1  -48.8950 -48.8950 -144.78
CYLINDER  5 1 71.4375  2P144.78
HOLE    1   3.4925  66.3575  0.
HOLE    1   3.4925  59.3725  0.
HOLE    1   3.4925  52.3875  0.
HOLE    1  10.4775  66.3575  0.
HOLE    1  10.4775  59.3725  0.
HOLE    1  10.4775  52.3875  0.
HOLE    1  17.4625  59.3725  0.
HOLE    1  17.4625  52.3875  0.
```

HOLE	1	24.4475	59.3725	0.
HOLE	1	24.4475	52.3875	0.
HOLE	1	31.4325	59.3725	0.
HOLE	1	31.4325	52.3875	0.
HOLE	1	38.4175	52.3875	0.
HOLE	1	52.3875	3.4925	0.
HOLE	1	52.3875	10.4775	0.
HOLE	1	52.3875	17.4625	0.
HOLE	1	52.3875	24.4475	0.
HOLE	1	52.3875	31.4325	0.
HOLE	1	52.3875	38.4175	0.
HOLE	1	59.3725	3.4925	0.
HOLE	1	59.3725	10.4775	0.
HOLE	1	59.3725	17.4625	0.
HOLE	1	59.3725	24.4475	0.
HOLE	1	59.3725	31.4325	0.
HOLE	1	66.3575	3.4925	0.
HOLE	1	66.3575	10.4775	0.
HOLE	1	-3.4925	66.3575	0.
HOLE	1	-3.4925	59.3725	0.
HOLE	1	-3.4925	52.3875	0.
HOLE	1	-10.4775	66.3575	0.
HOLE	1	-10.4775	59.3725	0.
HOLE	1	-10.4775	52.3875	0.
HOLE	1	-17.4625	59.3725	0.
HOLE	1	-17.4625	52.3875	0.
HOLE	1	-24.4475	59.3725	0.
HOLE	1	-24.4475	52.3875	0.
HOLE	1	-31.4325	59.3725	0.
HOLE	1	-31.4325	52.3875	0.
HOLE	1	-38.4175	52.3875	0.
HOLE	1	-52.3875	3.4925	0.
HOLE	1	-52.3875	10.4775	0.
HOLE	1	-52.3875	17.4625	0.
HOLE	1	-52.3875	24.4475	0.
HOLE	1	-52.3875	31.4325	0.
HOLE	1	-52.3875	38.4175	0.
HOLE	1	-59.3725	3.4925	0.
HOLE	1	-59.3725	10.4775	0.
HOLE	1	-59.3725	17.4625	0.
HOLE	1	-59.3725	24.4475	0.
HOLE	1	-59.3725	31.4325	0.
HOLE	1	-66.3575	3.4925	0.
HOLE	1	-66.3575	10.4775	0.
HOLE	1	3.4925	-66.3575	0.
HOLE	1	3.4925	-59.3725	0.
HOLE	1	3.4925	-52.3875	0.
HOLE	1	10.4775	-66.3575	0.
HOLE	1	10.4775	-59.3725	0.
HOLE	1	10.4775	-52.3875	0.
HOLE	1	17.4625	-59.3725	0.
HOLE	1	17.4625	-52.3875	0.
HOLE	1	24.4475	-59.3725	0.
HOLE	1	24.4475	-52.3875	0.
HOLE	1	31.4325	-59.3725	0.
HOLE	1	31.4325	-52.3875	0.
HOLE	1	38.4175	-52.3875	0.
HOLE	1	52.3875	-3.4925	0.
HOLE	1	52.3875	-10.4775	0.
HOLE	1	52.3875	-17.4625	0.
HOLE	1	52.3875	-24.4475	0.
HOLE	1	52.3875	-31.4325	0.
HOLE	1	52.3875	-38.4175	0.
HOLE	1	59.3725	-3.4925	0.
HOLE	1	59.3725	-10.4775	0.
HOLE	1	59.3725	-17.4625	0.
HOLE	1	59.3725	-24.4475	0.
HOLE	1	59.3725	-31.4325	0.
HOLE	1	66.3575	-3.4925	0.
HOLE	1	66.3575	-10.4775	0.
HOLE	1	-3.4925	-66.3575	0.
HOLE	1	-3.4925	-59.3725	0.
HOLE	1	-3.4925	-52.3875	0.

```
HOLE     1 -10.4775 -66.3575  0.
HOLE     1 -10.4775 -59.3725  0.
HOLE     1 -10.4775 -52.3875  0.
HOLE     1 -17.4625 -59.3725  0.
HOLE     1 -17.4625 -52.3875  0.
HOLE     1 -24.4475 -59.3725  0.
HOLE     1 -24.4475 -52.3875  0.
HOLE     1 -31.4325 -59.3725  0.
HOLE     1 -31.4325 -52.3875  0.
HOLE     1 -38.4175 -52.3875  0.
HOLE     1 -52.3875  -3.4925  0.
HOLE     1 -52.3875 -10.4775  0.
HOLE     1 -52.3875 -17.4625  0.
HOLE     1 -52.3875 -24.4475  0.
HOLE     1 -52.3875 -31.4325  0.
HOLE     1 -52.3875 -38.4175  0.
HOLE     1 -59.3725  -3.4925  0.
HOLE     1 -59.3725 -10.4775  0.
HOLE     1 -59.3725 -17.4625  0.
HOLE     1 -59.3725 -24.4475  0.
HOLE     1 -59.3725 -31.4325  0.
HOLE     1 -66.3575  -3.4925  0.
HOLE     1 -66.3575 -10.4775  0.
CYLINDER  6 1  72.3900  2P151.3840
CUBOID    7 1  4P102.39 2P151.3840
UNIT 5
HEMISPHE+Z 1 1 97.0475      CHORD  -66.0583
HEMISPHE+Z 6 1 98.0000      CHORD  -66.0583
CUBOID       7 1 4P102.39   128.0000 66.0583
UNIT 6
CYLINDER     1 1 71.4375    4.253  0.0
CYLINDER     6 1 72.3900    4.253  0.0
CUBOID       7 1 4P102.39   4.253  0.0
UNIT 7
HEMISPHE-Z 1 1 97.0475     CHORD -66.0583
HEMISPHE-Z 6 1 98.0000     CHORD -66.0583
CYLINDER     0 1 72.3900  -66.0583 -98.0000
CUBOID       7 1 4P102.39 -66.0583 -98.0000
UNIT 8
CUBOID       8 1 4P102.39  60.48      0.0
GLOBAL UNIT 20
ARRAY 2 2R-102.39 -248.0587
END GEOM
READ ARRAY
 ARA=1 NUX=14 NUY=14 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=' WCA  SWR' END
XUL=-103 YUL=0 ZUL=218 XLR=103 YLR=0 ZLR=-249 UAX=1 WDN=-1 NAX=130
END PLOT
END DATA
END
```

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