FAST FLUX TEST FACILITY
UNSHIELDED SODIUM COOLED
FUEL HANDLING MACHINE
PROGRESS REPORT

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ABSTRACT

Secondary cooling system concepts were studied for the unshielded sodium cooled fuel handling machine (USCFHM). These concepts are simplified and more reliable than those conceived to date for the shielded sodium cooled fuel handling machine (SSCFHM). Ten candidate secondary cooling system configurations or methods were surveyed. One configuration was selected by PNL for in-depth study. Three concepts of the selected cooling configuration were developed and are discussed in detail. The unshielded fuel handling machine concepts utilize reactor hot cell atmosphere (gas) as the secondary cooling system media. A forced gas system is used for cooling during normal operation, with a natural convection gas system used as a backup. The differences between the three concepts are in the detail mechanical arrangements. The USCFHM can be used to transport FFTF reactor core components with decay heats of up to 30 kw. The maintenance, development, safety and costs of the concepts were investigated. These three concepts satisfy PNL's Reactor Refueling System (RRS) design requirements for FFTF service.

I. INTRODUCTION AND SUMMARY

The document presents the results of a study which investigated ways to simplify and increase the reliability of the secondary cooling system and other components of the SCFHM without the limitations imposed by shielding. This unshielded sodium cooled fuel handling machine (USCFHM) was sized to handle driver fuel subassemblies (PNL drawing SK-3-12739) with a 0 - 30 kw decay heat. This is the same basis used for the shielded sodium cooled fuel handling machine (SSCFHM)* study. The SSCFHM internal assembly containing the primary sodium coolant and core component was initially used as the basis for identification of the potential secondary cooling configurations or methods. The common features, heat transfer basis, and operational assumptions are delineated to provide a basis for comparison of the cooling methods.

Ten secondary cooling system cooling methods were identified and then evaluated, based on heat transfer capability, preheat, and temperature control methods. Based on the evaluation, two cooling methods were recommended to PNL for further study. PNL selected the recirculating gas cooled cask cooling method. They requested that 2 concepts of the USCFHM using this cooling method be studied. The first concept was a machine with a minimum diameter, straight internal assembly. The second concept was a machine with a stepped diameter internal assembly to minimize the FHM size. A third concept using the same cooling method, and separating the secondary cooling gas from direct contact with the internal assembly, evolved later in the study as shown on Drawing 1.

Heat transfer analysis, cooling system design, reliability, development, and analysis of the effect of sodium leakage out of the internal assembly were performed on each of the three concepts. The maintenance and overall height reduction studies were performed on the USCFHM as one concept since the differences between the three concepts did not affect these studies.

The design features of the USCFHM concepts, wherever possible, were based on existing technology to minimize development requirements and to maximize

*NAA-SR-MEMO-12619, "Sodium Cooled Fuel Handling Machine Progress Report," June 19, 1968

Drawing 1. Unshielded SCFHM,
Concept III
AI-AEC-MEMO-12661
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operational effectiveness. The USCFHM systems and components that require development are the sodium level control system, the wet valve and valve actuator, and the snorkel and reactor nozzle interface seal. The USCFHM is the first-of-a-kind system and must be proof-tested prior to reactor operation.

In summary, the studies indicate that all three concepts of the USCFHM are feasible for handling and cooling core components and for being maintained and operated in the remote mode. The three concepts, with a secondary gas cooling system capable of removing 30 kw or more of decay heat from a driver fuel subassembly, meet the established RRS requirements (Appendix I). The development program for the USCFHM is the same as that required for the SSCFHM. The proof-testing of the remote maintenance equipment of the unshielded machine is greater than would be required with the shielded machine. The gas secondary cooling system of the unshielded machine is more reliable than the NaK secondary cooling system of the shielded machine. The secondary gas cooling system studied for the USCFHM is applicable to a SSCFHM. The improvements in the design of the grapple actuator and the wet valve actuator for this machine are equally applicable to the shielded machine concept, and increase the reliability of either SCFHM.

It is feasible to maintain the USCFHM using state-of-the-art remote handling and viewing techniques and equipment. The consideration of an unshielded machine — with components unobstructed by shielding and therefore accessible, and a reactor hot cell equipped with general purpose manipulative equipment and remote viewing provision — permits many of the expected maintenance tasks to be accomplished in the reactor hot cell rather than in the Maintenance and Decontamination (M&D) cell complex. Reactor hot cell maintenance is possible if some remote handling and viewing equipment in addition to the general purpose equipment is provided in the reactor hot cell. The design of the reactor hot cell* and the general purpose remote handling and viewing equipment in it should be reviewed for possible incorporation of features described in this report which could improve the remote maintainability of the USCFHM.

*BNWL-470, "Progress Report — Fast Flux Test Facility Reference Concept"

The third concept, without a gas barrier bellows and with double sodium containment, provides the greatest safety from an internal assembly sodium leakage standpoint. Due to its higher operating reliability, greater safety due to less sodium leaks, and less development, this concept is recommended as the concept for comparison with the SSCFHM.

The USCFHM will have high reliability because of the redundancy of the cooling system and the maintainability features of the machine, provided that the required prototype development and proof and life testing recommendations to be made are followed carefully and thoroughly.

II. CONCEPT DESCRIPTION

A. CONCEPTS CONSIDERED

1. Common Features

The configuration of the ten USCFHM cooling methods, shown on Drawing 2, consists of an internal assembly and an external assembly. The internal assembly is the same as shown for the SSCFHM* and is shown on Drawing 1. The major components of the internal assembly are the wet valve, snorkel, wet valve and snorkel cooling system, guide tube, grapple, grapple drive, wet valve actuator system, and sodium level control system. The major components of the external assembly are the movable skirt, seal valve, drip pan, gas barrier bellows, main body support and containment structure, and internal assembly actuator.

The internal assembly size of the ten concepts (the same as the SSCFHM) was a 12-3/4-in.-diameter by 50-ft-high internal assembly wall, with the sodium level 24 ft above the wet valve.

2. Heat Transfer Basis

To maintain the required 1200 and 1600°F temperature limits of the fuel cladding (center pin) for normal and backup cooling, 30 kwt of heat must be discharged from the 24-ft internal assembly sodium-filled height. The basis for the thermal calculations were: 100°F ambient reactor hot cell walls and atmosphere; air or nitrogen reactor hot cell atmosphere; and stainless steel construction with the exposed surfaces having an emissivity of 0.6 Btu/hr-ft²-°F. Oxidized stainless steels have emissivities of 0.6 to 0.8. The detailed thermal calculations are included as Appendix II.

The previous thermal analysis* of the internal assembly of the SSCFHM reported the temperature drop from the "hot spot" center pin cladding to the bulk sodium for natural convection and radial conduction cases. Analysis of radial conduction in a driver fuel subassembly with 30-kwt decay heat load showed a 650°F Δt between the center pin cladding and the sodium surrounding

*Op. Cit. NAA-SR-MEMO-12619

the fuel subassembly at equilibrium. Axial conduction and natural convection will tend to reduce this Δt downward toward the 140°F Δt calculated for natural convection with an assumed adiabatic guide tube. The thermal analysis performed on the ten cooling methods therefore conservatively assumed, that for a 30-kwt decay heat, a 650°F Δt exists between the average internal assembly outer wall temperature to the fuel subassembly center pin cladding temperature. The average internal assembly wall temperature is 550°F with a resultant fuel pin cladding temperature of 1200°F,* and 950°F for a 1600°F fuel pin cladding temperature. This 1600°F temperature was originally chosen during the SSCFHM study* since it is slightly less than the sodium boiling point.

3. Operational Assumptions

To assist in the evaluation of the ten identified cooling concepts, the following assumptions were made.

- 1) The FHM should be preheated to about 400°F prior to its operation to minimize thermal shock during refueling operations. Preheat will be accomplished in 12 hours, i. e. at about 25°F/hour to minimize thermal gradients and resultant stresses.
- 2) During operation, the internal assembly should be heated or maintained at temperature to prevent Na freezing. The upper end may require heating while the lower end is being cooled.
- 3) Decay heat loads will vary from 0 to 30 kwt.
- 4) To accommodate the variable core component heat loads, means of sodium temperature control will be required.
- 5) The internal assembly should be capable of being discharged to the M&D cell complex for maintenance.
- 6) Containment around the internal assembly should be provided during transfer of the internal assembly to the M&D cell complex, to maintain the integrity of reactor containment.

*Requirement No. 9, Appendix I

4. Cooling Methods

a. Bare Cask (Method A)

The bare cask cooling method dissipates the heat directly from the exposed internal assembly which is shown on Drawing 2, Method A. Heat is discharged to the reactor hot cell by radiation and convection from the sodium-containing internal assembly wall. As tabulated on Drawing 2, with a 550°F wall, 113,400 Btu/hr are discharged from the wall, 77,500 Btu/hr by radiation and 35,900 Btu/hr by convection. For comparison, this is greater than the required 102,390 Btu/hr (30 kw) capacity. As the modes of heat transfer are passive, a backup cooling system is not required. The calculated maximum fuel pin temperature will be a little less than 1200°F. If the wall temperature were to be 950°F — a maximum fuel pin temperature of 1600°F — a total of 395,000 Btu/hr would be discharged, 316,000 Btu/hr by radiation and 79,500 Btu/hr by convection. This is equivalent to 115 kw. These numbers indicated that as the maximum fuel pin temperature approaches 1200°F, significantly larger amounts of heat are discharged, primarily by radiation.

To preheat the lower section of the internal assembly to 400 or 500°F, which is typical for this service, more than 30 kw of electrical heaters would be required, depending on actual heat losses from this area. The upper section of the internal assembly could be insulated to minimize heat loss. If electrical heaters were used, they could be mounted either outside or inside the assembly. Maintenance or replacement of the heaters should be easier when attached to the outside of the assembly. The lower section heaters could be used for core component temperature control. In the event fuel becomes stuck in the internal assembly, the internal assembly must be discharged to the M&D cell complex. Containment integrity of the reactor hot cell must be maintained during this transfer operation by use of a containment shell or lock. The heaters would have to be disconnected prior to internal assembly discharge.

b. Finned Cask (Method B)

The heat transfer capability of the bare cask can be increased by finning the lower section of the internal assembly wall. If the fins double the assembly surface area, the total heat transferred with a 550°F wall temperature is 147,200 Btu/hr (43 kw), 83,600 Btu/hr by radiation and 63,600 Btu/hr

by convection. Except for the heat transfer capability, the previous discussion of the bare cask is applicable to this cooling method.

c. Double Contained Cask (Method C)

The double contained cask has two barriers to radioactive sodium leaking from the internal assembly, the internal assembly wall and an outer wall.

The annular space between these two walls is filled with clean sodium. If the surface area of the outer wall is about the same as the surface area of the finned cask, the heat transfer capacity of this method should be greater than of the bare cask method and about the same as that of the finned cask. The previous discussion of the bare cask is also applicable to this method except that maintenance time probably would be greater due to the handling of the sodium-filled annulus.

d. Chimney Cask (Method D)

The chimney cask cooling method adds a shell or tube surrounding the internal assembly of the bare cask. An annular gas flow area is formed for natural convection cooling of the internal assembly. This natural convection cooling is the normal secondary cooling system. The added external tube extends to the top of the internal assembly, forming a chimney to increase the cooling gas flow. Heat is transferred from the internal assembly by convection to the cooling gas in the annulus and by radiation to the chimney. The heat radiated to the chimney is subsequently discharged three ways: (1) radiation to the reactor hot cell; (2) convective removal via gas in the reactor hot cell; and (3) convective removal via gas in the annulus.

The chimney is insulated at the upper section of the internal assembly to reduce heat losses in that area, maintain the annular gas temperature, and thereby maintain the convective driving head. During operation, the gas is heated in the annulus as it cools the fuel subassembly primary coolant, flows around the upper section of the internal assembly, and maintains the temperature of the upper section to help reduce sodium frost deposition. Thermostatically controlled dampers on the cooling gas outlet may be used for temperature control. The dampers would be closed during preheating.

Electric heat would be used for preheat. The electrical heaters could be mounted on the chimney to facilitate internal assembly discharge to the M&D cell. The advantage is that the heaters would remain in the reactor hot cell and thereby reduce the time required to exchange internal assemblies.

Failure of the normal secondary cooling system (convective gas flow) is possible with this cooling method. The cooling gas temperature control dampers could fail in the closed position or could be incorrectly installed following maintenance. The backup cooling system for this cooling method, assuming no cooling due to chimney gas flow, is radiation from the internal assembly to the chimney, and radiation and convection from the chimney to the reactor hot cell.

The normal secondary cooling system, with a 550°F internal assembly wall temperature will transfer 129,000 Btu/hr (37.7 kw). Of that, 19,000 Btu/hr is radiation out from the chimney, and 110,000 Btu/hr is convection both inside and outside of the chimney. If the assembly wall were 950°F, for the backup cooling mode, 175,000 Btu/hr would be discharged by radiation to the chimney, 124,500 Btu/hr radiated to the cell and 30,500 Btu/hr transferred convectively to the cell gas. Only a 770°F internal assembly wall temperature is required to transfer 30 kw in the backup cooling mode. This 770°F temperature, and the 650°F Δt in the assembly, would result in a worst case pin clad temperature of about 1420°F.

The chimney may be utilized as "containment" when the internal assembly is discharged to the M&D cell complex. A separate containment structure installed over the length of the internal assembly would not be required. The chimney cask has the potential of adding shielding.

e. Chimney and Finned Cask (Method E)

The heat transfer capability of the chimney cask can be increased by adding fins to the internal assembly in the area of the primary coolant to increase the heat transfer area. Because the chimney cask cooling method (Method D) met the 30-kwt capacity requirement, the alternate cooling method was not analyzed. Previous discussions of the chimney cask are applicable to this cooling method.

f. Chimney and Louver Cask (Method F)

The chimney and louver cask is a chimney cooling method to which louvers were added to provide a backup cooling arrangement for the internal assembly. With a convection flow blockage of the chimney, the temperature of the chimney rises. Thermostatically actuated 25-ft high vertical louvers would open, exposing the internal assembly to the reactor hot cell and allowing direct radiation from the internal assembly. This method of cooling approaches the bare cask cooling method in backup cooling capability.

The previous discussion of the chimney cask cooling method is applicable to this method. One potential disadvantage of this method is that the louvers would be difficult to seal if the chimney is part of reactor containment when positioned over the M&D cell complex. The vertical louvers could be used on any chimney cask as a backup cooling method.

g. Forced Convective Gas Flow Cask (Method G)

A forced flow of reactor hot cell gas may be used through a chimney cask to cool the internal assembly. This cooling method is a "once-through" type of system. Ambient gas is pumped into the bottom of the chimney, is heated as it passes upward to cool the internal assembly, and is discharged at the top. The backup cooling method could be: (1) radiation, as in Method D; (2) vertical louvers, as in Method F; or (3) natural convection cooling, as used for the normal cooling system in Method D.

Temperature control would be accomplished by varying flow using blower inlet dampers and/or blower motor speed control. Preheating could be done by the method discussed for the chimney cask method, or by using a packaged (modular) heater located in the cooling gas inlet line. Using a modular heater package would simplify heater maintenance or replacement compared to using a multiplicity of individually mounted heaters. A large electrical input would be required due to the energy waste of a "once-through" system. The previous discussion of the rest of the chimney cask cooling method is applicable to this method.

h. Recirculating Gas Cooled Cask (Method H)

The recirculating gas cooled cask cooling method is an adaptation of the forced convective gas flow cask. Reactor hot cell atmosphere is the secondary coolant. A line is added which recirculates the hot gas discharged at the top of

the cask back to the blower inlet. Valving or dampers and gas inlets are added to: (1) control recirculation of the hot gas for preheat, (2) control the mixture of hot and cold gases to provide a 250°F cooling gas inlet to the internal assembly to prevent localized Na freezing, and (3) provide a natural convection flow path for backup secondary cooling in case of failure of the normal secondary system. The chimney is insulated over the entire length to minimize heat losses. The use of insulation reduces the energy input to the system for preheat and increases the driving head for natural convection cooling. The cooling system is modular in construction for ease of component replacement. The chimney may be utilized as containment when positioned over the M&D cell to transfer the internal assembly.

i. NaK U-Tube Cooling Cask (Method I)

The NaK U-tube cooling method is similar to the first cooling concept discussed in the SSCFHM report.* In both this cooling method and the SSCFHM concept, the normal secondary cooling system consists of NaK U-tubes immersed in the sodium-filled internal assembly and the remainder of the NaK cooling system mounted on top of the internal assembly, together with the wet valve and snorkel NaK cooling system. Temperature control is achieved by varying NaK flow and controlling temperature from the radiator. The backup secondary cooling system is a natural convection NaK cooling system mounted inside the insulated external assembly main body wall. This wall could serve the containment function for internal assembly transfers to the M&D cell.

Preheat is accomplished by electrical heaters located in the pumped NaK system and by pump heat.

Maintenance of the backup NaK system must be accomplished in the reactor hot cell. Work on the pumped NaK loop (normal secondary cooling system) could be accomplished either in the reactor hot cell or in the M&D cell.

This cooling method provides the greatest cooling capability for the normal secondary cooling system. The NaK tubes, in direct contact with the primary sodium coolant, minimize the fuel temperature for any given decay heat power level. The natural convection backup cooling system was sized for the specified 30-kwt decay heat load; however, larger capacity is possible.

*Op. Cit. NAA-SR-MEMO-12619

j. NaK Forced Cooling Cask (Method J)

The NaK forced cooling method is similar to the second cooling concept discussed in the SSCFHM Report.*

This cooling method is identical to the NaK U-tube cooling method discussed previously, except that the normal secondary cooling system is mounted on the external assembly main body wall in conjunction with the backup cooling system. This cooling method is capable of cooling a 30-kwt driver fuel subassembly. Both the normal and backup cooling systems would be maintained inside the reactor hot cell.

k. Cooling Method Selection

The cooling, preheat, and temperature control characteristics of the ten cooling methods for the USCFHM are summarized on Drawing 2. The cooling system of the bare cask, finned cask, and double contained cask is a reliable and simple system in that it is passive and uses radiation and natural convection as the methods of heat transfer. Backup cooling systems should not be required. Remote replacement of electrical heaters and discharge of the internal assembly to the M&D cell, which is assumed to require containment, are disadvantages of these cooling methods. The heaters must be used to both preheat the assembly and to control temperatures.

The chimney cask, chimney and finned cask, and the chimney and louver cask also have a simple, reliable method of normal cooling temperature control. The backup cooling system is as reliable (a passive system) as the cooling system of the first three concepts, i. e., cooling by radiation. With the chimney surrounding the internal assembly, the preheat energy requirements should not be as great as for the bare cask type cooling method. With gas flow control dampers on the chimney, the heater duty cycle for temperature control should be less than for the bare cask cooling method. Maintenance of the heaters could be as difficult for these chimney cooling methods as for the bare cask method. The chimney could provide containment during replacement of the internal assembly at the M&D cell. Sealing of the louvers in the louver cask cooling method to meet containment requirements at the M&D cell could be difficult.

*Op. Cit. NAA-SR-MEMO-12619

The forced convective gas flow cask and the recirculating gas cooled cask cooling methods provide forced gas circulation for normal cooling. Backup cooling could be by natural convection with insulated chimneys or by radiation with bare chimneys. A modular heater could be used in the gas line for preheat. The "once-through" feature of the forced convective gas flow cask would require a large heater. The recirculating gas feature of the other method should minimize heater requirements. Maintenance of these cooling methods should be less than that required for the two NaK cooling methods, because the cooling systems are easily replaceable modules of off-the-shelf hardware. The two NaK cooling methods should have a lower reliability than for the forced gas cooling method in that the NaK system lines may not be as easily replaceable as the gas ducting. A break in the gas ducting does not necessarily stop the gas cooling system, but a break in a NaK line would stop the NaK cooling system. Two of the NaK system components — the heat exchanger and pump — are state-of-the-art but not off-the-shelf components.

The two cooling methods recommended by AI were the bare cask and the recirculating gas cooled cask methods. The bare cask concept was chosen because of its simple cooling. The recirculating gas cooled cask method was chosen because of the apparent ease of cooling system maintenance (modular construction), ease of preheat and temperature control, and the potential of adding shielding. The ten cooling methods were reviewed by PNL* and one of AI's recommendations, the recirculating gas cooled cask was selected for further study. In addition to this primary selection, PNL asked that an alternate variation of the selected cooling method be studied. The alternate was to be directed toward achieving the minimum FHM internal assembly diameter with a view toward application of shielding.

B. CONCEPTS STUDIED

Three versions of concepts of the selected cooling method were studied. These concepts were: (I) the recirculating gas cooled concept selected by PNL, (II) the recirculating gas cooled concept with a stepped diameter of the FHM internal assembly also selected by PNL, and (III) a recirculating gas cooled

*Minutes of Meeting, January 10 and 11, 1968, "Reactor Refueling System Program Review at AI"

concept variation eliminating the bellows seal between the FHM internal and external assemblies. This version eliminating the bellows seal was developed during study of the first two concepts and was studied as applied to Concept I but is equally applicable to Concept II with the minimum diameter internal assembly.

The configurations of the three concepts are shown in Drawings 3, 4, and 5. The following description of Concept I, the recirculating gas cooled cask, shown on Drawing 3, is applicable to the other two concepts except for specific variations which will be explained later.

1. Concept I

The FHM concept consists of three basic assemblies, the external assembly, the internal assembly, and the environmental control system.

The external assembly would support and guide the internal assembly. The external assembly would have the provisions for mating with (1) the floor valves which provide access to the reactor nozzles, (2) the interim decay storage facility, and (3) the transfer ports. The external assembly would provide contamination control by maintaining reactor and hot cell atmosphere separation during refueling. It also would direct the cooling gas flow around the internal assembly.

The internal assembly would contain the reactor core components during transfer and provide the containment for the sodium used as the primary coolant of the core components. It also would have provisions to insert and remove the reactor core components into and out of the reactor core, the interim storage facility, and the transfer cell. The internal assembly would be lowered into the M & D cell complex for major maintenance such as recovery from stuck fuel.

The environmental control system is a grouping of subsystems which would be mounted on either the internal or external assembly as described later. The system would provide cooling for the core components and cooling to freeze sodium on the wet valve and snorkel. It also would control the sodium level in the machine when a core component is moved into or out of the FHM.

a. External Assembly

The concept of the external assembly consists of the movable skirt, the seal valve, the drip pan, the gas barrier bellows, the main body, the upper body, and the upper body and internal assembly actuation mechanism.

(1) Movable Skirt

The movable skirt would consist of a section connected to the seal valve and a movable outer annular section which would be connected to the static section with a bellows. The movable outer annular section would be used to establish the containment seal between the FHM and the floor valve.

(2) Seal Valve

During FHM transport, the seal valve would provide containment of the gas in the volume between the gas barrier bellows and the internal assembly. It also would be the final containment of sodium in the event of leakage from the lower end of the internal assembly.

(3) Drip Pan

The drip pan would be used to collect any small amounts of sodium that might drain from the internal assembly. As conceived it would contain a snorkel plug which would be used as an additional line of sodium containment in the event of sodium leakage from the wet valve. If a leak occurred, the internal assembly could be lowered, socketing the snorkel onto the plug, and thereby sealing the end of the snorkel. A gate valve actuator would be used to move the drip pan. The tracks on which the drip pan rides would be capable of supporting the forces applied to establish the snorkel to drip pan seal. The drip pan could be emptied by disconnecting it from the tracks and lowering it into the M&D cell using the machine grapple.

(4) Main Body

The outer wall of the main body would structurally support the FHM. The inner wall would consist of telescoping sections. One section would be attached to the upper flange of the main body and the other section attached to the lower flange. The telescoping construction of the inner wall would accommodate the differential thermal expansion between the inner and outer walls.

The cooling gas inlet plenum would be located at the lower end of the main body, directing the gas flow into the annulus between the inner wall of the main body and the internal assembly wall. The annulus between the inner and outer walls of the main body would be filled with insulation to minimize heat losses and preheat power requirements.

(5) Upper Body

The upper body would be single wall construction. It would be attached to the upper end of the internal assembly, supporting the internal assembly, and accommodating the vertical movement of the internal assembly by telescoping into the main body. The cooling gas outlet plenum would be located near the top of the upper body.

(6) Upper Body and Internal Assembly Actuation Mechanism

The upper body and internal assembly actuation mechanism would raise and lower the upper body and internal assembly. Either air cylinders or ball screws would provide the motive force. A 64-in. stroke would be required for an assumed 2-ft snorkel length of the internal assembly to socket the snorkel into a reactor nozzle assumed to be 18 in. below the movable skirt. The actuating mechanisms would act between the upper flanges of the external assembly main and upper bodies.

(7) Gas Barrier Bellows

The gas barrier bellows would connect a flange on the FHM internal assembly and the top flange of the drip pan actuator housing. It would provide containment of reactor cover gas and separation between the reactor cover gas and the internal assembly cooling gas. The gas barrier bellows would be protected by a support which transfers the structural loads from the drip pan housing assembly to the main body. The 64-in. internal assembly stroke would be accommodated by the bellows.

b. Internal Assembly

The major components of the internal assembly concept are the snorkel, the wet valve and valve actuating mechanism, the core component guide, and the grapple and grapple drive. The outer wall of the internal assembly would be the primary sodium containment during fuel handling operations.

(1) Snorkel

The snorkel is a tube used to contain the sodium between the FHM and the reactor nozzle as conceived and described^{*} for the SSCFHM. Other methods

*Op. Cit. NAA-SR-MEMO-12619

could be used to establish this interface between the SCFHM and the reactor; these are also discussed in the SSCFHM report.^{*†}

A NaK cooling system, incorporated into the snorkel, would minimize dripping of sodium by freezing residual sodium on the snorkel, if required. The concept of the snorkel walls are two concentric tubes closed at the wet valve housing end and at the piston ring seal end. The NaK coolant inlet would be through a header and down through tubing in the annulus. The return cooling flow would be in the annulus and around the inlet tubes. This arrangement would minimize thermal gradients and thermal stresses between the snorkel and snorkel cooling tubes. The snorkel design and length are the same as described for the SSCFHM.^{*}

A demonstration test will be required to confirm the operability of the snorkel concept, and to indicate if snorkel cooling is required.

(2) Wet Valve and Valve Actuating Mechanism

The wet valve configuration is the concept described for the SSCFHM.[†] The valve primary seal would be attained by the metal-to-metal contact between the plug and seat. The secondary seal would be accomplished by freezing sodium in the annulus between the plug and seat. Differential pressure control across the valve seat could also be used to decrease Na flow through the plug/seat annulus in the event of primary and secondary seal malfunction. The valve assembly would be mounted to the outer wall of the internal assembly with a bolting flange. The snorkel would be bolted to the wet valve flange.

The wet valve would be actuated by vertically moving the core component guide tube relative to the internal assembly wall. Upward movement would open the valve and downward movement close the valve. The actuating force would be transferred from the guide tube to the actuating linkage through a fixed yoke which is integral with the guide tube lower end. A linkage raises the valve plug approximately 1/8 in. away from the seat before valve plug

*Op. Cit. NAA-SR-MEMO-12619

†The sodium level control system is described in detail in AE-AEC-MEMO-12663, "Liquid Level Control Concepts for Sodium Cooled Fuel Handling Machines."

rotation is allowed. This prevents the possibility of damaging the seat through galling.

(3) Core Component Guide Tube

The concept of the core component guide tube is a split tube used to guide core components and the grapple through the wet valve and into the snorkel. The slots would be used to prevent grapple rotation. The core component guide would be supported from the top by the wet valve actuator drive and pinned to the wet valve actuating linkage at the bottom. The split tube would be stiffened and guided within the internal assembly by rings welded to the outer surface of the split tube. Axial spacing of the support rings would be established from the column loading requirements imposed by actuation of the wet valve.

(4) Grapple and Grapple Drive

A two-chain operated grapple with grapple fingers undercut to prevent unlatching under load was assumed for this study. Rotational guidance would be provided by key or rollers, attached to the upper fitting of the grapple housing, and guided by the slots in the core component guide. Lateral guidance would be provided by wear pads on the grapple housing bearing against the core component guide and the snorkel. This grapple drive and guidance system would result in a reduction in FHM height compared to the system shown for the SSC FHM* because only one grapple-drive tie point is required versus 2 tie points, 2 ft apart, shown for the SSC FHM. It would also eliminate the cantilevering of the grapple shown for the shielded concept.

The grapple drive chains would be link chains rolling over drive sprockets at the upper end of the internal assembly. The loose ends of the chains would be weighted and travel in the annulus between the core component guide and the outer wall of the internal assembly.

The two grapple drive sprockets would be mounted on independent and offset shafts. This would be required to accommodate the required sprocket diameters and chain drop off points within a minimum diametral envelope of 10-1/4 in. The grapple drive sprocket shafts would penetrate and be sealed to the internal

*Op. Cit. NAA-SR-MEMO-12619

assembly wall and to the upper body of the external assembly. The drive shafts would be mechanically synchronized with provision for differential relative rotation for actuation of grapple latch and release functions.

c. Environmental Control System

The concept for the environmental control system consists of the sodium level control system, the wet valve and snorkel cooling system, the primary cooling system, and the secondary cooling system. The equipment associated with these systems would be physically located on both the internal and external assemblies.

(1) Sodium Level Control System

A sodium level control system using suction (vacuum) to draw sodium into the FHM was selected as the concept for use in the FHM's of this study. The selection was made as a result of concurrent Liquid Level Control Study.* Redundant vacuum systems are employed for increased reliability. Each vacuum system would be provided with sodium vapor protection as required up to a maximum of a demister, absolute filter, and molecular sieve. The pump outlet would be connected to the plant radioactive gas disposal system.

A wet valve bypass line would connect the level control system with the volume in the snorkel immediately below the wet valve. The wet valve bypass line would act as a vent to allow the sodium below the wet valve to drain back into the reactor after closing the wet valve. It also would be used to draw sodium up in the channel below the wet valve before opening the wet valve to lower the fuel subassembly and sodium from the FHM internal assembly.

A separate vacuum control system would be required to maintain the pressure balance at the snorkel to refueling nozzle seal as previously described. This control system would utilize the main vacuum pumping systems on the FHM.

(2) Wet Valve and Snorkel Cooling System

The concept of this system consists of a pump, radiator, radiator cooling air blower, valves and an expansion tank which are mounted on top of the internal assembly. As the system is discharged with the internal assembly

*Op. Cit. AI-AEC-MEMO-12663

into the M&D cell, it must be the same envelope diameter as the internal assembly. The NaK lines to the wet valve and snorkel would be routed to the outside of the internal assembly wall to avoid picking up excessive heat load from the primary sodium coolant.

(3) Primary Cooling System

The primary cooling system of the SCFHM is the sodium filled internal assembly. The sodium coolant transfers the core component decay heat by conduction and natural convection to the wall of the internal assembly and hence to the secondary cooling system.

(4) Secondary Cooling System

The gas secondary cooling system would consist of a blower, electric preheat coil, butterfly valves, and ductwork. The system would circulate gas through the fuel handling machine cooling gas space and discharges the gas to the surrounding environment. The circulating gas would be either air or nitrogen depending on the atmosphere chosen for the reactor hot cell. Controls would be provided to allow the system to operate in any of the three required modes. The first mode is a preheat cycle; the second is a normal decay heat removal cycle; and the last is a backup decay heat removal cycle precipitated by loss of forced cooling gas flow.

The preheat mode would be used to preheat the FHM prior to filling with sodium. In the preheating mode, 100% of the gas flow supplied by the blower would be recirculated to minimize the amount of electric heating required. An assumed design requirement is to preheat the FHM and connecting gas cooling system to 400°F in twelve hours. A pressure-vacuum relief valve would be provided in the ductwork to ensure atmospheric pressure operation at all times. Preheat would be attained with a return gas duct thermostat controlling the electric preheat coil.

The normal cooling mode would remove the decay heat from the internal assembly. In this decay heat removal cycle, part of the FHM exhaust gas would be returned and mixed with makeup ambient gas to provide the proper inlet gas temperature to the cooling gas space. This would be done to reduce the use of electric heat capacity for low decay heat core components. In Concept III, shown on Drawing 6, a helium gas barrier tube separates the internal assembly

from the cooling gas space. In the other two concepts, the cooling gas inlet temperature would be maintained at 250°F to avoid potential solidification of the liquid sodium coolant contained within the internal assembly. For Concept III, with the added thermal barrier, the cooling gas inlet temperature could be the 100°F ambient and still avoid potential sodium solidification.

The backup cooling mode would be a natural convection cooled system. In this emergency heat removal cycle, the gas cooling system would revert to a "once-through" cycle to use natural convection circulation of ambient gas (100°F) through the FHM cooling gas space to cool the internal assembly by opening butterfly valves on the cooling gas inlet and outlet lines.

All operations would be automatic with fail-safe features for emergency operation. FHM supply gas temperature may be automatically maintained by a duct thermostat controlling the appropriate butterfly valves.

2. Concept II

Concept II, shown on Drawing 4, is the minimum diameter version of Concept I. The only difference between Concepts I and II is the reduced diameter of the FHM internal assembly and surrounding external assembly at elevations above the wet valve and its actuating linkages.

In attempting to reduce the size of the wet valve, its housing, and the actuating linkage, the possibility was investigated of inverting the wet valve and accomplishing the actuation through rods external to the FHM internal assembly. No advantage of the inverted assembly was found to counterbalance the problems of providing penetrations for the actuating mechanisms. The reduction in size offered no advantage. The actuating force would be increased since the sodium head in the FHM internal assembly would be acting to unseat the valve instead of increasing sealing force as in the normal configuration.

The methods of achieving valve actuation were also investigated. This resulted in the use of the core component guide to transmit the valve actuating force. This feature eliminated the use of pull rods in the annulus between the core component guide and the outer wall of the FHM internal assembly. This actuating method was considered to be better than the pull rod method of actuation developed under the SSCFHM study.* It was adopted for all concepts in this study.

*Op. Cit. NAA-SR-MEMO-12619

The minimum internal assembly diameter is shown as 11-1/4 inches, based on the core component guide, a 1-in. ID valve bypass line, and an allowance for sodium level and temperature sensors.

3. Concept III

Concept III, as shown on Drawings 1 and 5, is a variation of Concept I which eliminates the gas barrier bellows between the internal and external assemblies. The differential movement between the internal and external assemblies would be accommodated by a sliding seal located above the maximum sodium level in the machine. This seal is assumed to be similar to the same type of seal shown for the SSCFHM.* A gas barrier tube, surrounding the internal assembly, would be made in two sections. The upper section would be attached to the upper end of the internal assembly and telescopes inside the lower section. The sliding seal would be located at the telescopic joint. During operation, helium would occupy the annulus between the gas barrier tube and the internal assembly. The secondary cooling gas annulus would be located between the inner wall of the main body and the gas barrier tube. As in the other two concepts, insulation would be located between the inner and outer walls of the main body. The insulation would be required for the natural convection emergency cooling operation and to minimize machine preheat requirements.

4. Height Reduction Study

A separate study was conducted to determine if a height reduction of the FHM could be achieved by relocating subsystem equipment at the top of the FHM. The concept Drawings 3, 4, and 5 show the locations for the NaK cooling system for wet valve and snorkel cooling on the vertical centerline of the machine. In these designs the envelope diameter of the NaK system is held to a dimension that allows the NaK system to be lowered into the M&D cell with the internal assembly. This arrangement eliminates the need for disconnecting the NaK system for this operation but occupies approximately 7 ft of elevation. Since this elevation requirement may affect both the reactor hot cell and the M&D cell, there could be considerable incentive for height reduction. This will depend upon whether the FHM or another piece of equipment, such as the intermediate heat exchanger, is the height-controlling item.

*Op. Cit. NAA-SR-MEMO-12619

The alternate arrangement is shown in Drawing 7. In this arrangement the height reduction is obtained by relocating the NaK system and other subsystem equipment on a platform below the top of the FHM upper body. Remotely operable disconnects would be required for the NaK lines and for the other subsystem connections in order to retain the capability of lowering the internal assembly into the M&D cell. The NaK line connections would be critical because the disconnection is a source of NaK contamination with subsequent potential plugging. A NaK cleanup system would be required. The arrangement of NaK line remote disconnects shown in the drawing meet the space and access requirements of remote NaK line disconnects developed at AI for the S8DR coolant sampling system* as shown in Figure 1. Similar space and access provisions would be provided for the other lines requiring remote disconnect capability. This minimum height equipment arrangement results in an overall height of the USCFHM of ~51 feet, an ~7-ft reduction.

5. System Operation

a. System Operational Description

The refueling operations of the three concepts would be identical. There would be three phases of normal operation; the preparation for fuel handling, the removal of a fuel subassembly from reactor or storage facility, and the insertion of a fuel subassembly into the reactor or storage facility.

(1) Preparation for Fuel Handling

The FHM interior gas volumes would be purged and filled with clean reactor cover gas. The secondary cooling gas system would be put into the recirculating mode and the electrical heaters turned on to preheat the FHM. After the FHM had been heated to the normal 400°F operating temperature, the operational status of all equipment and systems would be verified. The FHM would be ready for use.

The reactor nozzle would be prepared by the nozzle preparation machine for refueling. The preparation would consist of disconnecting instrumentation from the nozzle, installing a floor valve, and removing any cover,

*DTP-568-82-001, "S8DR Remote Handling and Viewing Test Procedures"

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Figure 1. Typical Remote NaK Line Disconnect

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holddown or locking devices. The floor valve would be the containment lock through which the FHM gains access to the nozzle to be refueled.

(2) Removal of Fuel Subassembly from Reactor or Storage Facility

The FHM would be indexed to the nozzle to be refueled. The movable skirt would be lowered, establishing a seal to the floor valve. The enclosed gas volume between the floor valve and FHM seal valve would be purged and filled with clean reactor cover gas. The floor valve and FHM seal valve and drip pan valve would be opened and the FHM internal assembly lowered through the floor valve. The snorkel would be seated in the reactor nozzle, establishing the seal between snorkel and nozzle.

The FHM grapple would be lowered and engaged to the fuel subassembly. The fuel subassembly and reactor coolant sodium would be raised into the FHM internal assembly. The sodium level would be regulated so that the instrumentation connections on the fuel subassembly would not be wetted and that the top of the active fuel would not be uncovered. After the fuel subassembly is fully withdrawn into the FHM internal assembly, the sodium level would be raised for transport above the coolant outlet holes in the fuel subassembly. This would allow convective cooling within the fuel. The wet valve would be closed and frozen while the sodium below the wet valve was allowed to drain back into the reactor. The wet valve would be cooled to freeze the sodium between the valve seat and plug. The sodium level in the FHM internal assembly would be monitored. If the level did not change, the snorkel would be cooled to freeze the adherent sodium film, if required, and the internal assembly would be raised into the FHM and the seal valve and drip pan closed. The floor valve would be closed and, after purging, the FHM would be ready to move to its next station. If the level in the FHM internal assembly lowered, a leak would be indicated at the wet valve. In this event the fuel subassembly would be lowered back into the core or storage position and the FHM removed for repair.

(3) Insertion of Fuel Subassembly from FHM Into Reactor or Storage Position

A fuel subassembly would be inserted into the reactor or storage position in an operational sequence similar to the removal sequence. The seal between the FHM internal assembly and reactor nozzle would be established in the same manner. The sodium level would be raised in the nozzle and the holding vacuum

established before opening the wet valve. This would be required to maintain control of sodium level during insertion of the fuel subassembly.

(4) Time Cycle

The time cycle was not investigated for these concepts since the operating sequence would be nearly identical to that of the shielded machines.* One possible area of difference would be in transit times between stations. The lighter unshielded machines may be slightly faster in moving and indexing operations because of the lower weight and inertia forces. Determination of these transit and indexing times, with sufficient accuracy to permit comparison between shielded and unshielded machines, would require better definition of transporting and indexing mechanisms than presently available. Other components of the RRS, such as the nozzle preparation machine and the secondary gamma shield, would have a greater effect on cycle time than whether or not the FHM is shielded.

*Op. Cit. NAA-SR-MEMO-12619

III. CONCEPT EVALUATION

A. THERMAL ANALYSIS

1. Secondary Cooling Systems

Initial calculations of the secondary cooling system thermal performance were based on uniform internal assembly wall temperatures as discussed in Section II-A-2. These are 550°F for the forced flow mode and 950°F for the backup natural convection mode. The initial parametric calculations, shown in Appendix II, calculated the heat transferred from a 9- and 12.75-in.-diameter internal assembly as the diameter had not been established. The cooling-gas annulus width was varied to determine the heat dissipation capabilities. No system inlet and outlet pressure drop losses were assumed. The results, shown on Figure 2, indicate that the 2-in. diametral cooling gas gap would convectively transfer about 34 kwt with a 12.75 internal assembly; a 3-in. gap transfers about 60 kwt. The 3-in. cooling gas gap was selected to provide an adequate design margin which also compensates for the unestablished system pressure drops. Further thermal analyses of the three concepts were based on the final concept dimensions and configurations as shown in Section II-B.

The results of the analysis of the heat dissipation capabilities of Concept I are shown on Figures 3 and 4. Figure 3, with a 100°F cooling gas inlet, indicates that the backup (natural convection) secondary cooling system is capable of discharging 30 kwt with a uniform internal assembly heated wall area at about 700°F. With the assumed 650°F Δt ,* hot-spot cladding to internal assembly wall, the maximum cladding temperature should be about 1350°F. Figure 4 indicates that a normal (forced) secondary cooling system flow of 1500 lb/hr is required.

The normal secondary cooling system flow requirements for Concepts I and II, with 250°F inlet cooling gas, are also shown on Figure 4. The 2500 lb/hr cooling requirements of Concept II are almost the same as the 2400 lb/hr for Concept I. The natural convection cooling and resultant temperatures of Concept II are also about the same as Concept I.

*Section II-A-2

Figure 2. Heat Removal Capabilities of Natural Convection Between Internal Assembly and Main Body for an Internal Assembly Diameter = 9 in.

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Figure 3. Secondary Heat Removal Capability for Forced and Natural Convection with 100° F Air of USC FHM, Concept I

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Figure 4. Heat Removal Capability of Forced Convection of Air, Concepts I and II

The Concept III secondary cooling system analysis results are shown on Figure 5. The 30-kwt backup cooling case results in a uniform internal assembly wall temperature of about 750°F, versus about 700°F for Concepts I and II. The added thermal resistance of the helium annulus and gas barrier tube is not large compared to the gas film coefficients for convective cooling. The normal secondary cooling system flow requirements are shown on Figure 6. The flow rate is a factor of 2 greater than required for Concept I with 100°F inlet air and 30 kw heat removal; for 250°F air, the flow rate is a factor of 4 greater. A normal secondary cooling system gas inlet temperature for Concepts I and II was assumed to be 250°F to preclude potential sodium freezing near the bottom of the internal assembly. For Concept III, with the added gas barrier tube thermal resistance, a 250°F air inlet is not required. The normal cooling system is designed to operate with 100°F inlet air into the cooling gas annulus. Table 1 summarizes the results of the thermal analyses of the three concepts.

2. Primary Cooling System

The primary (sodium) cooling system was analyzed to determine the temperature drop from the internal assembly wall to the fuel cladding. To calculate the sodium temperatures, the secondary cooling system must be included in the analysis. Concepts I and III were used for this analyses. The results for Concept II would be similar to Concept I.

The thermal analysis was based on the following simplifying assumptions:

- 1) The flow was blocked inside the fuel subassembly
- 2) Radial and axial conduction of heat occurs through the sodium from the fuel pins to the duct
- 3) Sodium circulates up between the fuel subassembly and the guide tube, out through holes in the guide tube near the sodium surface, down along the internal assembly wall, and back up around the fuel duct
- 4) Sodium flows up the guide tube around the fuel subassembly without mixing with the downflowing sodium on the outside of the guide tube

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Figure 5. Heat Removal Capability of Forced and Natural Convection with 100°F Air, Concept III

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Figure 6. Heat Removal Capability of Forced Convection of Air, Concept III

TABLE 1
THERMAL PERFORMANCE COMPARISON, USC FHM SECONDARY COOLING SYSTEMS, CONCEPTS I, II, AND III

Parameter	Concept		
	I	II	III
Heat Load (kwt)	30	30	30
Reactor Hot Cell Ambient Temperature (°F)	100	100	100
<u>Normal Cooling Case</u>			
Cooling Gas Temperature, Into Cooling Annulus (°F)	250	250	100
Gas Flow (Air) (lb/hr)	2400	2500	3000
Internal Assembly Wall Temperature (°F)*	550	550	550
Δt , Internal Assembly Wall to Maximum Cladding Temperature (°F)*	650	650	650
Maximum Cladding Temperature (°F)	1200	1200	1200
<u>Backup Cooling Case</u>			
Cooling Gas Temperature Into Cooling Annulus (°F)	100	100	100
Gas Flow (Air) (lb/hr)	980	980	1080
Internal Assembly Wall Temperature (°F)	700	700	750
Δt , Internal Assembly Wall to Maximum Cladding Temperature (°F)*	650	650	650
Maximum Cladding Temperature (°F)	1350	1350	1400

*Assumed, see Section II-A-2.

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- 5) Heat transfer occurs through the guide tube between the up and down flowing columns of sodium
- 6) Radial and axial peaking factors of the fuel are included in the analysis
- 7) The heat losses through the main body insulation are included in the analysis

The results of this analysis are shown on Figures 7 and 8 for Concepts I and III, respectively. Figure 9 shows a typical temperature profile of the fuel and machine for Concept III (30 kw decay heat). The results of the analysis are also summarized and compared in Table 2.

B. COOLING SYSTEM PROCESS ANALYSIS

The secondary cooling system is similar for all three concepts. The three operating modes (preheating, normal cooling, and backup cooling) are indicated on Figure 10. The cooling system design calculations are shown in Appendix III.

The blower conceived has non-overloading performance characteristics and variable inlet vanes for modulated gas flow control. The off-the-shelf blower is designed to withstand 400°F operating conditions. The proposed electric pre-heat coil is a 24-kw unit containing individually replaceable incoloy-sheathed tubular heating elements. The heater is sized to preheat the internal assembly to 400°F in 12 hours, a temperature change of about 25°F/hour to minimize thermal stresses. When operating in the normal cooling mode, hot exhaust gases would be recirculated to mix with intake ambient hot cell atmosphere to provide the 250°F inlet temperature for Concepts I and II. Concept III would use ambient gas for cooling. For temperature control, the blower variable inlet vanes and the butterfly valves would be used. For core components with low decay heat, the heater would be used in conjunction with the recirculating system. The butterfly valves conceived are metal-to-metal seated wafer type suitable for high operating temperatures. Two inches of fiber glass insulation was assumed in the calculations to minimize heat losses during preheat.

Concept III would require the largest cooling gas flow, 3000 lb/hr at 100°F inlet temperature versus 2500 lb/hr at 250°F for Concept II. The maximum blower capacity is 5400 lb/hr at 100°F. The flow capacity would be in excess of the service requirements, but it is the smallest "off the shelf" commercially

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Figure 7. Secondary Heat Removal Capability vs Internal Assembly and Driver Fuel Pin Cladding Temperatures of USC FHM, Concept I

Figure 8. Secondary Heat Removal Capability vs Internal Assembly and Driver Fuel Pin Cladding Temperatures of USC FHM, Concept III

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Figure 9. USC FHM Concept III Temperature Profile, Secondary Convective Gas Cooling

TABLE 2
THERMAL PERFORMANCE SUMMARY, USC FHM CONCEPTS I AND III

Parameter	Concept I	Concept III
Heat Load (kwt)	30	30
Reactor Hot Cell Ambient Temperature (°F)	100	100
Normal Cooling Case Temperatures (°F)		
Cooling Gas		
Inlet	100	100
Normal Sodium Level	193	176
Discharge	190	174
Internal Assembly Wall		
Bottom	285	519
Maximum	348	554
Normal Sodium Level	308	542
Discharge	190	174
Driver Fuel Subassembly (Maximum)		
Duct	431	620
Center Fuel Pin Cladding	1003	1196
Backup Cooling Case Temperatures (°F)		
Cooling Gas		
Inlet	100	100
Normal Sodium Level	488	459
Discharge	470	430
Internal Assembly Wall		
Bottom	634	724
Maximum	683	777
Normal Sodium Level	677	763
Discharge	470	430
Driver Fuel Subassembly (Maximum)		
Duct	751	844
Center Fuel Pin Cladding	1325	1418

PREHEATING MODE
(100% RECIRCULATION)

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NORMAL COOLING MODE
*100°F. MIN. FOR CONCEPT NO. 3 (HELIUM SPACE)

BACKUP COOLING MODE
(NATURAL CONVECTION)

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Figure 10. Secondary Cooling System Operating Modes

available standard unit. The 1-1/2 hp motor is based on startup power demand. Due to the density change, the power required at startup conditions, 1200 cfm and 75 to 100°F ambient, is greater than 1200 cfm at higher temperatures.

The butterfly valves at the bottom and top of the FHM would be normally open valves, the valve in the recirculating line would be normally closed. In the event of blower, valve, or system failure, the top and bottom valves "fail" in the open position, thereby allowing natural convection backup cooling.

Table 3 summarizes the normal secondary cooling system operating parameters.

TABLE 3
FORCED SECONDARY COOLING SYSTEM OPERATING
PARAMETERS

Preheat Operating Mode	
Maximum Preheat Temperature (°F)	400
Ambient Temperature (°F)	75 to 100
Time to Achieve Preheat (hr)	12
Heat Capacity (kw)	
Total	24
Required	18
Spare	6
Normal Operating Mode	
Maximum Flow (cfm)	1200
Variable Blower Inlet Vane Control Range (%)	20 to 100
Normal Cooling Gas Annulus Inlet Temperature (°F)	
30-kwt Decay Heat Core Component	
Concepts I and II	~250
Concept III	~100
<30-kwt Decay Heat Core Component	
Concepts I and II	250 to 400*
Concept III	100 to 400*
Maximum Cooling Gas Inlet Temperature to Cooling Annulus, 0 kwt Decay Heat Core Component (°F)	~400

*Dependent upon decay heat, desired core component temperature and cooling gas flow

C. RELIABILITY

The reliability of the USCFHM was qualitatively and quantitatively compared to the SSC FHM.* This qualitative evaluation discusses the reliability aspects of the cooling concepts of the shielded and unshielded SCFHM's because mechanical changes in the unshielded machine (i. e. wet valve and grapple actuation methods) are feasible for both SCFHM concepts. The quantitative evaluation used (1) failure mode and effect analyses to determine the unavailability of the FHM due to each cooling concept and (2) block diagrams with assigned failure rates to determine the estimated reliability of each concept. The Technical Information Report[†] covering the reliability evaluation of the concepts has been included in this report as Appendix IV.

1. Requirements

The reliability comparison of the unshielded and shielded SCFHM's cooling concepts is based on the following requirements.

- 1) The ability to remove 0 to 30 kwt during normal cooling while maintaining a cladding or surface temperature of 400°F minimum to 1200°F maximum, dependent upon the heat capacity of item being handled.
- 2) The ability to preheat the FHM prior to use to a minimum of 400°F.
- 3) The cooling, under emergency conditions, must maintain driver fuel cladding temperature $\leq 1600^\circ\text{F}$ with a 30-kwt decay heat.
- 4) The machine is assumed to be in use during a normal shutdown for 300 hours. This is an assumed time used as a basis of comparison for the various FHM concepts. A 100-hr average repair time is also assumed. Exact times are not required for a relative comparison of concepts.
- 5) The FHM cooling system control shall be designed to maintain components at some desired temperature between 400 and 1200°F (dependent on the component's capacity as a heat source; e. g. , a 30-kwt component could not be controlled to 600°F, but a 10-kwt component

*Op. Cit. NAA-SR-MEMO-12619, Figure 6

†TI-681-81-021

TABLE 4
RELIABILITY OF COOLING SYSTEMS, SSCFHM AND USCFHM

System	Reliability *	Comment
SSCFHM – NaK Cooling of Internal Assembly		The value for emergency reliability varies from 0.99925 for 10 hr to 0.963 for 500 hr. The 100 hours used is an average repair time use of back-up system.
1. No redundancy		
Normal	0.9755	
Emergency	0.9925	Normal refers to the U-tube HX system.
2. Redundant pumps		
Normal	0.9866	
Emergency	0.9925	Emergency refers to the shield HX system.
3. Redundant pumps and air blast HX		
Normal	0.991	
Emergency	0.9925	
4. Complete redundant systems		
Normal	0.9994	Normal refers to two U-tube or one of each type capable of cooling as shown on SK-N68181103.
Emergency	0.9925	Emergency refers to the 2nd system reliability for 100 hours after 1st failure.
5. Wet valve and snorkel cooling	0.983	
USCFHM – Forced Gas Cooling of Internal Assembly with Natural Convective Gas Emergency Cooling		Emergency reliability equals 0.9997 for 10 hr 0.985 for 500 hr
1. No redundancy		
Normal	0.9957	
Emergency	0.997	Value shown for 100 hr average repair time assumed for comparison.
2. Redundant normal systems		
Normal	0.99998	
Emergency	0.997	
3. Wet valve and snorkel cooling	0.986	Smaller pump required due to lines in gas annulus compared to SSCFHM.

*The reliability calculations are based on a 300-hr time period arbitrarily established for all FFTF FHM studies, thereby allowing direct reliability comparisons for all AI studies. Comparison with other reliability figures will require conversion to a common time base.

might be so controlled; conversely a 0-kwt could not be maintained above 400°F).

- 6) Common equipment types or methods will be considered equivalent with respect to reliability.

2. Summary and Conclusions of the Evaluation

The following is a summary of the conclusions of the reliability study of the USCFHM.

- 1) On the basis of the analyses, and in consideration that only design sketches were made, it is concluded that the method of the forced gas secondary cooling system with full redundancy is more reliable for cooling a FHM than are methods using NaK systems. A shielded machine with secondary gas cooling could be the most reliable of any of the SCFHM concepts considered.
- 2) A requirement which does not affect the cooling system reliability but does affect the unavailability is the need for very skilled operators to operate the remote handling equipment. The estimated repair times can increase many fold when jobs must be done with operators of less skill. The time increase can be due to a cautious approach to new work and to the (much more serious) increase due to errors in operation.
- 3) The large effect that the remote handling equipment interface with the FHM could have on the operation of a machine tends to negate any small variance between the concepts evaluated.
- 4) The reliability estimates for the cooling system are shown in Table 4. The FHM is assumed to be returned to "new" condition after each period of use.
- 5) As shown in Table 4, the secondary gas cooling with full redundancy for normal cooling has a reliability of 0.99998* compared to the NaK system with full redundancy which has a reliability of 0.9994.* There

* λt (failures): 2/100,000 vs 60/100,000

is little difference indicated between the second NaK system for emergency cooling and the natural convective backup, 0.9925 to 0.997,* respectively.

The unavailability difference is much more speculative and more greatly influenced by the remote handling equipment than these reliability values for the cooling system because the ability to and speed of remote repair of the FHM during operation will have a large effect on system availability.

- 6) A problem area encountered in this study of the unshielded environmental control system is the wet valve and snorkel NaK cooling system repair or replacement. Development of quick disconnects or other types of cooling line separations is needed.
- 7) The repair of NaK lines internally buried behind the shielding and through the internal assembly is a problem for the shielded machine.
- 8) Design and development of modular cooling units are desirable for either concept to achieve the lowest unavailability.
- 9) Long stroke welded bellows would add more failure modes than an internal assembly moving in a gas barrier tube and sealed to the tube. The bellows reliability will be lower than the tubes with a seal assembly. Concept III without bellows and with the gas barrier tube sealed to the internal assembly was chosen for reliability analysis.

Each concept depends on the "hot cell" cooling system and the reliability of this system was assumed to be adequate for all, such that the product of its reliability and the FHM cooling system reliability would be essentially that of the FHM cooling system.

For the detailed block diagrams and failure mode analyses of the USCFHM cooling systems, refer to Appendix IV.

* λt (failures): 7/1,000 vs 3/1,000

D. MAINTENANCE

A maintenance study of the SCFHM's was made to: (1) provide reasonable assurance that the FHM concepts currently under consideration can be remotely maintained; (2) determine what capability is required of the handling and viewing equipment used to perform the remote operations; and (3) identify special features and requirements which might be imposed on the building spaces in which the remote maintenance activities will be conducted, thereby gauging the adequacy of the reference reactor hot cell and M&D cell complex designs.

1. Approach

The remote maintenance feasibility study was conducted in the following manner:

- 1) The reference USCFHM design and method of operation were studied to provide the basis for the study.
- 2) The reference FHM concepts were examined to identify those components and/or subassemblies requiring service or maintenance, the operation involved, the probable frequency of the operation, and the physical location on the machine of the component or subassembly requiring service.
- 3) Each component and/or subassembly, and necessary maintenance tasks were reviewed to determine where the operation could best be performed -- whether in the reactor hot cell or in the M&D complex -- when considering the high plant availability factor, biological hazards involved, and possible FHM contamination.
- 4) For those maintenance tasks proposed to be done in the reactor hot cell, consideration was given to: (1) contamination control, (2) location in the cell where the operation would be performed, (3) identifying equipment required to perform the task, and (4) determination of the influence that performing the operation in the reactor hot cell would have on the cell configuration.
- 5) The information compiled is tabulated on Tables 5 and 6 and is shown on Figures 11 and 12.

TABLE 5
REMOTE HANDLING AND VIEWING EQUIPMENT GROUPS
(Estimate of equipment required to remotely maintain FHM)

I. Reactor Hot Cell, Pit Group

(a) Remote Handling Equipment

1. Powered manipulator: Mechanical arm mounted on circular support structure capable of moving around FHM*
2. Heavy duty, extended reach, sealed, master-slave manipulators; one pair located over each window
3. Telescoping jib crane, one located over each window
4. Elevating and turning table (lazy susan)

(b) Remote Viewing Equipment

1. Lead glass, oil-filled, shielding window with binocular mount
2. Wall-mounted periscope with camera
3. Closed circuit television
4. Remotely controlled mirrors

II. Reactor Hot Cell, High Group

(a) Remote Handling Equipment

1. Powered manipulator: Mechanical arm mounted on vertically telescoping polar bridge†
2. Heavy duty, extended reach, sealed, master-slave manipulators; one pair located over each window
3. Five-ton capacity polar crane

(b) Remote Viewing Equipment

1. Lead glass, oil-filled, shielding window with binocular mount
2. Wall-mounted periscope with camera
3. Closed circuit television
4. Remotely controlled mirrors mounted on available structure such as in-cell cranes

III. Reactor Hot Cell, General Equipment

(General purpose manipulative and viewing capability through cell interior)

(a) Remote Handling Equipment

1. Powered manipulator: Mechanical arms supported by wall mounted booms (minimum of two)
2. Heavy duty, extended reach, sealed, master-slave manipulators; one pair located over each window
3. In-cell cranes

(b) Remote Viewing Equipment

1. Lead glass, oil-filled, shielding windows with binocular and telescope mounts
 2. Wall-mounted periscopes with cameras
 3. Wall mounted and free closed circuit television cameras
 4. Remotely controlled, portable mirrors
-

*Optional Concept, mobile manipulator unit for access to sides and back of machine

† Single mechanical arm possibly could be shared between upper polar bridge mounting and lower pit circular support structure, making procurement of two mechanical arms unnecessary

TABLE 6

REMOTE MAINTENANCE SUMMARY

	COMPONENT (REF FIG)	PROCEDURE	CONDITION REQUIRING MAINTENANCE	LOCATION (SEE NOTE 1)	COOLANT CONTAMINATED (SEE NOTE 2)	SEPARATE MODULE	SPARES ON HAND	HANDLING EQUIP- MENT LOCATION	VIEWING EQUIP- MENT LOCATION	REMOVED PART DISPOSITION(NOTE 3)	CONNECTING P PING INVOLVED	ELECT 4/OR INST CONJ INVOLVED	SPECIAL FIXTURES REQUIRED	STATE OF DESIGN ADEQUATE TO ASSESS REQUIREMENTS	M&D COMPLEX PER NAA- SR-MEMO 12367 ADEQUATE
1	MOVABLE SKIRT	REMOVE & REPLACE	BELLOWS OR SEAL FAILURE	RHC-PIT	POSSIBLE	YES	YES	PIT EQUIPMENT	RHC PIT	DECON, INSPECT, REPAIR OR SCRAP	NONE	PROBABLE	POSITIONING EQUIP IN PIT	YES	DOES NOT DIRECTLY INVOLVE M&D COMPLEX
2	SEAL VALVE	REMOVE & REPLACE	SEAL OR ACTUATOR FAILURE	RHC-PIT	POSSIBLE	YES	YES	PIT EQUIPMENT	RHC PIT	DECON, INSPECT, REPAIR OR SCRAP	NO LIQ METAL POSSIBLE PNEU	PROBABLE	POSITIONING EQUIP MENT IN PIT	YES	DOES NOT DIRECTLY INVOLVE M&D COMPLEX
3	DRIP PAN	REMOVE & REPLACE	SEAL OR ACTUATOR FAILURE	RHC-PIT	YES	YES	YES	PIT EQUIPMENT	RHC PIT	DECON INSPECT, REPAIR OR SCRAP	NO LIQ METAL POSSIBLE PNEU	PROBABLE	POSITIONING EQUIP MENT IN PIT	YES	DOES NOT DIRECTLY INVOLVE M&D COMPLEX
4	DRIP PAN	SERVICE-DRAIN&CLEAN IN M&D COMPLEX TRANSFER CELL	SERVICE	DISCHARGE FROM FHM TO M&D TRANSFER CELL	YES	YES	YES(EXCHANGE IS STANDARD PRO- CEDURE)	TRANSFER CELL CARRAIGE	M & D TRANSFER CELL	DRAIN & CLEAN	NO	NO	NONE	YES	NO THESE OPERATIONS WERE NOT ANTICIPATED GREATER REMOTE HAND- LING CAPABILITY IN M&D TRANSFER CELL REQ'D
5	GRAPPLE	REMOVE & REPLACE OR CLEAN	FAILURE	RHC-PIT	YES	YES	YES	PIT EQUIPMENT	RHC PIT	DECON, INSPECT, REPAIR OR SCRAP	NO	NO	NONE	YES	DOES NOT DIRECTLY INVOLVE M&D COMPLEX
6	SNORKEL	CHANGE SEALS	WEAR OR FAILURE	RHC-PIT	YES	YES PART OF INTERNAL ASSY	SPARE SEALS	PIT EQUIPMENT	RHC PIT	SCRAP	CHG SEALS NO REMOVE SNORK YES	TC's	NONE	YES	DOES NOT DIRECTLY INVOLVE M&D COMPLEX
7	WET VALVE	REMOVE & REPLACE	WEAR OF LINKAGE AND/OR SEAL FACE	RHC-PIT(RELEASE AT TOP OF FHM)	YES	YES-PART OF INTERNAL ASSY	YES	PIT EQUIPMENT & RHC-HIGH EQUIP- MENT	RHC PIT & RHC HIGH	DECON, INSPECT, REPAIR OR SCRAP REFACE VALVE	YES	NO	NONE	YES	DOES NOT DIRECTLY INVOLVE M&D COMPLEX
8	GRAPPLE DRIVE	REMOVE & REPLACE	WEAR OR FAILURE	M&D CELL COMPLEX	YES	NO- PART OF INTERNAL ASSY	YES RIGGED IN SPARE INTERNAL ASSY	EQUIPMENT IN M&D CELL COMPLEX	M & D CELL COMPLEX	SCRAP	YES	YES	'TOP HAT' WITH HOIST	YES	YES
9	GAS COOLING SYSTEM (DUCTING, PUMPS, VALVES, HEATER, etc)	REMOVE & REPLACE BY MODULES	WEAR OR FAILURE	RHC(GENERAL)	YES	YES	YES-MOTORS, ACTUATORS, HEATER, ETC	RHC CRANES & POWERED MANIP- ULATORS	RHC WINDOWS OPTICAL & TV	DECON, INSPECT, REPAIR OR SCRAP	YES	YES	NONE	YES	DOES NOT DIRECTLY INVOLVE M&D COMPLEX
10	WET VALVE ACTUATOR	REMOVE & REPLACE	FAILURE	RHC-HIGH	NO	YES	YES	RHC-HIGH EQUIP- MENT	RHC HIGH	SCRAP	NO	YES	NONE	YES	DOES NOT DIRECTLY INVOLVE M&D COMPLEX
11	GRAPPLE DRIVE	REMOVE & REPLACE	FAILURE	RHC-HIGH	NO	YES	YES	RHC HIGH EQUIP- MENT	RHC HIGH	SCRAP	NO	YES	NONE	YES	DOES NOT DIRECTLY INVOLVE M&D COMPLEX
12	WET VALVE & SNORKEL COOLING MODULE	REMOVE & REPLACE	FAILURE	RHC-HIGH	NO	YES	COMPONENTS	RHC-HIGH EQUIP- MENT	RHC HIGH	DECON, INSPECT, REPAIR OR SCRAP	YES	YES	NONE	YES	DOES NOT DIRECTLY INVOLVE M&D COMPLEX
13	WET VALVE & SNORKEL COOLING MODULE-NA&K SERVICE	SERVICE-CONNECT TO NA&K FILL & CLEANING SYSTEM	ROUTINE AND AS REQUIRED	RHC(GENERAL)	NO	JUMPERS	NOT APPLICABLE	RHC	RHC	NOT APPLICABLE	YES	YES	JUMPERS	YES	NOT APPLICABLE
14	INTERNAL ASSY DRIVE MECHANISM	REMOVE & REPLACE	BEARING OR OTHER FAILURE	RHC-HIGH	NO	YES	YES	RHC-HIGH EQUIP- MENT	RHC HIGH	DECON, INSPECT, REPAIR OR SCRAP	NO	YES POSITION INDICATION	NONE	YES	DOES NOT DIRECTLY INVOLVE M&D COMPLEX
15	INTERNAL ASSY DRIVE	REMOVE & REPLACE	FAILURE	RHC-HIGH	NO	YES	YES	RHC-HIGH EQUIP- MENT	RHC HIGH	SCRAP	NO	YES	NONE	YES	DOES NOT DIRECTLY INVOLVE M&D COMPLEX
16	WET VALVE ACT- uator BELLOWS PLATE	REMOVE & REPLACE	BELLOWS FAILURE	RHC-HIGH	POSSIBLE	YES	YES	RHC-HIGH EQUIP- MENT	RHC HIGH	SCRAP	POSSIBLE	NO	NONE	YES	DOES NOT DIRECTLY INVOLVE M&D COMPLEX
17	NA LEVEL CONTROL SYSTEM MODULES	REMOVE & REPLACE	COMPONENT(MODULE) WEAR OR FAILURE	RHC	YES	YES	YES	RHC EQUIPMENT	RHC	DECON, INSPECT, REPAIR OR SCRAP	POSSIBLE	PROBABLE	DEPENDENT ON CONCEPT ADOPTED	CONCEPT NOT ADOPTED	PROBABLY
18	NA LEVEL INDICATORS	REMOVE & REPLACE-TRANS FER INTERNAL ASSY TO M&D CELL COMPLEX	PROBE MALFUNCTION OR FAILURE, SEAL LEAK	M&D CELL COMPLEX	YES	YES	YES	RHC EQUIPMENT & M&D CELL EQUIP- MENT	RHC & M&D CELL COMPLEX	SCRAP	NOT PROBABLE	YES	NONE	YES	YES
19	SEALS(BETWEEN INTERNAL&EXTERNAL ASSY'S)	REMOVE & REPLACE	LEAK OR MAXIMUM RADIATION EXPOSURE	RHC	YES	YES(SEAL & RING ASSY)	YES	RHC EQUIPMENT	RHC	SEALS-SCRAP RINGS-FIT NEW SEALS	POSSIBLE LEAK DETECTION AND/ OR PRESSURIZATION	YES	NONE	YES	DOES NOT DIRECTLY INVOLVE M&D COMPLEX
20	INTERNAL ASSY- (INCLUDING GRAPPLE, GUIDES,WET VALVE, SNORKEL ETC.)	REMOVE & REPLACE (TRANSFER ENTIRE ASSY TO M&D CELL COMPLEX	MULTI FAILURE OF SUB-ASSEMBLIES, TIME COMPLEX REPAIR	RELEASE BY RHC EQUIPMENT TO M&D TRANSFER CELL	YES	YES	YES	RHC EQUIPMENT & M & D CELL EQUIP- MENT	RHC & M&D CELL COMPLEX	DECON, INSPECT, REMOTE AND/OR CONTACT REPAIR, SALVAGE OR SCRAP	YES	YES	'TOP HAT' WITH HOIST	YES	YES
21	ELECTRICAL HARNESS(S)	REMOVE & REPLACE	INSTRUMENT NOISE, MAX RADIATION EX- POSURE, FAILURE	RHC	NO	YES	YES	RHC EQUIPMENT	RHC	SCRAP	NO	YES	NONE	YES	DOES NOT DIRECTLY INVOLVE M&D COMPLEX
22	CLEAN INTERIOR OF FHM INTERNAL ASSY	SERVICE-PULL CLEANING HEAD INTO MACHINE WITH GRAPPLE	ROUTINE AND AS REQUIRED	FHM OVER M&D TRANSFER CELL	YES	NOT APPLICABLE	NOT APPLICABLE	M&D COMPLEX TRANSFER CELL EQUIPMENT	M&D COMPLEX TRANSFER CELL	NOT APPLICABLE	NOT TO FHM-IN M&D CELL COMPLEX-YES	NOT PROBABLE	YES- CLEANING DEVICE & SYSTEM IN M&D COMPLEX TRANSFER CEL	YES	NO

NOTES

1 MAINTENANCE OPERATIONS WILL GENERALLY BE RESTRICTED TO THREE REACTOR HOT CELL AREAS (1) REACTOR HOT CELL PIT USED FOR MAINTAINING THE LOWER END OF FHM, (2) REACTOR HOT CELL HIGH USED FOR MAINTAINING UPPER END OF FHM, AND (3) REACTOR HOT CELL GENERAL WHICH UTILIZES THE GENERAL PURPOSE REMOTE HANDLING AND VIEWING PROVISIONS OF THE REACTOR HOT CELL.

2 "YES" IMPLIES COMPONENT SUBJECT TO PLATING-OUT OF FISSION PRODUCTS AND/OR Na_2^{22} AND FOR Na^{24} "NO" IMPLIES COMPONENT NOT SUBJECT TO CONTAMINATION, HOWEVER THERE IS RADIATION FROM ADJACENT CONTAMINATED COMPONENTS. CONTAMINATION AND ASSOCIATED RADIATION HAZARD DEPENDENT ON PREVIOUS HISTORY, i.e. PRESENCE OF FISSION PRODUCTS, QUANTITIES OF ISOTOPES, DECAY TIMES, ETC.

3 PROBABLE DISPOSITION OF MALFUNCTIONING PART BASED ON CURRENT UNDERSTANDING OF POTENTIAL PROBLEMS

Table 6. Remote Maintenance Summary

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Figure 11. Concept-Reactor Hot Cell FHM Maintenance Pit
and Equipment Group

Figure 12. Elevation at FHM Maintenance Station – Reactor Hot Cell
FHM Remote Maintenance Station Concept

- 6) Recommendations for changes or additions to the FHM and reference facility concept were identified and listed. Equipment requirements and recommendations for follow-on design and R&D items were also identified.

2. Assumptions

The following assumptions and philosophy were used as basis for this remote maintenance study of USCFHM.

- 1) Three FHM concepts were studied, as illustrated on Drawings 3, 4, and 5.
- 2) The reactor concept assumed is that described in BNWL-470, "Progress Report-Fast Flux Test Facility Reference Concept," with the exception of the maintenance and decontamination cell complex (M&D complex).
- 3) The maintenance and decontamination cell complex assumed is that described in NAA-SR-MEMO-12367, "A Conceptual Design for Fast Flux Test Facility Maintenance and Decontamination Cell."
- 4) Isolation of the reactor hot cell atmosphere from the M&D Complex-Transfer Cell is considered to be mandatory. The passage between the two cells should be equipped with one or more remotely operated gate valve(s).
- 5) The worst case failure of the FHM was limited to the case in which a fuel subassembly is stuck in the machine.
- 6) Recovery from a failure in which a fuel subassembly is stuck part way in the FHM was beyond the scope of the study.
- 7) It is understood that contact maintenance techniques will be used in preference to remote maintenance whenever such operations can be conducted in a safe manner and without exposing personnel to hazardous radiation.
- 8) For this study, it is assumed that personnel entry into the reactor hot cell is restricted and that only remote handling and viewing techniques can be utilized to perform maintenance of the FHM.

- 9) General purpose remote handling equipment in the reactor hot cell should consist of wall-mounted and/or overhead supported, rectilinear, powered, manipulator(s); one or more window stations with heavy-duty extended-reach, sealed master-slave manipulators; a 5-ton crane for small FHM components; and a heavy-duty crane with lifting capacity capable of hoisting the heaviest component or sub-assembly of the FHM.
 - 10) This study considers only the FHM and does not include positioning-supporting equipment such as the transporter.
 - 11) Proven state-of-the-art remote-handling and viewing-techniques, procedures and assembly features, developed as part of the Processing Refabrication Experiment and SNAP 2, 8, and 10A compact reactor programs will be utilized in the design of the FHM concepts.
3. Utilization of Reactor Hot Cell for Remote Maintenance of the USC FHM

In a previous study^{*} it appeared that all remote maintenance operations on the SCFHM would have to be performed in the Maintenance and Decontamination Cell Complex. Since issuance of the previous report, the facility concept has been changed to include a reactor hot cell in which the FHM will operate. This reactor hot cell will be equipped with manipulative devices and remote viewing provisions which, it is assumed, will provide a general remote handling capability inside the reactor hot cell. Consideration can now be given to utilization of the shielded reactor hot cell for performing remote maintenance of an FHM without transporting components to the M&D Cell Complex.

Examination of the unshielded FHM concepts indicates there are two areas of the machine where components requiring maintenance are concentrated; these are the two ends, "upper and lower," of the machine. With the exception of the gas cooling system, that part of the machine between the two ends, the "middle part," is virtually maintenance free. Required operations in the middle

*J. H. Burton and C. L. Peckinpugh, "A Conceptual Design for Fast Flux Test Facility Maintenance and Decontamination Cell," NAA-SR-MEMO-12367, July 27, 1967

part of the machine appear to be of the type which could be accomplished with general purpose remote handling equipment. Maintenance of the components located at the two ends of the machine, such as the grapple drive at the upper end and the valves at the lower end, will require the use of manipulators capable of greater precision than that which can be expected of the general purpose manipulators adequate for servicing the machine middle. A comparison of the remote maintenance activities required at the lower end of the FHM with those at the upper end indicates that the lower equipment group must be capable of performing more delicate and complex work than required of the upper equipment group. An estimate of the number and types of equipment required for the lower, or pit equipment group and the upper or high, equipment group is listed in Table 5. Table 6 is a summary of the remote maintenance requirements of the FHM components, systems, and subassemblies. The FHM components, maintenance procedures, conditions requiring maintenance, and the proposed maintenance equipment and locations are listed.

4. Features of the FHM Concepts Which Require the Reactor Hot Cell for Maintenance of the Machines vs Transfer of the Machines to the M&D Cell Complex for Maintenance

Certain features of the FHM concept designs can influence the maintenance location of some components. Examination of these features reveals the following information pertaining to maintenance of the FHM:

- 1) To maintain integrity of the reactor hot cell atmosphere and to isolate it from the exterior of the cell, any component being moved into or out of the cell should be handled through a lock or similar device. In the case of a FHM, this implies that only the machine internal assembly can be transferred to the M&D Cell Complex assuming that (1) the FHM external assembly is sealed and valved to the common port between the reactor hot cell and M&D Cell Complex, and (2) the FHM external assembly serves as the barrier maintaining the integrity of the reactor hot cell interior. This also implies that the FHM external assembly must be of such a design and construction that it can be stripped of components requiring maintenance and never be transferred out of the reactor hot cell.

- 2) The machine lower-end components, such as the seal valve, must be of modular design capable of being removed as modules, using proven techniques to handle gaskets and seals between modules and assemble or "stack" the modules to one another. Maintenance of these components consists of removing an entire module and replacing it with an available spare. The removed malfunctioning component is then either repaired in the reactor hot cell, utilizing the lower or pit group of remote-handling equipment, or passed out of the reactor hot cell to the M&D Cell Complex for decontamination, inspection, and repair or disposal. Transfer of the component out of the reactor hot cell, while maintaining cell integrity, would be accomplished by raising the component to be transferred into a valved unshielded cask which would engage with and seal to the common port between the reactor hot cell and M&D Cell Complex and which would permit the component to be lowered into the M&D Cell Complex with the cask maintaining the reactor hot cell integrity. This transfer cask would be used to introduce the repaired component and/or other "spares" back into the reactor hot cell.
- 3) Examples of components which would be beyond the repair or replacement capabilities of the pit remote handling equipment group would be cracked bellows, assembly and disassembly of pneumatic cylinders, replacing of internal seals in valves, replacement of actuating shaft seals in valves, or any operation requiring welding. Components requiring any of the operations described would be transferred to the M&D Cell Complex unless, after removal from the machine, the component could be repaired by contact maintenance in the reactor hot cell. Contact maintenance of such a component would be dependent upon allowable exposure to the personnel involved and/or radiation level of the dirty component. It is doubtful that any decontamination operations involving components will be permitted within the reactor hot cell. This would require transfer of all "hot" contaminated components to the M&D Cell Complex for decontamination.

Because of the DBA, the reactor hot cell containment should be maintained when transferring subassemblies of the FHM between the Hot Cell and the M & D Cell Complex. When the FHM internal assembly is

lowered into the M & D cell, the machine external assembly, plus a cover or "top hat" which seals to the external assembly provides the reactor hot cell containment. The top hat has a self-contained hoist to raise and lower the internal assembly. The top hat for the three concepts is shown on Drawing 8. The top hat for the alternate arrangement machine (minimum height machine) is shown on Drawing 7.

5. Reactor Hot Cell Configuration and Special Features Imposed by In-Reactor-Hot-Cell Approach to Maintaining FHM's

If components and/or subassemblies of the FHM's are to be maintained in the reactor hot cell, certain requirements, listed below, will be imposed on the cell configuration as shown in Figures 11 and 12:

- 1) Components requiring maintenance at the lower end of the machine are located close to the reactor hot cell floor surface. To properly manipulate these components the lower remote-handling equipment group should be grouped near the floor level. To permit floor level operations, a pit or depression in the reactor hot cell floor should be provided where the FHM can be positioned for maintenance. The in-cell pit should be situated adjacent to, but separated by a shielding wall, from a subfloor operating gallery outside of the cell. Since it is improbable that the FHM supporting dolly and bridge will be capable of positioning the FHM close to an interior surface of a reactor hot cell wall, the in-cell pit and out-of-cell operating gallery will probably resemble a blister protruding into the cell interior to move the shielding wall and operating gallery to the point where the manipulator(s) can contact the FHM. The depth of the pit in relation to the reactor hot cell floor level will allow a lift table device to assist in vertically positioning components in relation to the lower end of the FHM.
- 2) Design and placement of the upper or "high" equipment group will be dependent on the size and location of the in-cell crane system. The high equipment group may utilize a blister in the ceiling of the reactor hot cell to provide space into which equipment, such as a telescoping tube supported manipulator, could be withdrawn and also provide space for the static length of the telescoping tube assembly. The exact design of such a blister would be dependent upon factors such as the

manipulator and other remote equipment coverage requirements, the position and size of the in-cell cranes, and the relative position of the reactor hot cell ceiling and cranes in relation to the upper end of the FHM. It is probable that the upper equipment group would be located in line with the lower, or pit group, to permit simultaneous operations to be performed at both ends of the machine. Some components of the high remote-handling equipment group may have to be positioned so they can also provide access to the FHM when it is positioned over the port common to the reactor hot cell and M&D Cell Complex. This positioning would be advantageous during transfer of the FHM internal assembly between the reactor hot cell and M&D Cell Complex.

Locating the upper and lower equipment groups adjacent to a corner of the reactor hot cell would offer certain advantages since this would permit direct viewing and master-slave manipulator access from two sides.

- 3) The third feature concerned with maintaining the FHM's in the reactor hot cell, and one which could influence the design of the cell interior to some degree—especially in the space adjacent to the pit—is that some means could be required to isolate and control the spread of contamination resulting from the maintenance operations conducted in the pit. It is conceivable that the degree of contamination control required could be met by the use of (a) partitions and sheet-metal barriers which would fit tightly as a cuff around the body of the FHM above the pit, and/or (b) a high volume exhaust and filter system in the vicinity of the pit.

E. DEVELOPMENT

The only difference in development requirements between the unshielded machines and the previously studied SSCFHM is the added testing of the gas barrier bellows for Concepts I and II of the unshielded machines. The remote maintenance of either the shielded or unshielded machines would have to be developed and proven prior to reactor operation. The three NaK cooling systems which comprise the environmental control secondary cooling systems of the shielded machine would require development. Basically, one NaK pumped system would require development which would be used for the other pumped NaK

Figure 13. Sodium Coolant Levels
with Internal Assembly Leakage
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TABLE 7
SODIUM COOLANT LEVELS WITH INTERNAL
ASSEMBLY LEAKAGE

Concept No.	Case No.	Type of Na Leakage	Secondary Cooling System Sizes (in.)				Drop in Na Level (in.)	Resultant Na Level Above Active Fuel (ft)
			A	B	C	D		
			(Annulus)	(Pipe)	(Pipe)	(Annulus)		
1	1	Into lower FHM area	-	-	-	-	7.2	5.2
	2	Into secondary cooling annulus	17-1/4 ODX 12-1/4 IDX 12 high	10 Dia X 30 long	6 Dia	15-1/4 ODX 12-1/4 ID	12.4	1.0
	3	Into secondary cooling annulus	18-1/4 ODX 12-1/4 IDX 12 high	12 Dia X 30 long	12 Dia	15-1/4 ODX 12-1/4 ID	15.9	-2.5 [†]
2	4	Into lower FHM area	-	-	-	-	8.7	4.7
	5	Into secondary cooling annulus	16-1/4 ODX 11-1/4 ID X 10 high	10 Dia X 30 long	6 Dia	14-1/4 ODX 11-1/4 ID	13.1	0.3
3	6	Into lower FHM area	-	-	-	-	9.9	3.5

*See Figure 13

†Fuel uncovered

systems.* The unshielded machine also requires development of the pumped NaK cooling system for the wet valve and snorkel. The gas secondary cooling systems will require testing in conjunction with the internal assembly tests, but should not require separate development.

F. SAFETY

The safety aspects of the unshielded machine were qualitatively compared to the shielded machine* and have not significantly changed. An area that has changed, due to the change in secondary cooling systems, is sodium leakage from the internal assembly. The internal assembly sodium levels resulting from a sodium leak were calculated for the three concepts to be sure the fuel is not uncovered. Three leak conditions were assumed: (1) a leak in the area of the wet valve, filling the volume inside the gas barrier bellows of Concepts I and II; (2) a leak through the internal assembly wall, filling the cooling gas annulus and pipe (the lower gas valve assumed to be leak tight) for Concepts I and II; and (3) a leak which fills the volume inside the gas barrier tube of Concept III. The results of the analysis are shown in Figure 13 and Table 7. If the wet valve area leaks in Concepts I (Case 1) and II (Case 4), the sodium level drops 7.2 and 8.7 ft, respectively. A leak into the original sized secondary cooling system was calculated for Concept I (Case 3). These original sizes are shown on Drawing 3. The resultant sodium level almost completely uncovers the fuel. The secondary cooling system pipe sizes necessary to prevent fuel exposure were calculated as tabulated in Case 2. These resultant sizes have not been incorporated into the cooling system design. The added forced flow pressure drops could be accommodated since the originally assumed off-the-shelf equipment is the smallest available and is oversized. The smaller piping was also assumed for Concept II, Case 5. Concept III sodium leakage is tabulated as Case 6. Concept III provides double sodium containment in the event of an internal assembly wall rupture and the secondary cooling system remains operative.

*Op. Cit. NAA-SR-MEMO-12619

G. COST COMPARISON SUMMARY

"Budgetary" capital cost estimates were prepared for each of the three USCFHM concepts described in this report in order to assess the relative cost differences. These estimates will be submitted to PNL under separate cover. The estimates include design and fabrication costs of these concepts from preliminary design to delivery at the site. The cost estimates were normalized as a percentage increase to be compared to a base factor of 1.0 assigned to Concept I. The percentages are not the overall cost differences between the concepts since the estimates include only about 40% of the total equipment expenditures. Estimates were made in areas, or between major items, where cost difference could be identified. The items included and excluded in the cost evaluation are listed below:

1) Items Included in the Estimate

- a) Seal Valve Assembly
- b) Drip Pan Assembly
- c) Main Body Assembly
- d) Upper Body Assembly
- e) Internal Assembly
- f) Cooling Gas System
- g) Wet Valve and Snorkel Cooling System

2) Items Excluded from the Estimate

- a) Electrical Wiring and Circuit Accessories
- b) Instrumentation (Thermocouples, Sensors, Special Devices, etc.)
- c) Control System -- Local and Remote (SCFHM Override Controls, Complete Control Room Complex)
- d) Closed Circuit TV (Cameras and Receiver Equipment)
- e) Gimbals and Gimbal Drive System; Drives to Raise and Lower FHM; Gantry and Trolley; FHM Indexing Systems; and Cask Purge System)
- f) Use of AEC Facilities and Equipment

g) Spare Parts and Special Tools

h) Development Costs

Labor and material cost estimates were based on April 1, 1968, rates; escalation of cost rates was not included.

The capital cost evaluation shows that Concept III has a slightly lower cost factor than the other two concepts studied. By normalizing the cost of Concept I to a base factor of 1.00, Concept II was found to have a cost factor of 1.011, or 1.1% greater than Concept I. The cost factor for Concept III was found to be 0.992, or 0.8% less than Concept I.

The increased cost of Concept II over Concept I is due to the stepped construction at the internal and external assemblies. Concept III with the gas barrier tube and fixed gas ducts, versus Concept I with a gas barrier bellows and slip joints in the gas ducting and cooling gas annulus, was slightly higher in engineering costs, but lower in fabrication and overall cost.

Predesign cost estimates of this type have an accuracy of ± 25 to 50%. Even though these estimates were made on a differential comparison basis, it is obvious that the differences are too small to be considered significant. For all practical purposes, the cost of the three concepts must be considered equal.

APPENDIX I

PNL TENTATIVE REACTOR REFUELING SYSTEM REQUIREMENTS

REQUIREMENT 1.

The Reactor Refueling System shall be designed for the reference, truncated, split, conical core, and will not be designed to handle the backup or future core designs.

REQUIREMENT 2.

The Reactor Refueling System shall handle integral full length core components which consist of core element and attached hanger instrument package.

REQUIREMENT 3.

The Reactor Refueling System shall interface with a reactor nozzle configuration which consists of individual nozzles for each routinely removable core component. Each nozzle shall be "in line" with its respective component and thus will be nonvertical except for the closed loops.

REQUIREMENT 4.

The Reactor Refueling System shall be designed to operate from outside the hot cell, including nozzle preparation and all other functions.

REQUIREMENT 5.

The Reactor Refueling Equipment shall be maintained in a contact mode for scheduled maintenance. Contact maintenance is defined as the ability to perform work with hand tools on the inside and outside of the equipment after decontamination.

REQUIREMENT 6.

The Reactor Refueling System shall include features which will permit recovery from malfunctions by use of contact and/or remote maintenance equipment.

REQUIREMENT 7.

The Reactor Refueling System shall be designed to handle only normal, undamaged, driver-fuel subassemblies.

REQUIREMENT 8.

The Reactor Refueling System shall be capable of handling driver fuel twenty-four hours after shutdown with a 30-kw decay-heat load.

REQUIREMENT 9.

The Reactor Refueling System shall maintain the driver-fuel cladding surface temperature below the specified design temperature of 1200°F.

REQUIREMENT 10.

The Reactor Refueling System shall provide the capability for measuring coolant temperature, flow, and other parameters necessary to determine the driver-fuel cladding temperature during transfer.

REQUIREMENT 11.

The Reactor Refueling System shall be capable of making 25 complete driver fuel transfers between any two hot cell stations in 100 hours.

REQUIREMENT 12.

The Reactor Refueling System shall be designed to safely contain the fuel handling accident which consists of loss of primary cooling.

REQUIREMENT 13.

The Reactor Refueling System shall be designed so that critical systems involving safety are redundant.

REQUIREMENT 14.

The Reactor Refueling System design shall conform with all reactor safety standards and the Code of Federal Regulations (10CFR100 and 10CFR20).

REQUIREMENT 15.

The Reactor Refueling System shall be capable of reinserting core components which have been previously removed from the reactor with instrumentation in an operable condition.

REQUIREMENT 16.

The Reactor Refueling System shall be capable of connecting and disconnecting core component instrumentation.

REQUIREMENT 17.

The Fuel Handling Machine grapple drive mechanism shall have controlled push-pull capability.

APPENDIX II
THERMAL ANALYSIS

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ANALYSIS OF HEAT REMOVAL CAPABILITY OF CHIMNEY CASK CONCEPTUAL DESIGN

CASK DIAMETER = 12.75 IN.

CHIMNEY DIAMETER = 18.00 IN.

CASK WALL TEMP. = 550°F (NORMAL)

950°F (EMERGENCY)

CASK HEIGHT = 50 FT TOTAL
(ONLY THE LOWER 24 FT IS HEATED)

FIND:

1. HEAT DISSIPATION WITH NATURAL CONVECTION OF AIR IN CHIMNEY AND WITH 550° CASK WALL.
2. HEAT DISSIPATION WITH BLOCKED FLOW IN CHIMNEY AND WITH 950° CASK WALL.
3. CASK WALL TEMPERATURE WITH BLOCKED FLOW AND WITH 30 KW HEAT.
4. HEAT DISSIPATION FROM BARE CASK WITH 550°F WALL.
5. HEAT DISSIPATION FROM CASK WITH FINS AND A 550°F WALL.

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CROSS-SECTIONAL AREA OF ANNULAR SPACE

$$\frac{\pi}{4} \left(\frac{18.00}{120} \right)^2 = 1.770 \text{ FT}^2$$

$$\frac{\pi}{4} \left(\frac{12.75}{120} \right)^2 = 0.886 \text{ FT}^2$$

$$A_x = 0.884 \text{ FT}^2$$

PERIMETER:

$$\pi \times \frac{18.00}{12} = 4.72 \text{ FT} = p_2$$

$$\pi \times \frac{12.75}{12} = 3.34 \text{ FT} = p_1$$

$$8.06 \text{ FT} = p$$

HYDRAULIC DIAM:

$$D_h = \frac{4A_x}{p} = \frac{4 \times 0.884}{8.06} = 0.438 \text{ FT}$$

SURFACE AREA OF 24 FT LENGTH:

$$\text{OUTER WALL} = 4.72 \times 24 = 113 \text{ FT}^2 = A_2$$

$$\text{INNER WALL} = 3.34 \times 24 = 80 \text{ FT}^2 = A_1$$

(ASSUME OUTER WALL IS THIN, SO THAT ITS OUTSIDE SURFACE AREA IS ALSO $\approx 113 \text{ FT}^2$)

RADIATION FACTORS:

ASSUME $\epsilon = 0.6$ ON ALL SURFACES.

FROM INNER WALL TO OUTER WALL:

$$F_{12} A_1 = \frac{A_1}{\frac{1}{\epsilon_1} + \frac{A_1}{A_2} \left(\frac{1}{\epsilon_2} - 1 \right)} = \frac{80}{1.67 + (0.71 \times 0.67)} = 0.47 \times 80 = 37.6 \text{ FT}^2$$

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HEAT DISSIPATION WITH BLOCKED AIR IN ANNULAR SPACE

(TO BE CONSERVATIVE, ASSUME THAT THE AIR DOES NOT CONDUCT ANY HEAT.)

FOR FREE CONVECTION FROM OUTSIDE OF CHIMNEY, USE $h = 0.22 (\Delta T/D)^{0.25}$,
WHERE $\Delta T = T_{WALL} - T_{AIR}$ ($^{\circ}F$), AND $D = \text{DIAM. (FT)}$.

SELECT VARIOUS OUTER WALL TEMPERATURES, AND FIND HEAT DISSIPATION FOR EACH.

①	$T_{WALL,2}$ $^{\circ}F$	300	400	450	500	550	600	580
②	T_{AIR} $^{\circ}F$	100	100	100	100	100	100	100
③	ΔT $^{\circ}F$	200	300	350	400	450	500	480
④	h BTU/FT ² HR- $^{\circ}F$	0.75	0.83	0.86	0.89	0.92	0.94	0.93
⑤	Q_{CONV} BTU/HR	17000	28000	34000	40300	46700	53000	50500
⑥	$E_{W2} = \sigma T_{W2}^4$	571	936	1173	1453	1780	2160	2002
⑦	$E_{AMB} = \sigma T_{AMB}^4$	168	168	168	168	168	168	168
⑧	$\Delta E = ⑥ - ⑦$	403	768	1005	1285	1612	1992	1834
⑨	$Q_{RAD} = 0.6 \times 113 \times ⑧$	27300	52000	69100	87200	109500	135000	124500
⑩	$Q_{TOT} = ⑤ + ⑨$	44300	80000	102100	127500	156200	188000	175000
⑪	Q_{TOT} KW	13.0	23.4	30.0	37.4	45.9	55.0	51.3
⑫	T_{W1} $^{\circ}F$				950		950	950
⑬	$E_{W1} = \sigma T_{W1}^4$				6765		6765	6765
⑭	$E_{W1} - E_{W2}$				5312		4605	4763
⑮	Q_{1-2} KW				58.6		50.7	52.4
⑯	COMPARE ⑮ WITH ⑪				HIGH		LOW	OK

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FIND TEMPERATURE OF INNER WALL FOR
30 KW HEAT DISSIPATION:

FROM TABLE ON PAGE 3, WE HAVE $T_{w2} = 450^{\circ}\text{F}$.

$$E_{w1} - E_{w2} = \frac{Q_{1-2}}{2 A_1} = \frac{3413 \times 30}{37.6} = 2725$$

[NOTE: $E(T) = 0.1714 \times 10^{-8} \times (T + 459.69)^4$ BTU/HR-FT²
TABLES OF E VS. T ARE AVAILABLE.]

$$E_{w1} = E_{w2} + 2725 = 1173 + 2725 = 3898$$

$$\text{THUS } T_{w1} = 770^{\circ}\text{F}$$

FIND HEAT DISSIPATION IF $T_{w1} = 950^{\circ}\text{F}$.

SEE ROWS (12) THROUGH (16) OF TABLE ON PAGE 3.

$$Q_{1-2} = 2 A_1 (E_{w1} - E_{w2}) / 3413 \text{ KW}$$

THE LAST COLUMN WAS ACCEPTED AS
BALANCED.

$$Q_{\text{RAD}} = 124,500 \text{ BTU/HR}$$

$$Q_{\text{CONV}} = 50,500$$

$$Q_{\text{TOTAL}} = 175,000 \text{ BTU/HR}$$

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HEAT DISSIPATION FROM BARE CASE

A. WITHOUT FINS:

$$\begin{aligned}
 \text{EMITTANCE} &= 0.60 \\
 \text{DIAMETER} &= 12.75 \text{ IN.} = 1.062 \text{ FT} \\
 \text{SURF. AREA} &= 80.0 \text{ FT}^2 \\
 \text{SURF. TEMP.} &= 550^\circ\text{F} & E(550) &= 1780 \text{ BTU/FT}^2\text{-HR} \\
 \text{AMB. TEMP.} &= 100^\circ\text{F} & E(100) &= 168 \text{ BTU/FT}^2\text{-HR} \\
 \Delta T &= 450^\circ\text{F} & \Delta E &= 1612 \text{ BTU/FT}^2\text{-HR} \\
 h_{\text{CONV}} &= 0.22 (\Delta T/D)^{0.25} = 0.99 \text{ BTU/FT}^2\text{-HR-}^\circ\text{F} \\
 Q_{\text{CONV}} &= 0.99 \times 80 \times 450 = 35900 \text{ BTU/HR} \\
 Q_{\text{RAD}} &= 0.60 \times 80 \times 1612 = 77500 \text{ BTU/HR} \\
 Q_{\text{TOTAL}} &= 113400 \text{ BTU/HR} \\
 &= 33.3 \text{ KW}
 \end{aligned}$$

B. WITH FINS WHICH DOUBLE SURFACE AREA:

USING 16 FINS OF RADIAL HEIGHT, Δr ,
 AND WITH THE BASIC PERIMETER, $p_b = 3.34 \text{ FT}$,
 $\Delta r = 3.34 / (16 \times 2) = 0.104 \text{ FT} = 1.25 \text{ IN.}$
 THE OVERALL DIAMETER IS THEN $12.75 + 2.50 = 15.25 \text{ IN.}$
 ASSUME RADIANT HEAT LOSS IS AS FROM A
 CYLINDER OF 15.25 IN. DIAM WITH $E = 0.6$,
 AND WITH MEAN SURFACE TEMP. = 500°F .

$$\begin{aligned}
 E(500) &= 1453 & \text{RADIATING AREA} &= \frac{\pi}{12} 15.25 \times 24 = 96 \text{ FT}^2 \\
 E(100) &= 168 \\
 \Delta E &= 1285 & Q_{\text{RAD}} &= 0.60 \times 96 \times 1285 = 83600 \text{ BTU/HR} \\
 Q_{\text{CONV}} &= 0.99 \times 160 \times (500 - 100) = 63600 \text{ BTU/HR} \\
 Q_{\text{TOTAL}} &= 147200 \text{ BTU/HR} \\
 &= 43.2 \text{ KW}
 \end{aligned}$$

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HEAT DISSIPATION FROM BARE CASK

(ADDENDUM)

A' . WITHOUT FINS : 950°F SURFACE

$$\begin{array}{ll}
 E(950) = 6765 \text{ BTU/FT}^2\text{-HR} & T_{\text{CASK}} = 950 \\
 E(100) = \underline{168} & T_{\text{AIR}} = \underline{100} \\
 \Delta E = 6597 & 850
 \end{array}$$

$$h_{\text{CONV}} = 0.22 \times (850/1.062)^{0.25} = 1.17 \text{ BTU/FT}^2\text{-HR-}^\circ\text{F}$$

$$Q_{\text{CONV}} = 1.17 \times 80 \times 850 = 79,500 \text{ BTU/HR}$$

$$Q_{\text{RAD}} = 0.60 \times 80 \times 6597 = \underline{316,000}$$

$$Q_{\text{TOTAL}} = 395,500 \text{ BTU/HR}$$

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HEAT DISSIPATION WITH AIR FLOWING IN THE ANNULAR SPACE

PROCEDURE :

1. ASSUME SEVERAL INLET FLOW VELOCITIES.
2. FIND REYNOLDS NUMBER, FRICTION FACTOR, AND CONVECTION COEFFICIENT FOR EACH VELOCITY.
3. CALCULATE APPROXIMATE PRESSURE DROP FOR EACH VELOCITY, IGNORING EFFECTS OF DENSITY CHANGES.
4. CALCULATE APPROXIMATE TEMPERATURE RISE IN AIR FOR EACH VELOCITY, FINDING APPROXIMATE PRESSURE HEAD AVAILABLE DUE TO BUOYANCY.
5. SELECT A VELOCITY FOR WHICH THE AVAILABLE PRESSURE EQUALS OR EXCEEDS THE REQUIRED PRESSURE, AND CALCULATE AIR TEMPERATURE AS A FUNCTION OF DISTANCE ALONG THE PASSAGE. USE A STEPWISE PROCEDURE, WORKING IN 3-FOOT SEGMENTS OVER THE 24-FOOT HEIGHT.
6. REFINE THE CALCULATIONS OF AVAILABLE AND REQUIRED PRESSURE DROPS, AND VERIFY THAT $\Delta P_{AVAIL} \geq \Delta P_{REQD}$ FOR THE SELECTED VELOCITY.

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PROPERTIES OF AIR AT 100°F:

$$C_p = 0.24 \text{ BTU/LB-}^\circ\text{F}$$

$$K = 0.0162 \text{ BTU/HR-FT-}^\circ\text{F}$$

$$\mu = 0.0467 \text{ LB/HR-FT}$$

$$\rho = 0.0710 \text{ LB/FT}^3$$

$$Pr = \mu C_p / K = 0.69 \quad (\text{PRANDTL NO.})$$

FRICTION FACTOR FOR TURBULENT FLOW IN
A SMOOTH TUBE:

$$4f = \frac{0.316}{Re^{0.25}} \quad 2300 \leq Re \leq 100,000$$

$$Re = \rho V D_h / \mu = G D_h / \mu \quad (\text{REYNOLDS NO.})$$

HEAT TRANSFER COEFFICIENT FOR TURBULENT
FLOW:

$$St = f / 2 (Pr)^{1/3} \quad (\text{STANTON NO.})$$

$$h = 3600 \rho V St \text{ BTU/HR-FT}^2\text{-}^\circ\text{F}$$

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$$\begin{aligned}
 \rho_{in} &= 0.071 \text{ LB/FT}^3 & L &= 50 \text{ FT} & A_x &= 0.884 \text{ FT}^2 \\
 \mu_{in} &= 0.0467 \text{ LB/HR-FT} & (Pr)^{1/3} &= 0.78 \\
 D_h &= 0.438 \text{ FT} & C_p &= 0.24 \text{ BTU/LB-}^\circ\text{F}
 \end{aligned}$$

①	Variable	Units	2.0	5.0	10.0	20.0		
②	$G = \rho_{in} \cdot V_{in}$	LB/FT ² SEC	0.142	0.355	0.710	1.420		
③	$Re = (G D_h / \mu) \times 3600$	-	4800	12000	24000	48000		
④	$4f = 0.316 / (Re)^{0.25}$	-	0.0380	0.0302	0.0254	0.0219		
⑤	$g_{in} = G \cdot V_{in} / 28.6$	LB/FT ²	0.0044	0.0276	0.1102	0.4408		
⑥	$(\Delta P)_{FRICT} = 4f (L/D) \cdot g_{in}$	LB/FT ²	0.019	0.095	0.320	1.080		
⑦	$(\Delta P)_{INLET/EXIT} = 2 \times ⑤$	LB/FT ²	0.009	0.055	0.220	0.882		
⑧	$(\Delta P)_{REQD} = ⑥ + ⑦$	LB/FT ²	0.028	0.150	0.540	1.962		
⑨	$St = ⑧ / (Pr)^{1/3} \times 8.0$		0.00610	0.00485	0.00408	0.00343		
⑩	$h = 3600 C_p G \cdot St$	BTU/HR-FT ²	0.75	1.49	2.50	4.21		
⑪	$\dot{m} = G \cdot A_x \times 3600$	LB/HR	452	1130	2260	4520		
⑫	$\dot{m} C_p = ⑪ \times C_p$	BTU/HR-°F	108	271	542	1084		
⑬	$(\Delta P)_{AVAL} \text{ (PAGE 10)}$	LB/FT ²			0.749			

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APPROXIMATE ANALYSIS

CONSIDER A HEAT EXCHANGER WITH A UNIFORM WALL TEMPERATURE. THEN:

$$\frac{T_{WALL} - T_{AIR\ EXIT}}{T_{WALL} - T_{AIR\ IN}} = e^{-\frac{L}{L^*}}$$

WHERE

$$L^* = \frac{\dot{m} c_p}{h p}$$

WHEN ONE WALL IS AT UNIFORM TEMPERATURE AND THE OTHER WALL IS HEATED INDIRECTLY BY RADIATION, THE FORMULA DOES NOT HOLD, BUT IT MAY BE USED AS AN APPROXIMATION.

USE

$$L^* = \frac{\dot{m} c_p}{h_1 p_1 + \left(\frac{1}{h_2 p_2} + \frac{1}{h_{12} p_1} \right)}$$

SUBSTITUTING VALUES FOR $V_{in} = 10$ FT/SEC:

$$h_1 = 2.50$$

$$h_2 = 2.50$$

$$p_1 = 3.34 \text{ FT}$$

$$p_2 = 4.72 \text{ FT}$$

$$h_{12} = \frac{E(T_1) - E(T_2)}{T_1 - T_2} \cdot \mathcal{F}_{12} = \frac{1780 - 736}{550 - 350} \cdot 0.47 = 2.46$$

(ASSUMING WALL TEMPS. OF 550 AND 350°F)

$$(h_2 p_2)^{-1} = 0.0848$$

$$h_1 p_1 = 8.35$$

$$(h_{12} p_1)^{-1} = \frac{0.1216}{0.2064}$$

$$(0.2064)^{-1} = 4.84$$

$$\Sigma(hp) = 13.19$$

$$\dot{m} c_p = 542$$

$$L^* = 542 / 13.19 = 41 \text{ FT}$$

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USING $L = 24$ FT AND $L^* = 41$ FT:

$$e^{-24/41} = 0.557$$

THUS

$$T_{WALL} - T_{AIR\,EXIT} = 0.557 \times (550 - 100) = 250$$

$$T_{AIR\,EXIT} = 550 - 250 = 300^\circ F$$

CALCULATION OF AVAILABLE PRESSURE HEAD:

THE FOLLOWING FORMULA CORRECTS FOR THE MEAN DENSITY IN A VERTICAL TUBE WITH THE GAS TEMPERATURE APPROACHING THE WALL TEMPERATURE ACCORDING TO AN EXPONENTIAL DECAY LAW:

$$\frac{\Delta P}{\rho_0 L} = 1 - \frac{T_0}{T_{WALL}} \left(1 + \frac{L^*}{L} \ln \frac{T_{exit}}{T_{in}} \right)$$

WHERE ρ_0 = DENSITY OF THE AMBIENT AIR (LB/FT³)

T_0 = TEMPERATURE OF AMBIENT AIR (°R)

SUBSTITUTING VALUES:

$$\begin{aligned} \frac{\Delta P}{0.071 \times 24} &= 1 - \frac{560}{1010} \left(1 + \frac{41}{24} \ln \frac{760}{560} \right) \\ &= 1 - 0.554 (1 + 0.525) = 1 - 0.845 = 0.155 \end{aligned}$$

$$\Delta P = 0.264 \text{ LB/FT}^2 \text{ OVER } 24 \text{ FT.}$$

IF CHIMNEY IS INSULATED OVER ITS UPPER 26 FT,

$$\begin{aligned} \Delta P &= 0.071 \times 26 \times \left(1 - \frac{560}{760} \right) \\ &= 0.485 \text{ LB/FT}^2 \end{aligned}$$

$$\text{OVERALL } \Delta P = 0.749 \text{ LB/FT}^2$$

SINCE $\Delta P_{REQ'D} = 0.540 \text{ LB/FT}^2$, THE ASSUMPTION OF $V_{in} = 10 \text{ FT/SEC}$ IS GOOD, WITH SOME MARGIN TO SPARE.

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IMPROVEMENT OF ANALYSIS BY USE OF STEPWISE CALCULATION

CONSIDER THE 24-FT HEATED LENGTH TO BE DIVIDED INTO 8 SEGMENTS OF 3 FT EACH. THE HEAT FLOW PATHS FOR EACH SEGMENT MAY BE REPRESENTED BY THE ANALOGOUS ELECTRICAL CIRCUIT SHOWN BELOW:

FOR EACH SEGMENT, $A_1 = 10 \text{ FT}^2$ AND $A_2 = 19.12 \text{ FT}^2$.

FOR $V_{in} = 10 \text{ FT/SEC}$, $h_1 = h_2 = 2.50 \text{ BTU/FT}^2 \text{ HR-}^\circ\text{F}$.
 (THE DEPENDENCE OF h UPON AIR TEMPERATURE IS NEGLECTED IN THESE PRELIMINARY CALCULATIONS. IT WILL BE INCLUDED IN THE FINAL DESIGN ANALYSIS.)

FOR RADIATION FROM WALL-1 TO WALL-2, THE $J_{12} A_1$ PARAMETER IS $0.47 \times 10 = 4.7 \text{ FT}^2$. THE EQUIVALENT LINEAR CONDUCTION PARAMETER (CALLED THE "ADMITTANCE") IS FOUND AS FOLLOWS:

$$h_{R1-2} A_1 = J_{12} A_1 \frac{E(T_{w1}) - E(T_{w2})}{T_{w1} - T_{w2}}$$

THE HEAT TRANSFER COEFFICIENT FOR FREE CONVECTION OUTSIDE WALL-2 IS FOUND BY:

$$h_c A_2 = 0.22 A_2 [(T_{w2} - 100)/D_2]^{0.25}$$

WHERE $D_2 = \text{DIAMETER OF OUTER WALL} = 1.5 \text{ FT}$.

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THE EQUIVALENT LINEAR ADMITTANCE FOR RADIATION FROM THE OUTER WALL IS FOUND BY:

$$h_r A_2 = 0.6 A_2 \frac{E(T_{w2}) - E(100)}{T_{w2} - 100}$$

THE AIR TEMPERATURE, T_A , SHOULD BE A SUITABLE MEAN VALUE BETWEEN THE TEMPERATURES OF THE AIR ENTERING AND THE AIR LEAVING THE SEGMENT. IN THE CALCULATIONS, THE EFFECT OF A MEAN VALUE IS ACHIEVED BY USE OF THE FOLLOWING CIRCUIT:

IN THE STEADY STATE, THIS CIRCUIT IMPLIES THE FOLLOWING HEAT BALANCE EQUATION:

$$\dot{m} c_p (T_{A,e} - T_{A,i}) = \beta h_1 A_1 (T_{w1} - T_{A,e}) + \beta h_2 A_2 (T_{w2} - T_{A,e})$$

IN THE PRESENT CASE, $\Delta L = 3$ FT AND $L^* = 41$ FT. THUS $\phi = 0.0732$ AND $\beta = 1.040$.

AS SHOWN ON PAGE 8, $\dot{m} c_p = 542$ BTU/HR-°F.

THE AIR INLET TEMPERATURE TO EACH SEGMENT IS SET EQUAL TO THE EXIT TEMPERATURE FROM THE PREVIOUS SEGMENT.

THE COMPLETE CIRCUIT FOR EIGHT SEGMENTS IS SHOWN ON THE NEXT PAGE.

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PREPARATION OF THERMAL NETWORK

CONNECTORS:

- 1-8: hA , WALL-1 TO AIR
- 11-18: $m\dot{C}_p$ OF AIR
- 21-28: hA , WALL-2 TO AIR
- 31-38: RADIATION, WALL-1 TO WALL-2
- 41-48: RADIATION, WALL-2 TO ROOM
- 51-58: CONVECTION, WALL-2 TO AMBIENT AIR

(AXIAL CONDUCTION IS OF NEGLIGIBLE ORDER OF MAGNITUDE COMPARED WITH RADIAL HEAT FLOW.)

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THE WALL TEMPERATURES AND AIR TEMPERATURES FOR STEADY-STATE HEAT FLOW WERE FOUND BY AN ITERATIVE METHOD OF BALANCING THE HEAT FLOWS. THIS WAS DONE BY HAND CALCULATION IN THIS FIRST CASE, AND BY USE OF A DIGITAL COMPUTER IN LATER CASES. THE HAND-CALCULATED RESULTS ARE GIVEN ON PAGE 15.

THE MEAN VALUE OF $p_A/p_o = 0.85$. THUS THE AVAILABLE PRESSURE HEAD FROM BUOYANCY IS:

$$\begin{aligned}
 0.071 \times 24 \times (1-0.85) &= 0.256 \text{ LB/FT}^2 \\
 0.071 \times 26 \times (1-0.75) &= 0.462 \text{ LB/FT}^2 \\
 \text{TOTAL} &= 0.718 \text{ LB/FT}^2
 \end{aligned}$$

THE HEAT DISSIPATION IS AS FOLLOWS:

$$\begin{aligned}
 Q_{\text{TOTAL}} &= 129,200 \text{ BTU/HR (38.0 KW)} \\
 Q_{\text{RAD.}} &= 19,050 \text{ BTU/HR (5.6 KW)} \\
 Q_{\text{CONV}} &= 110,150 \text{ BTU/HR (32.4 KW)}
 \end{aligned}$$

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CASK DIAMETER = 12.75 IN.
 CHIMNEY DIAMETER = 18.00 IN.
 CASK WALL TEMP. = 550°F

STATION	Z (FT)	T _{AIR} °F	T _{WALL-Z} °F	$\dot{Q}_{WI-A}$ BTU/HR	$\dot{Q}_{W2-A}$ BTU/HR	$\dot{Q}_{W2-OUT}$ (RAD) BTU/HR	$\dot{Q}_{W2-OUT}$ (CONV.) BTU/HR	$P_A/P_0 =$ (T_0/T_A)
0	0	100.0	206					1.00
				12400	3900	1750	1000	
1	3	130.2	226					0.95
				11600	3700	2000	1200	
2	6	158.4	238					0.90
				10800	3100	2200	1350	
3	9	184.2	250					0.87
				10100	2600	2350	1500	
4	12	207.8	261					0.84
				9400	2000	2500	1600	
5	15	228.9	270					0.81
				8800	1600	2650	1700	
6	18	248.2	278					0.79
				8300	1200	2750	1800	
7	21	265.6	285					0.77
				7800	800	2850	1900	
8	24	281.2	291					0.75
TOTALS				79200	18900	19050	12050	
				98100		31100		
				129200				
				(38 kw)				

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PARAMETRIC SURVEY OF AIR COOLING OF CASKS
HAVING VARIOUS DIAMETERS

THE ANALYSIS WAS EXTENDED TO INCLUDE CASK DIAMETERS (D_1) OF 9.00 IN. IN ADDITION TO THE 12.75 IN. DIAMETER USED IN THE PRELIMINARY ANALYSIS.

THE INNER DIAMETER (D_2) OF THE CHIMNEY DUCT WAS VARIED FOR EACH VALUE OF D_1 , SO THAT THE HYDRAULIC DIAMETERS, $D_h = D_2 - D_1$, WERE 2.0, 3.0, AND 4.0 IN.

FOR EACH COMBINATION OF D_1 AND D_h , THE AIR FLOW RATE WAS VARIED OVER A WIDE RANGE OF VALUES. THE RESULTS THUS COULD BE USED FOR ESTABLISHING BLOWER REQUIREMENTS AS WELL AS FOR PREDICTING NATURAL CIRCULATION RATES.

AN AIR INLET TEMPERATURE OF 100°F WAS USED FOR MOST OF THE CALCULATIONS, WITH 250°F USED FOR A FEW CASES. ALTHOUGH THE COOLING GAS WAS ASSUMED TO BE AIR, THE RESULTS WOULD BE NEARLY THE SAME IF PURE NITROGEN WERE USED. IF IT IS DECIDED THAT THE HOT CELL IS TO BE NITROGEN FILLED, SUITABLE CORRECTIONS TO THE PERFORMANCE PREDICTIONS WILL BE MADE LATER.

THE THERMAL NETWORK SHOWN ON PAGE 13 WAS USED IN THIS SURVEY, EXCEPT THAT THE OUTER SURFACE OF WALL-2 WAS ASSUMED TO BE PERFECTLY INSULATED. PARAMETERS DESCRIBING THIS NETWORK WERE INPUT TO A DIGITAL COMPUTER, USING THE TAP-9 THERMAL ANALYZER PROGRAM,

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CASK WALL TEMPERATURES OF 550°F AND 950°F WERE USED. THE LOWER VALUE CORRESPONDS TO THE NORMAL OPERATING CONDITION FOR FUEL HANDLING, AND IS SUPPOSED TO CORRESPOND WITH A 1200°F MAXIMUM FUEL PIN TEMPERATURE.

THE 950°F IS SUPPOSED TO CORRESPOND WITH A 1600°F MAXIMUM FUEL PIN TEMPERATURE, WHICH IS CONSIDERED TO BE A LIMITING TEMPERATURE FOR EMERGENCY CONDITIONS, SUCH AS BLOWER FAILURE.

THE SCHEDULE OF COMPUTER RUNS MADE IS SHOWN ON PAGES 18 AND 19, WITH THE CALCULATED HEAT REMOVAL RATES AND PRESSURE DROPS. (THE PRESSURE DROPS ARE FOR THE 50 FT ANNULAR PASSAGE ONLY. INLET AND EXIT LOSSES ARE NOT INCLUDED.)

ANALYSIS OF RESULTS

FIGURE 1 SHOWS THE VARIATION OF AIR TEMPERATURE WITH DISTANCE ALONG THE PASSAGE FOR CASES 1, 2, AND 3. THE STRAIGHTNESS OF THE GRAPHS ON SEMI-LOG PAPER JUSTIFIES THE USE OF THE EXPONENTIAL RELATIONSHIP GIVEN ON PAGE 9, EVEN THOUGH THE HEAT FLOW SYSTEM CONTAINS NON-LINEAR (RADIATION) ELEMENTS. THE VALUES OF L^* TURNED OUT TO BE HIGHER THAN PREDICTED, HOWEVER, THE REVISED VALUES WERE USED IN THE CALCULATION OF PRESSURE DROP AND BUOYANCY HEAD.

N 152-B-2

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CASE NO.	D_i IN.	D_h IN.	T_{WALL-1} °F	V_{in} FT/SEC	$\dot{m}$ LB/HR	T_{in} °F	T_{exit} °F	Q KW	ΔP_{LOSS} LB/FT ²
1	9.00	2.00	950	2	112	100	943	6.6	0.17
2				5	280		923	16.2	0.80
3				10	560		888	30.9	2.59
4	9.00	3.00		2	176		900	9.9	0.10
5				5	440		840	22.9	0.47
6				10	880		772	41.6	1.52
7	9.00	4.00		2	246		815	12.4	0.06
8				5	615		736	27.6	0.31
9				10	1230		664	48.7	1.02
10				20	2460		575	82.1	3.24
21	12.75	2.00	950	2	153	100	944	9.1	↑
22				5	383		924	22.2	
23				10	765		890	42.5	10
24	12.75	3.00		2	238		900	13.4	↓
25				5	595		843	31.2	↑
26				10	1190		777	56.8	↑
27	12.75	4.00		2	329		816	16.6	↑
28				5	823		741	37.1	↑
29				10	1645		671	66.0	↑
30				20	3290		586	112.5	3.26
21A	12.75	2.00	550	2	153	100	595	4.8	0.12
22A				5	383		528	11.6	0.57
23A				10	765		503	21.7	1.82
24A		3.00		2	238		516	7.0	0.07
25A				5	595		474	15.7	0.33
26A				10	1190		431	27.8	1.06
27A		4.00		2	329		466	8.5	0.05
28A				5	823		414	18.2	0.22
29A				10	1645		370	31.2	0.71
30A				20	3290		325	52.1	2.31

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FIGURE 2 SHOWS THE PRESSURE DROPS DUE TO WALL FRICTION AND ACCELERATION OF AIR WITHIN THE 50 FT PASSAGES. THE PRESSURE DROPS FOR CASKS OF 9.00 AND 12.75 IN. DIAMETER WERE FOUND TO BE THE SAME FOR COMPARATIVE HYDRAULIC DIAMETERS AND AIR INLET VELOCITIES.

THE PRESSURE HEADS DUE TO BUOYANCY OF THE HEATED AIR IN THE PASSAGES WERE FOUND TO BE ABOUT 1.5 TO 2.0 LB/FT², CORRESPONDING TO INLET VELOCITIES OF 8 TO 12 FT/SEC.

FIGURE 3 SHOWS THE HEAT REMOVAL RATES FROM CASKS OF 9.00 IN. DIAMETER AND 950°F WALL TEMPERATURE. IT MAY BE SEEN THAT 30 KW MAY BE REMOVED BY NATURAL CONVECTION WITH A DIAMETRICAL GAP OF 2.5 OR MORE INCHES. IF THE CASK DIAMETER IS 12.75 IN, THE CROSS-SECTIONAL AREA OF THE PASSAGE IS ABOUT 35 PERCENT LARGER, AND THE HEAT REMOVAL CAPABILITY INCREASES BY THE SAME PERCENTAGE

FIGURE 4 SHOWS PRESSURE DROPS AND FIGURE 5 SHOWS HEAT REMOVAL CAPABILITIES FOR A CASK OF 12.75 IN. DIAMETER WITH A 550°F WALL. AN AIR INLET TEMPERATURE OF 100°F WAS ASSUMED FOR MOST OF THE POINTS PLOTTED, BUT 4 CASES WERE RUN FOR 250°F INLET AIR. THIS WAS DONE BECAUSE IT WAS FEARED THAT THE SODIUM INSIDE THE CASK MIGHT SOLIDIFY AT THE LOWER END IF THE AIR WAS TOO COLD. THE HEAT-REMOVAL CAPABILITIES ARE NEARLY HALVED WITH 250°F AIR.

Fig. 5: Heat Removal Rates From Cask With Various Flow Rates and Various Diametral Gaps Between Cask and Shield.

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BLOWER REQUIREMENTS FOR REMOVING
 30 TO 40 KW OF HEAT WITH A CASK
 WALL TEMPERATURE OF 550°F ARE
 SHOWN IN FIGURE 6. IT MAY BE SEEN
 THAT A BLOWER OF A VERY MODEST SIZE,
 SUCH AS 500 CFM WITH A 2 IN. H₂O
 PRESSURE RISE, WILL SUFFICE WITH
 AMPLE CAPACITY TO SPARE.

N 183-R-2

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EFFECT OF CASK WALL TEMPERATURE ON
HEAT REMOVAL RATE

THREE CONFIGURATIONS WERE STUDIED TO DETERMINE THE HEAT REMOVAL RATES AS FUNCTIONS OF CASK WALL TEMPERATURE, AIR FLOW RATE, AND AIR INLET TEMPERATURE.

ONE OF THE CONFIGURATIONS INCLUDED AN ADDITIONAL TUBE BETWEEN THE CASK AND THE COOLING AIR, WITH HELIUM IN THE GAP BETWEEN THE CASK AND THE TUBE.

A THERMAL MODEL WAS DEvised AS SHOWN ON PAGE 29. THE HEIGHT OF THE AIR-COOLED PORTION OF THE FUEL-HANDLING MACHINE WAS CONSIDERED TO BE DIVIDED INTO 10 REGIONS, THE LOWER REGIONS, EACH OF 3-FT LENGTH, REPRESENTED THE SODIUM-FILLED PORTION OF THE CASK, WITH A UNIFORM CASK WALL TEMPERATURE. THE UPPER REGIONS, EACH OF 6 OR 7 FT LENGTH, WERE INCLUDED SO THAT HEAT LOSSES FROM THE AIR COLUMN COULD BE COMPUTED.

AND LENGTHS
DIAMETERS¹ USED FOR THE 3 CONFIGURATIONS ARE TABULATED BELOW:

CONFIGURATION	I	II	III
CASK O.D. (IN.)	12.25	11.25	12.25
SEAL TUBE I.D.	-	-	13.25
SEAL TUBE O.D.	-	-	14.25
AIR JACKET I.D.	15.25	14.25	17.25
AIR JACKET O.D.	16.00	15.00	18.00
EXT. WALL I.D.	20.00	19.00	22.00
EXT. WALL O.D.	21.50	20.50	23.50
HEATED WALL LENGTH(FT)	21	21	24
UNHEATED WALL LENGTH(FT)	18	18	14

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CONTINUE FOR 10 REGIONS

THERMAL NETWORK FOR HELIUM-GAP CASES
 (ALSO USED FOR NO-HELIUM CASES BY
 DROPPING NODES AND CHANGING DIMENSIONS)

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THE SPACE BETWEEN THE AIR JACKET AND THE EXTERNAL WALL WAS CONSIDERED TO BE FILLED WITH THERMOBESTOS INSULATION, WHICH HAS A THERMAL CONDUCTIVITY OF 0.090 BTU/HR-FT-°F AT THE EXPECTED OPERATING TEMPERATURE OF ABOUT 400 °F.

HEAT IS TRANSFERRED ACROSS THE HELIUM-FILLED GAP BY CONDUCTION AND BY RADIATION. THE THERMAL CONDUCTIVITY WAS ASSUMED TO BE CONSTANT AT 0.14 BTU/FT-HR-°F. THE THERMAL EMITTANCE OF THE CASK OUTER SURFACE AND OF THE SEAL TUBE INNER SURFACE WERE ASSUMED TO BE 0.6 .

THE THERMAL ANALYZER PROGRAM WAS SET UP SO THAT ANY OF THE THREE CONFIGURATIONS COULD BE COMPUTED WITH A MINIMUM OF SET-UP TIME SIMPLY BY SPECIFYING THE VARIOUS DIAMETERS, REGION LENGTHS, CASK TEMPERATURE, AIR INLET TEMPERATURE, AND AIR FLOW RATE.

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THE RESULTS OF THIS SERIES OF COMPUTER RUNS ARE SHOWN IN FIGURES 7 THROUGH 10. FIGURES 7 AND 8 SHOW THE EFFECTS OF VARYING INLET AIR TEMPERATURE AND AIR FLOW RATE FOR THE THREE CONFIGURATIONS, ALL WITH A CONSTANT CASK WALL TEMPERATURE OF 550°F. (WITH A 30 KW THERMAL DECAY HEAT RATE, THIS CORRESPONDS TO A 1200°F MAXIMUM FUEL PIN CLADDING TEMPERATURE.)

THE USE OF 250°F INLET AIR HAD BEEN PROPOSED TO ENSURE THAT THE SODIUM IN THE LOWER END OF THE CASK WOULD NOT FREEZE. (LATER STUDIES SHOWED THAT NATURAL CIRCULATION WITHIN THE SODIUM WOULD DISTRIBUTE THE HEAT SO WELL THAT FREEZING WOULD NOT OCCUR.)

TABULATED BELOW ARE THE AIR FLOW RATES AND PRESSURES REQUIRED FOR REMOVAL OF 30 KW OF HEAT WITH A 550°F CASK TEMPERATURE:

CONFIGURATION	I	I	II	III	III
AIR INLET TEMP (°F)	100	250	250	100	250
AIR FLOW RATE (LB/HR)	1500	2900	2500	3000	10000
PRESSURE DROP (LB/FT ²)	1.8	4.6	6.0	4.3	30.0

NONE OF THESE FLOWS IS UNREASONABLY HIGH, BUT THERE WOULD BE A SIGNIFICANT LARGER BLOWER REQUIRED IF THE HELIUM-GAP CONFIGURATION III WERE USED WITH 250°F INLET AIR. (THE PRESSURE DROPS ARE ONLY FOR THE INTERNAL SYSTEM, INCLUDING INLET AND EXIT LOSSES, BUT NOT INCLUDING EXTERNAL DUCTS, VALVES, AND HEAT EXCHANGERS.)

Figure 10. Heat Removal Capability of Forced and Natural Convection of 100° F Air Surrounding a Seal Tube that is Separated From A Cask by a 0.5 in. Helium Gap.

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FIGURES 9 AND 10 SHOW THE HEAT REMOVAL RATES FOR CONFIGURATIONS I AND III AS FUNCTIONS OF AIR FLOW RATE AND CASK WALL TEMPERATURE. OPERATING POINTS FOR NATURAL CONVECTION OF AIR ARE SHOWN. THESE ARE BASED ON BALANCES OF THE PRESSURE HEADS AVAILABLE DUE TO BUOYANCY OF AIR IN THE SYSTEM AND THE PRESSURE DROPS THROUGH THE SYSTEM, INCLUDING MINIMUM-LENGTH INLET AND EXIT DUCTS WITH OPEN BUTTERFLY VALVES.

IT MAY BE SEEN THAT NATURAL CONVECTION IS ADEQUATE FOR REMOVAL OF 30 KW OF HEAT WITH A CASK WALL TEMPERATURE NOT EXCEEDING 750°F FOR BOTH CONFIGURATION I (NO HELIUM GAP) AND CONFIGURATION III (0.5 IN. HELIUM GAP).

THE RELATIONSHIP BETWEEN CASK WALL TEMPERATURE AND MAXIMUM FUEL PIN CLADDING TEMPERATURE HAD NOT BEEN DETERMINED AT THE TIME THAT THESE CALCULATIONS WERE MADE, OTHER THAN FOR ONE HYPOTHETICAL CASE OF STAGNANT SODIUM INSIDE THE FUEL ELEMENT. IF AXIAL CONDUCTION WITHIN THE ELEMENT WAS NEGLECTED, IT WAS FOUND THAT THE TEMPERATURE DIFFERENCE BETWEEN THE CENTRAL PIN CLADDING AND THE HEXAGONAL SHELL AROUND THE ELEMENT WAS 650°F FOR A THERMAL GENERATION RATE OF 30 KW. CIRCULATION OF SODIUM WITHIN THE CASK WAS EXPECTED TO DISTRIBUTE THIS HEAT OVER THE LENGTH OF THE CASK. THIS ASSUMPTION WAS EXAMINED IN THE NEXT PHASE OF THE ANALYSIS.

DATA SHEET

REC'D

[illegible]

D111 D220 D222 D226 D214 D215

FORM 40 Z REV 12-62

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FORM 40 Z REV 12 62

PRESSURE LOSSES:

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$$L_1 = 21$$
$$D_h = 0.25$$

T_w	CASE NO.	$g, \frac{lb}{FT^2}$	$4f \frac{L}{D_h}$	$T_w - T_i$	$T_w - T_e$	(L/L^*)	$T_e - T_i$	$\frac{T_e - T_i}{L/L^*}$	$T_w - ()$ °R
550	1.01	0.0218	3.37	300	74	1.400	226	161	849
	1.02	0.0872	2.84		97	1.130	203	180	830
	1.03	0.3488	2.40		122	0.900	178	198	812
	1.04	1.3952	2.01		148	0.705	152	216	794
950	1.05	0.0276	2.92	850	188	1.508	661	440	970
	1.06	6.1105	2.45		253	1.212	597	492	918
	1.07	0.4420	2.06		331	0.940	519	551	859
	1.08	1.7680	1.73		416	0.712	434	610	800
550	2.01	0.0218	3.37	300	75	1.388	225	160	850
		0.0872	2.84		98	1.120	202	180	830
		0.3488	2.40		123	0.893	177	198	812
		1.3952	2.01		149	0.700	151	216	794
950	2.05	0.0276	2.92	850	189	1.503	661	440	970
					254	1.207	596	494	916
					333	0.935	517	554	856
					418	0.710	432	608	802
750	1.09	0.0276		650	160	1.400	490	350	860
					214	1.112	436	391	819
					276	0.859	374	435	775
					337	0.658	313	476	734
550	1.13	0.0276		450	127	1.263	323	256	754
					166	1.000	284	284	726
					207	0.775	243	314	696
					245	0.609	205	337	683
350	1.17	0.0276		250	82	1.115	168	151	659
					103	0.885	147	166	644
					123	0.706	127	180	630
					141	0.570	109	191	619

FORM 40-Z REV 12-62

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42018

[illegible]

CASE NO.	$AP_{MN} = \frac{AP_{MN}}{2(g_c - g_c)}$	AP_{TOTAL}						
	0.011	0.239						
	0.044	0.800						
	0.162	2.790						
	0.580	9.710						
	0.058	0.428						
	0.223	1.474						
	0.796	4.978						
	2.704	16.577						
	0.011	0.239						
	0.044	0.800						
	0.160	2.787						
	0.574	9.691						
	0.058	0.428						
	0.221	1.468						
	0.794	4.960						
	2.674	16.527						
	0.043	0.370						
	0.161	1.267						
	0.574	4.307						
	1.944	14.412						
	0.028	0.314						
	0.106	1.077						
	0.372	3.694						
	1.264	12.712						
	0.014	0.261						
	0.055	0.907						
	0.194	3.161						
	0.674	11.047						

FORM 40-2 REV 12-62

2-21-68

FORM 40 Z REV 12 62

RUNS WITH
 NODES $8 \times 3' = 24'$ } 38'
 $2 \times 7' = 14'$ }

RUNS WITH NO GAP

2-27-68

$$T_{\infty} = 520^{\circ}R$$

AVAIL.

T _W	CASE	T _{in} °F	T _{e1} °F	T _{e2} °F	$\frac{\Delta P_1}{\rho_1}$ ft. GRAIN	ΔP_1 LB/FT ²	$1 - \frac{T_{e2}}{T_{e1}}$ °R/°R	ΔP_2 LB/FT ²	ΔP_{T1} LB/FT ²	
550	3.01	250.0	432.1	404.2						
			389.6	376.7						
			349.0	343.3						
			314.6	312.1						
950	3.05	100.0	723.1	669.7	0.378	0.645	0.505	0.505	1.150	
			596.2	573.9	0.315	0.534	0.458	→	0.994	
			458.6	450.3	0.245	0.418	0.385	→	0.803	
			335.7	332.9	0.172					
750	3.09	100.0	543.5	507.1	0.310	0.527	0.421		0.948	
			442.6	427.5	0.247	0.420	0.370		0.790	
			342.6	337.1	0.185	0.314	0.298		0.612	
			257.7	255.9	0.125					
550	3.13	100.0	382.5	359.5	0.215	0.366	0.318		0.684	
			313.9	304.6	0.170	0.289	0.269		0.558	
			250.0	246.6	0.120	0.204	0.208		0.412	
	3.16		196.8	195.7	0.080					
550	3.09A	250.0	288.4	287.5						
	3.09B	250.0	276.9	271.9						
350	3.17	100.0	244.4	232.5	0.128	0.218	0.194		0.412	
	3.18		208.4	203.7	0.095	0.162	0.156		0.318	
	3.19		175.7	174.0	0.070	0.119	0.116		0.235	
	3.20		148.7	148.1	0.050					
	3.21		128.7	128.6	0.025					
	3.22		-	-						

FORM 40 Z REV 12 62

AI-AEC-MEMO-12661

RUNS WITH HELIUM GAP
 $L_1 = 24$
 $L_2 = 14$

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FORM 40-Z REV 12-62

DATA SHEET

[illegible]

FORM 40-2 REV. 12-62

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EFFECTS OF SODIUM CIRCULATION WITHIN THE CASK

IT HAS BEEN ASSUMED IN THE ANALYSIS UP TO THIS POINT THAT THE CIRCULATION OF SODIUM DUE TO NATURAL CONVECTION WITHIN THE CASK WILL DISTRIBUTE THE DECAY HEAT UNIFORMLY OVER THE SODIUM-FILLED PORTION OF THE CASK. THE VALIDITY OF THIS ASSUMPTION HAS BEEN ESTABLISHED BY A SERIES OF CALCULATIONS WHICH WILL NOW BE DESCRIBED.

~~A THERMAL MODEL WAS DEVISED TO REPRESENT THE SODIUM INSIDE THE ELEMENT, THE DUCT SURROUNDING THE ELEMENT, THE SODIUM BETWEEN THE DUCT AND THE CASK, AND THE VARIOUS DUCTS AND GAS SPACES OUTSIDE THE CASK.~~

A THERMAL MODEL (FIG. 11) WAS DEVISED TO REPRESENT THE SODIUM SURROUNDING THE FUEL PINS, THE DUCT WHICH FORMS THE FUEL ELEMENT SUBASSEMBLY, THE SODIUM BETWEEN THE DUCT AND THE CASK, AND THE VARIOUS DUCTS AND GAS SPACES USED IN THE PREVIOUS MODELS.

ALTHOUGH SODIUM WILL ACTUALLY FLOW UPWARD THROUGH THE FUEL ELEMENT BY NATURAL CONVECTION, IT WAS DECIDED THAT THE MORE STRINGENT SITUATION OF ASSUMING THIS INTERNAL CIRCULATION TO BE BLOCKED WOULD BE ANALYZED FIRST. THUS, IN THE SITUATION ANALYZED, THE SODIUM WAS ASSUMED TO CIRCULATE ONLY IN THE SPACE BETWEEN THE FUEL ELEMENT AND THE CASK.

Figure II-11. Thermal Model of Fuel Element Inside Sodium-Filled Cask

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THE PATTERN OF FLOW IN THE SODIUM IS LARGELY INFLUENCED BY THE PRESENCE OF THE SPLIT GUIDE TUBE WHICH SURROUNDS THE FUEL ELEMENT. AS A FIRST CASE, IT WAS POSTULATED THAT THE SODIUM RISES IN THE REGION INSIDE THE GUIDE TUBE AND FALLS IN THE REGION BETWEEN THE GUIDE TUBE AND THE CASK, WITH NEGLIGIBLE LEAKAGE THROUGH THE SPLIT. THE TRANSFER OF HEAT THROUGH THE GUIDE TUBE WAS, OF COURSE, CONSIDERED. THIS HEAT LEAKAGE HAS A SIGNIFICANT EFFECT IN REDUCING THE TEMPERATURE DIFFERENCE BETWEEN THE TWO SODIUM STREAMS, HENCE REDUCING THE CIRCULATION RATE.

THE FUEL PINS WERE NOT SPECIFICALLY REPRESENTED IN THE MODEL. INSTEAD, IT WAS ASSUMED THAT THE HEAT GENERATED WITHIN A PIN WAS TRANSFERRED TO THE SODIUM WITH NEGLIGIBLE TEMPERATURE DROP BETWEEN THE CLADDING AND THE SODIUM. (THE TEMPERATURE IN THE FUEL ITSELF WAS NOT CALCULATED.) SODIUM COLUMN NO. 1 WAS ASSUMED TO RECEIVE ALL THE HEAT FROM THE CENTRAL PIN AND HALF THE HEAT FROM THE SURROUNDING 6 PINS. COLUMN NO. 2 RECEIVED THE OTHER HALF OF THE HEAT FROM 6 PINS AND HALF THE HEAT FROM THE NEXT RING OF 12 PINS, ETC., OUT TO THE NINTH COLUMN.

NUCLEAR CALCULATIONS SHOWED THAT THE HEAT WAS NOT GENERATED UNIFORMLY IN ALL PINS, BECAUSE OF THE ESCAPE OF GAMMAS FROM THE FUEL PIN ASSEMBLY. THE RELATIVE HEAT GENERATION IN

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EACH RING OF PINS IS SHOWN IN THE TABLE BELOW:

RING	RELATIVE Q_{GEN}
1	0.975
2	0.973
3	0.967
4	0.956
5	0.938
6	0.911
7	0.867
8	0.795
9	0.692
WEIGHTED MEAN	0.845

THE RELATIVE Q_{GEN} VALUES ARE REFERENCED TO THE HEAT THAT WOULD BE GENERATED IF NO GAMMAS ESCAPED. THUS 15.5 PERCENT OF THE GAMMA ENERGY ESCAPES FROM THE ELEMENT. A SMALL FRACTION OF THIS ENERGY IS DEPOSITED IN THE STEEL DUCTS, BUT THIS WAS NEGLECTED IN THE ANALYSIS. THE RESULTS ARE REPORTED ON THE BASIS OF THE ACTUAL THERMAL ENERGY DEPOSITED IN THE FUEL.

SEE NEXT PAGE

→ INSERT

RADIAL CONDUCTION OF HEAT BETWEEN SODIUM CHANNELS WAS CALCULATED BY THE USE OF COEFFICIENTS DETERMINED BY FLUX PLOTTING HEAT FLOW PATHS IN THE GAPS BETWEEN FUEL PINS. THE PINS THEMSELVES WERE TREATED AS NON-CONDUCTORS. A PRELIMINARY CALCULATION WITH RADIAL HEAT FLOW ONLY SHOWED THAT THE CENTRAL FUEL PIN CLADDING WOULD BE 650°F HOTTER THAN THE HEXAGONAL OUTER DUCT IF THE

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DECAY HEAT RATE WERE 30 KW.

(INSERT BACK ON PAGE 39)

THE AXIAL DISTRIBUTION OF HEAT GENERATION OVER THE 3-FT ACTIVE CORE HEIGHT WAS CALCULATED TO BE 40 PERCENT IN THE MIDDLE THIRD AND 30 PERCENT IN EACH OF THE END THIRDS. (NODE LENGTHS OF 1 FT WERE USED IN THE THERMAL MODEL OVER THE FUEL-FILLED REGION.)

THE CIRCULATION RATE OF THE SODIUM WAS CALCULATED WITHIN THE COMPUTER CODE BY INTEGRATION OF THE DENSITY OF THE SODIUM OVER THE HEIGHTS OF THE RISING FLOW AND THE FALLING FLOW. THIS GAVE A STATIC HEAD WHICH WAS COMPARED WITH THE FRICTIONAL LOSS OF PRESSURE IN THE PASSAGE, AND THE FLOW RATE WAS ADJUSTED AS REQUIRED FOR A BALANCE. A TYPICAL SODIUM VELOCITY WAS ABOUT 0.3 FT/SEC. COMPUTER RUNS WERE MADE FOR THE SYSTEMS WITH AND WITHOUT THE HELIUM GAP AND SEAL TUBE. AIR FLOW RATES WERE USED CORRESPONDING TO THE CASES OF NATURAL CONVECTION AND TO FORCED CONVECTION WITH AN INLET VELOCITY OF 40 FT/SEC. HEATING RATES OF 30 KW, 15 KW, AND 7.5 KW WERE USED.

FIGURE 12 SHOWS THE TYPICAL RESULTS OF ONE OF THESE COMPUTATIONS. THE FLATTENING OF THE TEMPERATURE PROFILE IS QUITE APPARANT. THE CASK TEMPERATURE VARIES BY LESS THAN 100 °F.

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DATA FROM FIGURES 9 AND 10 WERE CROSS-
 PLOTTED ON FIGURES 13 AND 14, ALONG WITH
 DATA FROM THE COMPUTATIONS OF THE
 SODIUM-CIRCULATION MODEL. THE AGREEMENT
 BETWEEN THE TWO SETS OF DATA IS VERY
 GOOD.

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Figure 12. Longitudinal Temperature Distributions in Fuel Handling Machine for Configuration Having Helium-Filled Seal Tube. Decay Heat Rate = 30 kw, Air Flow Rate = 1055 lb/hr (Natural Convection).

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CASES, 3, 10
AND 7...

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PRESSURE HEAD DUE TO BUOYANCY OF AIR
IN A VERTICAL HEAT EXCHANGER

$$\Delta P = \rho_0 L - \int_0^L \rho dx \quad (1)$$

$$\frac{\rho}{\rho_0} = \frac{T_0}{T} \quad (2)$$

ρ_0 = DENSITY OF AMBIENT AIR

ρ = DENSITY OF AIR IN DUCT

IF THE DUCT WALL TEMPERATURE IS UNIFORM,
 THE AIR TEMPERATURE INSIDE THE DUCT
 VARIES ACCORDING TO THE EQUATION:

$$\frac{T_w - T}{T_w - T_i} = e^{-x/L^*} \quad (3)$$

WHERE L^* IS A CHARACTERISTIC LENGTH
 DETERMINED AS FOLLOWS:

$$L^* = \dot{m} c_p / h p \quad (4)$$

THE MASS FLOW RATE OF AIR IS $\dot{m}$, AND
 c_p IS THE SPECIFIC HEAT CAPACITY OF AIR.
 THE CONVECTION COEFFICIENT IS h AND p
 IS THE PERIMETER OF THE DUCT,

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EQUATIONS (1) AND (2) MAY BE COMBINED:

$$\frac{\Delta P}{P_0 L} = 1 - \frac{L^*}{L} \int_0^{L^*/L} \frac{T_0}{T} d\left(\frac{x}{L^*}\right) \quad (5)$$

COMBINING (3) WITH (5) GIVES:

$$\frac{\Delta P}{P_0 L} = 1 - \frac{L^*}{L} \frac{T_0}{T_w} \int_0^{L^*/L} \frac{d(x/L^*)}{1 - \frac{T_w - T_i}{T_w} e^{-x/L^*}} \quad (6)$$

THE INTEGRAL IS OF THE FORM:

$$I = \int \frac{du}{p + q e^{mu}} = \frac{u}{p} - \frac{\ln(p + q e^{mu})}{mq} \quad (7)$$

THUS

$$\frac{\Delta P}{P_0 L} = 1 - \frac{L^*}{L} \frac{T_0}{T_w} \left[\frac{L}{L^*} + \frac{\ln\left(1 - \frac{T_w - T_i}{T_w} e^{-L^*/L}\right)}{\ln\left(1 - \frac{T_w - T_i}{T_w}\right)} \right]$$

OR

$$\frac{\Delta P}{P_0 L} = 1 - \frac{T_0}{T_w} \left[1 + \frac{L^*}{L} \ln\left(\frac{T_e}{T_i}\right) \right] \quad (8)$$

WHERE

$$T_e = T_w - (T_w - T_i) e^{-L^*/L} \quad (9)$$

$$T_i = T_o = 560^{\circ}R$$

ΔP DUE TO
BUOYANCY

DATA SHEET

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	T_{wall} (°F)	$T_w - T_i$ °R	T_c °R	$T_w - T_c$	$\frac{L}{L^*} = \ln \frac{(2)}{(4)}$	$\ln \frac{T_c}{T_i}$	$1 + \frac{(6)}{(5)}$	$\frac{T_o}{T_w} \times (7)$	$1 - (8)$
RDE 1-24-68	1410	850	560	850	0	0		1.000	0
	950		660	750	0.125	0.165	2.322	0.924	0.076
			760	650	0.269	0.308	2.143	0.852	0.148
			860	550	0.435	0.430	1.988	0.789	0.211
			960	450	0.636	0.539	1.848	0.733	0.267
			1060	350	0.889	0.639	1.719	0.682	0.318
			1160	250	1.223	0.729	1.595	0.634	0.366
			1260	150	1.735	0.811	1.467	0.582	0.418
			1360	50	2.835	0.889	1.314	0.522	0.478
			1410	0	∞	0.932	1.000	0.397	0.603
	1210	650	560	650		0			0
	750		660	550		0.165			
			760	450					
			860	350					
			960	250					
			1060	150					
			1160	50	2.565	0.729	1.284	0.594	0.406
			1210	0	∞	—	1	0.462	0.538
	1010	450	560	450		0			0
	500		660	350		0.165			
			760	250		0.308			
			860	150		0.430			
			960	50	2.200	0.539	1.245	0.690	0.310
			1010	0	∞	—	1	0.555	0.445
	810	250	560	250	0	0		1.000	0
	350		660	150	0.511	0.165	1.324	0.915	0.085
			760	50	1.610	0.308	1.191	0.825	0.175
			810	0	∞	—	1	0.691	0.309

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PRESSURE DROP DUE TO FRICTION AND ACCELERATION
IN A HEATED PASSAGE

FRICTION DROP:

$$\frac{dP}{dx} = - \frac{4f}{D_h} \frac{G V}{2g_c} \quad (1)$$

WHERE f = FANNING'S FRICTION FACTOR

D_h = HYDRAULIC DIAM. OF DUCT

G = FLOW INTENSITY = ρV

V = FLOW VELOCITY

IF THE AIR TEMPERATURE RISES ALONG THE DUCT, G IS CONSTANT, BUT V INCREASES:

$$\frac{V}{V_{in}} = \frac{\rho_{in}}{\rho} = \frac{T}{T_{in}} \quad (2)^*$$

(CONSTANT CROSS-SECTIONAL AREA IS ASSUMED.)

COMBINING (1) AND (2) GIVES:

$$\Delta P_f = \frac{4f}{D_h} \frac{G V_{in} L^*}{2g_c} \int_0^{L^*} \frac{T}{T_{in}} d\left(\frac{x}{L^*}\right) \quad (3)$$

IF THE WALL IS AT A UNIFORM TEMPERATURE, THE AIR TEMPERATURE FOLLOWS THE EQUATION:

$$\frac{T_w - T}{T_w - T_{in}} = e^{-x/L^*} \quad (4)$$

* THIS EQUATION HOLDS FOR LOW-MACH FLOW, FOR WHICH THE PRESSURE CHANGES ARE MUCH LESS THAN THE ABSOLUTE PRESSURE.

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FROM (4), IT CAN BE SHOWN THAT:

$$\frac{T}{T_{in}} = \frac{T_w}{T_{in}} - \frac{T_w - T_{in}}{T_{in}} e^{-x/L^*} \quad (5)$$

PUTTING (5) INTO (3) YIELDS AN INTEGRAL OF THE TYPE:

$$I = \int (p + q e^{mx}) dx = px + \frac{q}{m} e^{mx} \quad (6)$$

THUS

$$\int_0^{L/L^*} \left(\frac{T}{T_{in}} \right) d\left(\frac{x}{L^*} \right) = \frac{T_w}{T_{in}} \frac{L}{L^*} - \frac{T_w - T_{in}}{T_{in}} (1 - e^{-L/L^*}) \quad (7)$$

IT CAN ALSO BE SHOWN FROM (4) THAT

$$\frac{T_e - T_{in}}{T_w - T_{in}} = 1 - e^{-L/L^*} \quad (8)$$

WHERE T_e IS THE EXIT AIR TEMPERATURE.

COMBINING EQS. (3), (7), AND (8) YIELDS:

$$\Delta P_f = \frac{4fL}{D_h} \frac{G V_{in}}{2g_c} \left\{ \frac{T_w}{T_{in}} - \frac{L^*}{L} \left(\frac{T_e - T_{in}}{T_{in}} \right) \right\} \quad (9)$$

IF L^* IS NOT KNOWN, BUT T_e IS KNOWN, THEN THE FOLLOWING FORM OF EQ. (4) MAY BE USED:

$$\frac{L}{L^*} = \ln \left(\frac{T_w - T_{in}}{T_w - T_e} \right) \quad (10)$$

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ACCELERATION EFFECT:

$$\Delta P_{ACC} = \frac{\dot{m}}{A} \Delta V = \frac{G}{g_c} (V_e - V_{in}) \quad (11)$$

OR, USING EQ.(2):

$$\Delta P_{ACC} = \frac{G V_i}{g_c} \left(\frac{T_e - T_{in}}{T_{in}} \right) \quad (12)$$

THE DYNAMIC PRESSURE AT THE INLET IS:

$$q_i = \frac{G V_i}{2 g_c} \quad (13)$$

THUS

$$\Delta P_{ACC} = 2 q_i \left(\frac{T_e - T_{in}}{T_{in}} \right)$$

NOTE: IT IS ASSUMED IN EQ.(9) THAT f IS CONSTANT ALONG THE DUCT. ACTUALLY f VARIES AS FOLLOWS:

$$f = \frac{0.079}{Re^{0.25}} \quad \text{FOR } 2300 \leq Re \leq 100,000 \quad (\text{TURBULENT})$$

AND

$$f = \frac{16}{Re} \quad \text{FOR } Re < 2300 \quad (\text{LAMINAR})$$

WHERE

$$Re = G D_h / \mu.$$

IF THE TEMPERATURE RISE IS APPRECIABLE, THE VISCOSITY, μ , OF THE AIR SHOULD BE TREATED AS VARIABLE, AND f WILL VARY. THE VARIATIONS ARE SMALL FOR TURBULENT FLOW, BUT ARE NON-NEGLECTIBLE FOR LAMINAR FLOW.

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CALCULATION OF SODIUM CIRCULATION RATE

AVAILABLE ΔP DUE TO BUOYANCY:

DENSITY OF LIQUID SODIUM,

$$\rho = 59.9 - 0.0085 T \quad (\text{LB/FT}^3)$$

WHERE T = TEMPERATURE ($^{\circ}\text{F}$)

CONSIDER TWO VERTICAL COLUMNS OF HEIGHT, L , FILLED WITH SODIUM AT NONUNIFORM TEMPERATURES. SUPPOSE THE HYDROSTATIC PRESSURES AT THE TOPS OF THE TWO COLUMNS ARE ALIKE, AND EQUAL TO P_0 . THEN THE PRESSURES AT THE BOTTOMS OF THE COLUMNS ARE:

$$P_1 = P_0 + \int_0^L \rho_1 dx = P_0 + 59.9L - 0.0085 \int_0^L T_1 dx$$

$$P_2 = P_0 + \int_0^L \rho_2 dx = P_0 + 59.9L - 0.0085 \int_0^L T_2 dx$$

SUBTRACTING P_1 FROM P_2 ,

$$\Delta P = +0.0085 \int_0^L (T_1 - T_2) dx$$

IN FINITE DIFFERENCE, AS USED BY THE COMPUTER CODE:

$$\Delta P = 0.0085 \sum_i (T_1 - T_2)_i \Delta L_i$$

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SODIUM CIRCULATION RATE (CONTINUED)

REQUIRED ΔP TO OVERCOME FRICTION

$$\frac{\Delta P}{\Delta L} = 4f \frac{\rho u^2}{2g_c} \cdot \frac{1}{D_h}$$

FOR CONSTANT MASS FLOW IN A DUCT OF VARYING CROSS-SECTIONAL AREA:

$$\rho u^2 \propto \left(\frac{1}{A}\right)^2 \quad (\text{CONSTANT } P)$$

THUS IF WE ESTABLISH $\Delta P/\Delta L$ AT ONE STATION, WE CAN FIND OTHERS BY RATIOMS.

CONSIDER LEVELS 11-16 FOR THE FFTF MODEL:

$$A = 8.57 \text{ IN.}^2$$

$$D_h = 1.00 \text{ IN.} = 0.0833 \text{ FT}$$

SAY $U = 1.0 \text{ FT/SEC}$

$$\rho = 57 \text{ LB/FT}^3 @ 350^\circ\text{F}$$

$$\mu = 1.20 \text{ LB/HR-FT} @ 350^\circ\text{F}$$

$$Re = \frac{\rho U D_h}{\mu} = \frac{57 \times 1 \times 3600 \times 1/12}{1.2} = 14,300$$

$$4f = 0.316 / (Re)^{0.25} = 0.0290$$

$$\rho u^2 / 2g_c = 0.886 \text{ LB/FT}^2$$

$$\Delta P/\Delta L = 0.0290 \times 0.886 / 0.0833 = 0.308 \text{ PSF/FT}$$

THEN, AS AREA CHANGES:

$$\left(\frac{\Delta P}{\Delta L}\right) \propto (A)^{-1.75} (D_h)^{-1.25}$$

FROM TABLE ON PAGE —, $L_{CH} = 14.23 \text{ FT}$.

THUS

$$\frac{\Delta P}{g_{ref}} = 4f \frac{L}{D_h} = \frac{0.0290 \times 14.23}{0.0833} = 4.95$$

APPENDIX III
FHM GAS COOLING SYSTEM

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$A(OD) = .7854 \left(\frac{15.25}{12} \right)^2 = 1.268 \text{ FT}^2$
 $A(ID) = .7854 \left(\frac{12.25}{12} \right)^2 = 0.816$
 ANNULAR AREA = $0.452 \text{ FT}^2 \times 41.50' \times 22.5'$ FOR HEAT TRANSFER
 ASSUME 40 KW HEAT REMOVAL FOR SAFETY (30 KW REQ'D)
 ASSUME 1000 CPM @ 250°F INLET
 $W = 1000 \times .075 \times \frac{530}{710} \times 60 = 3340 \text{ #/HR}$, $\Delta T = \frac{40 \times 3414}{.24 \times 3340} = 170^\circ \text{F}$
 $T_{IN} = 250^\circ$
 $T_{OUT} = 420^\circ \text{F}$
 $\bar{T} = \frac{250 + 420}{2} = 335^\circ \text{F} = 795^\circ \text{R}$
 $\bar{Q} = 1000 \times \frac{795}{710} = 1120 \text{ CFM}$
 $\bar{V} = \frac{1120}{.452} = 2480 \text{ FT/MIN} = 41.3 \text{ FT/SEC}$
 $De = 15.25 - 12.25/12 = 0.25 \text{ FT}$
 $Re = \frac{0.050 \times 41.3 \times 0.25}{1.67 \times 10^{-5}} = 30,900$
 $(30,900)^{.8} = 3900$, $Pr = .683$, $(.683)^{.4} = .858$,
 $Nu = .023 \times 3900 \times .858 = 77 = \frac{hD}{k}$
 $h_c = \frac{77 \times .02142}{.25} = 6.6$, $T_1 = 550^\circ \text{F}$, $T_2 = \frac{250 + 420}{2} = 335^\circ$
 $\bar{T} = \frac{550 + 335}{2} = 442^\circ \text{F} = 902^\circ \text{R}$
 $h_R = 7 \sigma f(T_1, T_2)$ $f(T_1, T_2) = 4\bar{T}^3 = 4(902)^3 = 29.3 \times 10^8$
 $f = \frac{1}{\frac{1}{0.6} + \frac{12.25}{15.25} \left(\frac{1}{0.6} - 1 \right)} = \frac{1}{1.67 + .54} = .453$
 $h_R = .453 \times .173 \times 10^{-8} \times 29.3 \times 10^8 = 2.3$
 $h_T = 6.6 + 2.3 = 8.9$ $A(\text{HEAT TRANSFER}) = 3.14 \left(\frac{12.25}{12} \right) 22.5 = 72.4 \text{ FT}^2$
 $\begin{array}{ccc} 550 & \longleftrightarrow & 550 \\ 420 & \longleftrightarrow & 250 \\ 130 & & 300 \end{array}$ $LMTD = 204^\circ$ $Q = 8.9 \times 72.4 \times 204 = 131,000 \text{ BTUH} = 38.5 \text{ KW}$

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ADD WALL INSUL. LOSSES (2" INSUL, $k = 0.042$)

$$R = \ln \frac{20}{16} = \frac{0.096}{6.28 \times 0.042 \times 22.5} = \frac{0.096}{5.93} = .0162$$

$$Q = \frac{(335 - 100)}{.0162} = 14,500 \text{ BTUH} = 4.2 \text{ KW}$$

TOTAL $Q = 38.5 + 4.2 = 42.7 \text{ KW}$ vs 40 KW ASSUMED O.K.
 DESIGN SYSTEM FOR $1000 \times 1.2 \text{ SF} = 1200 \text{ CFM @ } 250^\circ \text{F INLET}$
 * (THIS ALLOWS FOR SYSTEM GAS LEAKAGE)

1. ANNULUS P.D.

$$f = 0.316 / (30,900)^{.25} = \frac{0.316}{13.2} = .0239 \quad V(\text{OUTLET}) = 41.3 \times \frac{880}{795} = 45.7 @ 1.2 = 55 \text{ FPS}$$

$$\Delta P = .0239 \times \frac{22.5}{.25} \times \frac{(49.6)^2}{64.4} + .0239 \times \frac{19}{.25} \times \frac{(55)^2}{64.4} = 83 + 86 = 169 \text{ FT FLUID}$$

3450 3570

$$\Delta P = (83 \times .05) + 86 \left(.05 \times \frac{795}{880} \right) = 4.15 + 3.88 = 8.03 \text{ #/FT}^2$$

$$\Delta P = 8.03 \times \frac{2.32}{144} \times 12 = 1.56 \text{ "H}_2\text{O DUE TO FRICTION}$$

$\Delta P(\text{INLET})$

$$V_1 = \frac{1200}{.7854} = 1530 \text{ FPM} = 25.5 \text{ FPS DUCT}$$

$$V_2 = \frac{1200}{.452} = 2660 \text{ FPM} = 44.4 \text{ FPS ANNULUS}$$

$$\frac{25.5}{44.4} = .575$$

$$\Delta P = .32 \times \frac{(44.4)^2}{64.4} = 9.75 \text{ FT @ } \frac{.056}{144} \times 2.32 \times 12 = 0.106 \text{ "H}_2\text{O}$$

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ΔP (OUTLET)

$$\text{OUTLET } V = \frac{1200 \times \frac{880}{710}}{.7854} = \frac{1490}{.7854 \text{ FT}^2} = 1900 \text{ fpm} = 31.7 \text{ fps DUCT}$$

$$\text{OUTLET } V = \frac{1490}{.452} = 3300 \text{ fpm} = 55 \text{ fps ANNULUS}$$

$$\frac{31.7}{55} = .575$$

$$\Delta P = .36 \frac{(55)^2}{64.4} = 16.95 \text{ FT.}$$

$$\Delta P = 16.95 \times \frac{.0451}{144} \times 2.32 \times 12 = 0.148 \text{ "H}_2\text{O} \quad \leftarrow \text{H}$$

$$\text{TOTAL } \Delta P = 1.56 + .106 + .148 = 1.814 \text{ "H}_2\text{O} \quad \leftarrow \text{H}$$

2. DUCTING P.D. (12" ϕ DUCT)

ΔP - 250° DUCT

STR. PIPE -
1 TEE 60 X 1

30'
60'
90' EQUIV

$$Re = \frac{.056 \times 25.5 \times 1}{1.67 \times 10^{-5}} = 85,500 \quad (85,500)^{.25} = 17, \quad f = \frac{0.316}{17} = .0186$$

$$\Delta P = .0186 \times \frac{90}{1} \times \frac{(25.5)^2}{64.4} = .0186 \times 90 \times 10.1 = 16.9 \text{ FT.}$$

$$\Delta P = 16.9 = \frac{.056}{144} \times 2.32 \times 12 = 0.183 \text{ "H}_2\text{O} \quad \leftarrow \text{H}$$

ΔP - 420° DUCT

STR. PIPE
1 TEE = 60 X 1 =

15'
60'
75' EQUIV

$$Re = \frac{.0451 \times 31.7 \times 1}{1.80 \times 10^{-5}} = 79,500 \quad (79,500)^{.25} = 16.8 \quad f = \frac{0.316}{16.8} = .0188$$

$$\Delta P = .0188 \times \frac{75}{1} \times \frac{(31.7)^2}{64.4} = .0188 \times 75 \times 15.6 = 22.0 \text{ FT}$$

$$\Delta P = 22.0 \times \frac{.0451}{144} \times 2.32 \times 12 = 0.192 \text{ "H}_2\text{O} \quad \leftarrow \text{H}$$

$$\text{TOTAL DUCT } \Delta P = 0.183 + 0.192 = 0.375 \text{ "H}_2\text{O} \quad \leftarrow \text{H}$$

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3. BUTTERFLY VALVES-12 ϕ ROCKWELL WAFER $C_v = 2900 \pm$
 $SCFM = 1200 \times \frac{530}{710} = 900$ (54,000 SCFH)
 $2900 = \frac{54000}{963} \sqrt{\frac{1+795}{\Delta P(14.7+14.7)}}$, $\Delta P = \frac{27}{2680} @ 2.32 \times 12 = 0.28'' H_2O EACH$
 2 VALVES @ .28'' $H_2O = 0.56'' H_2O$ ~~—H—~~

4. PREHEAT LOAD 12HR HEAT-UP TO 400°F REQD

a. INTERNAL ASSY. 12 $\frac{1}{4}$ OD X $\frac{1}{2}$ WALL X 45'

$$.7854 \left(\frac{12.25^2 - 11.25^2}{144} \right) 45' = 5.27 FT^3 @ 487 \# / FT^3 = 2600 \#$$

b. CARRIER TUBE 11 $\frac{1}{4}$ OD X $\frac{1}{2}$ WALL X 45'

$$.7854 \left(\frac{11.25^2 - 10.25^2}{144} \right) 45' = 5.23 FT^3 @ 487 \# / FT^3 = 2550 \#$$

c. GUIDE TUBE 6 $\frac{5}{8}$ OD X 6 ID X 45'

$$19 \# / FT \times 45 = 855 \#$$

d. GRAPPLE = 400 #

e. INNER WALL OF EXTERNAL ASSY
 16" OD X $\frac{3}{8}$ " WALL X 45'

$$.7854 \left(\frac{16^2 - 15.25^2}{144} \right) 45 = 5.9 FT^3 @ 487 \# / FT^3 = 2980 \#$$

TOTAL S.S. = 9385 #
 10% SF = 940 #
10,325 #

$Q_1 = \frac{10,325 \times .12 (400^\circ - 100^\circ)}{12 HRS} = 31,000 BTUH$ ~~—H—~~

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f. INSULATION 2" KAYCO (125° SURFACE TEMP.)
 $.7854 \left(\frac{20^2 - 16^2}{144} \right) 45' = 35.4 \text{ FT}^3 @ 11 \#/\text{FT}^3 = 390 \#$

g. OUTER WALL OF EXTERNAL ASSY
 21 1/2" OD X 3/4" WALL X 45'
 $.7854 \left(\frac{21.5^2 - 20^2}{144} \right) 45' = 15.5 \text{ FT}^3 @ 487 \#/\text{FT}^3 = 7550 \#$

$Q_2 = \frac{390 \times .22 (265^{165} - 100^{\circ})}{12 \text{ HRS}} = 1,200 \text{ BTUH} \leftarrow$

$Q_3 = \frac{7550 \times .12 (125^{25} - 100^{\circ})}{12 \text{ HRS}} = 1,900 \text{ BTUH} \leftarrow$

h. DUCTWORK #16 GA. WELDED STEEL 12" ϕ X 50'
 $3.14 (1) 50 = 157 \text{ FT}^2 @ 2.5 \#/\text{FT}^2 = 392 \#$

$Q_4 = \frac{392 \times .12 (400^{\circ} - 100^{\circ})}{12 \text{ HRS}} = 1,200 \text{ BTUH} \leftarrow$

i. DUCT INSUL. - 2" FIBERGLAS

$157 \text{ FT}^2 \times \frac{2}{12} = 26.2 \text{ FT}^3 @ 4 \#/\text{FT}^3 = 105 \#$

$Q_5 = \frac{105 \times .20 (200^{\circ} - 100^{\circ})}{12 \text{ HRS}} = 175 \text{ BTUH} \leftarrow$

j. CONTAINED AIR

FHM $.7854 \left(\frac{15.25^2}{12} \right) 41.5 = 52.7 \text{ FT}^3$

DUCT $.7854 (1)^2 \times 50' = \frac{39.2}{91.9}$

$Q_6 = \frac{100 \times .075 \times .24 (400^{\circ} - 100^{\circ})}{12 \text{ HRS}} = 45 \text{ BTUH} \leftarrow$

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R. HEAT LOSSES

$$FHM Q = \frac{400^\circ - 100^\circ}{.0162} = 18,500 \text{ BTUH} \leftarrow \text{H}$$

$$DUCT Q = 157 \text{ FT}^2 \times .083(400^\circ - 100^\circ) = 3,900 \text{ BTUH} \leftarrow \text{H}$$

$$L. \text{ TOTAL } Q = 31,000 + 1,200 + 1,900 + 1,200 + 175 + 45 + 18,500 + 3,900 = 57,920 \text{ BTUH}$$

$$M. \text{ TOTAL } KW = 57,920 / 3414 = 17 \text{ USE } 20 \text{ KW}$$

N. HEATER SELECTION

TRY CHROMALOX TDH - 24C $\frac{1}{2}$ 24 KW RATING @ 1400° SHEATH TEMP

$$FREE \text{ AREA} = .3 \times 20.375 \times \frac{24}{144} = 1.02 \text{ FT}^2 \quad (\text{IN ALLOY SHEATH})$$

$$VEL = 1,200 / 1.02 = 1175 \text{ fpm} = 19.6 \text{ fps}$$

$$Re_d = .050 \times 19.6 \times \frac{0.5}{12} = 24,500, f = 0.19, \text{ ROWS} = 4$$

$$\Delta P = 4(\Delta P)_{ROW} = 4 \times 0.19 \frac{(19.6)^2}{64.4} = 4.54 \text{ FT FLUID} \quad (\text{EQU. 9-31 ECKERT \& DRAKE})$$

$$\Delta P = 4.54 \times \frac{.050}{144} \times 2.32 \times 12 = 0.044 \text{ SAY } 0.05'' \text{ H}_2\text{O} \leftarrow \text{H}$$

USE CHROMALOX TDH - 24C

5. HEATER INLET TRANSITION

$$V_{IN} = 25.5 \text{ fps}, V_{HEATER} = 19.6 \text{ fps}, 30^\circ \text{ TRANSITION}$$

$$\Delta P = 0.02 \times \frac{(19.6)^2}{64.4} = 0.116 \text{ FT. FLUID}$$

$$\Delta P = 0.116 \times \frac{.050}{144} \times 2.32 \times 12 = .001'' \text{ H}_2\text{O} \leftarrow \text{H}$$

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6. HEATER OUTLET TRANSITION

$$V_{OUT} = 25.5 \text{ fps}, V_{HEATER} = 19.6 \text{ fps}, 30^\circ \text{ TRANSITION}$$

$$\Delta P = 0.59 \frac{(25.5 - 19.6)^2}{64.4} = 0.32 \text{ FT. FLUID}$$

$$\Delta P = 0.32 \times \frac{.050}{144} \times 2.32 \times 12 = .003 \text{ "H}_2\text{O} \quad \leftarrow$$

7. TOTAL ΔP

$$= 1.814 + 0.375 + 0.56 + 0.05 + .001 + .003 = 2.803 \text{ "H}_2\text{O}$$

8. FAN SELECTION 1200 CFM @ 2.803" TEMP 250°F, ALT. = 500 FT.

$$\text{CORR. FACTOR} = 1.36, \text{EQUIV S.P.} = 2.803 \times 1.36 = 3.82 \text{ "H}_2\text{O}$$

SELECT MASTER FAN #105 BCS FLAT BLADE, CLASS II WITH HEAT SLINGER RPM = 3300 OPER BHP $\frac{1.17}{1.36} = 0.86$

@ STARTUP AIR WILL BE @ 70°F, 500', CORR. FACTOR = 1.02

$$\text{STARTUP BHP} = \frac{1.17}{1.02} = 1.15 \text{ USE } 1\frac{1}{2} \text{ HP, 3600 RPM MOTOR}$$

USE INLET VANES FOR VOLUME CONTROL

MIN. FLOW = 6 fps THRU HEATER

$$(\frac{6}{19.6}) 1200 = 370 \text{ CFM MIN.}$$

$$\text{MIN. \%} = \frac{370}{1200} \times 100 = 31\%, \text{ RANGEABILITY} = \frac{1200}{370} = 3.25 \left. \vphantom{\frac{1200}{370}} \right\} \text{O.K.}$$

VARIABLE INLET VANES CAPABLE OF 20% MIN. FLOW, RANGEABILITY = $\frac{1}{0.2} = 5$

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9. CHECK HEAT TRANSFER FOR 12 HR PREHEAT
 $KW=20$, $\Delta T_{GAS} = \frac{20 \times 3414}{1200 \times .075 \times \frac{530}{860} \times 60 \times 24} = 86.5^\circ F$
 $\therefore T_g (\text{INITIAL}) = 100 + 86.5 = 186.5^\circ F$
 $T_g (\text{FINAL}) = 400 + 86.5 = 486.5^\circ F$
 $\bar{T} = \frac{2673.0}{336.5^\circ F}$
 $\bar{P} \bar{V}$ IS UNCHANGED
 $\therefore h_c = 6.6$ IN FHM ASSUME $h_r = 0$
 $\therefore Q(\text{FHM})^* = 6.6 \times 72.4 \times 86.5 = 41,400 \text{ BTUH AVAILABLE}$
 $\text{REQD } Q = 31,000 \text{ BTUH O.K.}$
 DUCT HEATUP
 $\bar{P} = .075 \times \frac{530}{796.5} = .050$
 $\bar{V} = \frac{1200}{.7854} = 1530 \text{ fpm} = 25.5 \text{ fps}$
 $Re = \frac{.050 \times 25.5 \times 1}{1.67 \times 10^{-5}} = 76,400, (76,400)^{.8} = 6250$
 $Pr = .683, (.683)^4 = .858$
 $Nu = .023 \times 6250 \times .858 = 123 = \frac{hD}{k}$
 $h_c = \frac{123 \times .02142}{1} = 2.64$ ASSUME $h_r = 0$
 $Q(\text{DUCT}) = 2.64 \times 157 \times 86.5 = 35,900 \text{ BTUH AVAILABLE}$
 $\text{REQD } 1200 + 175 + 45 + 3900 = 5,320 \text{ BTUH REQD } \left. \begin{array}{l} \text{O.K.} \end{array} \right\}$
 * FHM LOSSES ARE TREATED SEPARATELY AS FOLLOWS
 AVAILABLE $Q = 6.6 \times 72.4 \times 86.5 = 41,400 \text{ BTUH}$
 $\text{REQD } Q = 1200 + 1900 + 18,500 = 21,600 \text{ BTUH } \left. \begin{array}{l} \text{O.K.} \end{array} \right\}$
CONCLUSION : HEAT TRANSFER AT 1200 cfm
 @ 20KW WILL PROVIDE 12 HR HEATUP

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$A(OD) = .7854 \left(\frac{14.25}{12} \right)^2 = 1.109 \text{ FT}^2$ CONCEPT # 2
 $A(ID) = .7854 \left(\frac{11.25}{12} \right)^2 = .690$
 ANNULAR AREA = $0.419 \text{ FT}^2 \times 41' 0.4 \times 22'$ FOR HEAT TRANSFER
 ASSUME 40 KW ASSUME 1000 Cfm @ 250°F
 $W_{GAS} = 1000 \times .075 \times \frac{530}{710} \times 60 = 3340 \text{ #/HR}$
 $\Delta T_{GAS} = \frac{40 \times 3414}{0.24 \times 3340} = 170^\circ \text{F}$ $\bar{T} = \frac{250 + 420}{2} = 335^\circ = 795^\circ \text{R}$
 $T_{IN} = 250^\circ \text{F}$ $\bar{Q} = 1000 \times \frac{795}{710} = 1120 \text{ Cfm}$
 $T_{OUT} = 420^\circ \text{F}$ $V(INLET) = \frac{1000}{.419} = 2390 \text{ Fpm} = 39.8 \text{ FPS}$
 $\bar{V} = \frac{1120}{.419} = 2680 \text{ Fpm} = 44.6 \text{ FPS}$
 $D_e = \frac{14.25 - 11.25}{12} = 0.25 \text{ FT}$ $\bar{P} = .075 \times \frac{530}{795} = 0.050$
 $Re = \frac{0.050 \times 44.6 \times .25}{1.67 \times 10^{-5}} = 33,400$ $(33,400)^{.8} = 4130$ $P_r = .683$
 $Nu = .023 \times 4130 \times .858 = 81.5 = \frac{hD}{k}$ $(.683)^{.4} = .858$
 $R_c = \frac{81.5 \times .02142}{.25} = 7.0$ $T_1 = 550^\circ \text{F}$ $T_2 = \frac{250 + 420}{2} = 335^\circ$
 $T = \frac{550 + 335}{2} = 442^\circ \text{F} = 902^\circ \text{R}$
 $R_R = f(T_1, T_2)$ $f(T_1, T_2) = 4 T^3 = 4(902)^3 = 29.3 \times 10^8$
 $f = \frac{1}{\frac{1}{0.6} + \frac{11.25}{14.25} \left(\frac{1}{0.6} - 1 \right)} = \frac{1}{1.67 + .53} = .454$
 $h_R = .454 \times .173 \times 10^{-8} \times 29.3 \times 10^8 = 2.3$
 $A_T = 7.0 + 2.3 = 9.3$ $A(HEAT TRANSFER) = 3.14 \left(\frac{11.25}{12} \right)^2 \times 22 = 65 \text{ FT}^2$
 $550^\circ \longleftrightarrow 550^\circ$
 $420^\circ \longleftrightarrow 250^\circ$ LMTD = 204°
 $130^\circ \longleftrightarrow 300^\circ$
 $Q = 9.3 \times 65 \times 204 = 123,000$
 $KW = \frac{123000}{3414} = 36 \longleftrightarrow H$

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CONCEPT #2 (CONT.)

ADD WALL INSULATION LOSSES

(2" INSULATION, $R = \frac{0.50}{12} = 0.042$)

$$R = \frac{\ln \frac{D_o}{D_i}}{2 \pi k L} = \frac{\ln \frac{18.25}{14.25}}{6.28 \times 0.042 \times 22} = \frac{0.1065}{5.8} = .0184$$

$$Q = \frac{\Delta T}{R} = \frac{(335^{\circ} - 100^{\circ})}{.0184} = 12,800 \text{ BTUH} = 3.75 \text{ KW} \leftarrow$$

TOTAL KW = $36 + 3.75 = 39.75 \approx 40 \text{ KW ASSUMED}$ O.K.

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AIR FLOW CALCS

ASSUME 1000 Cfm @ 100°F

$$\dot{m} = 1000 \times .075 \times 60 = 4,500 \text{ #/HR}$$

$$\Delta T_{\text{GAS}} = \frac{40 \times 3414}{0.24 \times 4,500} = 126^\circ \text{F} \quad A(OD) = .7854 \left(\frac{17.25}{12} \right)^2 = 1.620 \text{ FT}^2$$

$$T_{\text{IN}} = 100^\circ \text{F} \quad A(ID) = .7854 \left(\frac{13.25}{12} \right)^2 = .956$$

$$\text{ANNULAR AREA} = 0.664 \text{ FT}^2$$

$$T_{\text{OUT}} = 226^\circ \text{F}$$

$$V = \frac{1000}{.664} = 1510 \text{ fpm} = 25.2 \text{ FPS @ ANNULAR INLET}$$

$$\bar{T} = \frac{226 + 100}{2} = 163^\circ = 623^\circ \text{R}, \quad \bar{P} = .075 \times \frac{530}{623} = .0639, \quad \bar{V} = 25.2 \times \frac{639}{530} = 28.8$$

$$D_e = \frac{17.25 - 13.25}{12} = .25 \text{ FT}$$

$$Re = \frac{.0639 \times 28.8 \times .25}{1.67 \times 10^{-5}} = 27,600 \therefore \text{TURBINE FLOW } P_R = .683$$

$$G = \frac{\dot{m}}{A} = \frac{4,500}{.664} = 6,780 \quad (27,600)^{.8} = 3500, \quad (.613)^{.4} = .858$$

$$Nu = .023 \times 3500 \times .858 = 69 = \frac{h D}{k}$$

$$h_c = \frac{69 \times .02142}{.25} = 5.92$$

$$h_R = f(T_1, T_2) \quad T_1 = 380^\circ \text{F}, \quad T_2 = \frac{100 + 226}{2} = 163^\circ \text{F} \quad \bar{T} = \frac{380 + 163}{2} = 272^\circ = 732^\circ \text{R}$$

$$f(T_1, T_2) = 4 \bar{T}^3 = 4(732)^3 = 15.7 \times 10^8$$

$$h_R = 0.470 \times .173 \times 10^8 \times 15.7 \times 10^8 = 1.28$$

$$h_T = 5.92 + 1.28 = 7.20$$

$$A = 3.14 \times \frac{14.75}{12} \times 24' = 92.8 \text{ FT}^2$$

$$\begin{array}{ccc} 379^\circ & \longleftrightarrow & 379^\circ \\ 226^\circ & \longleftrightarrow & 100^\circ \\ 153^\circ & & 279^\circ \end{array} \quad LMTD = \frac{126^\circ}{.598} = 210^\circ \text{F}$$

$$Q = 7.20 \times 92.8 \times 210^\circ = 140,000 \text{ BTUH}$$

$$KW = \frac{140,000}{3414} = 41 \approx 40 \text{ ASSUMED O.K.}$$

APPENDIX IV
RELIABILITY—Na COOLED FHM

ATOMICS INTERNATIONAL A Division of North American Rockwell Corporation ENGINEERING DOCUMENT		NUMBER TI-681-81-021															
		KEY NOUNS Reliability-Na Cooled FHM															
PREPARED BY J. V. Addison <i>J.V.A.</i>		DEPT & GROUP NO. 732-020															
APPROVALS W. B. Haigler <i>W.B. Haigler</i>		ORIGINAL ISSUE DATE February 23, 1968															
TITLE RELIABILITY/UNAVAILABILITY COMPARISON OF THE SHIELDED-Na COOLED FUEL HANDLING MACHINE WITH SECONDARY NaK COOLING AND THE UNSHIELDED-Na COOLED FUEL HANDLING MACHINE WITH SECONDARY GAS COOLING		REVISION LETTER															
		PAGE 1 OF 28 TOTAL PAGES 28															
		SECURITY CLASSIFICATION															
		<table border="1"> <tr> <th colspan="2">(CHECK ONE BOX ONLY)</th> <th colspan="2">(CHECK ONE BOX ONLY)</th> </tr> <tr> <td>UNCL.</td> <td>☒</td> <td>RESTRICTED DATA</td> <td>☐</td> </tr> <tr> <td>CONF.</td> <td>☐</td> <td>DEFENSE INFO.</td> <td>☐</td> </tr> <tr> <td>SECRET</td> <td>☐</td> <td></td> <td></td> </tr> </table>		(CHECK ONE BOX ONLY)		(CHECK ONE BOX ONLY)		UNCL.	☒	RESTRICTED DATA	☐	CONF.	☐	DEFENSE INFO.	☐	SECRET	☐
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UNCL.	☒	RESTRICTED DATA	☐														
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ABSTRACT This report consists of an attached II covering the qualitative evaluation of nine preliminary concepts of an unshielded-remote operated fuel handling machine and an evaluation of the Unshielded-Na Cooled FHM with Secondary Gas cooling selected for more detailed study by PNL. The evaluation was a reliability comparison of the approach to cooling of this concept with the approach used on the Shielded-Na Cooled FHM as depicted on SK-N68181103. The results indicate the cooling approach of the Unshielded concept to be more reliable.		AUTHORIZED CLASSIFIER															
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DISTRIBUTION	REV	SUMMARY OF CHANGE	APPROVALS & DATE														
D. Anderson (2)																	
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Foreword

Included as a part of this report is an IL giving a brief qualitative reliability evaluation of nine concepts of a Na Cooled-Unshielded FHM. The concept information supplied for evaluation consisted of the cross-sectional illustrations shown in the IL. The evaluation was based on the ability to remove enough heat to eliminate meltdown of a fuel element in an emergency (element stuck partly withdrawn or failure of normal cooling system) conditions.

The main body of the report covers the evaluation of the selected Unshielded-Na Cooled FHM with Secondary Gas Cooling concept, as compared to the "Na Cooled-Shielded" concept depicted on SK-N68181103.

The referenced sketch is a drawing of a shielded machine which allows contact operation and maintenance. The cooling is accomplished by NaK systems in conjunction with air blast heat exchangers. The unshielded remote operated and maintained machine has blower(s) circulating "hot cell" atmospheric gas (GN₂) through an annulus around the cask for cooling in normal conditions and has a natural convective flow through this annulus in emergency conditions. The item being cooled is submerged in sodium in both concepts.

Requirements

The requirements for basis of comparison of the two concepts are given below.

1. Remove 0-30 KW_t during normal cooling while maintaining a cladding or surface temperature of 400°F to 1200°F dependent upon the heat capacity of item being handled.
2. Preheat the FHM prior to use to a maximum of 400°F.
3. The cooling under emergency conditions must maintain driver fuel cladding temperature 1600°F with a 30 KW_t capacity element in the machine.
4. The machine shall be assumed to be in use for a period of 300 hours in a normal refueling period. This is a rounded average of estimates of use times for various equipment of a FHM during a refueling cycle used in previous FFTF availability evaluations of refueling times. A 100 hour repair time will be assumed for the same reason. An exact time is not required for the relative comparison of the concepts.

5. The control required on the heating and cooling shall be such that all items, the machine can handle physically, can be maintained at or below some maximum desired temperature between 400°F and 1200°F (dependent on item's capacity as a heat source; e.g., a 30 KW_t element could not be controlled to 600°F but a 10 KW_t element might).
6. Common equipment types or methods will be considered equivalent with respect to reliability.

Qualitative Evaluation

Both the cooling approaches under consideration are concepts only and it is assumed that "concept determining" items are sufficiently known to allow a meaningful comparison. There are portions of the unshielded machine which are considered to be improvements over what is shown on the drawing of the shielded machine. These improvements shall be discussed briefly, but most of these could be used on either a shielded or an unshielded machine and, therefore, do not enter into a comparison of the two concepts. The discussion will identify the improvements and show why they are common to both concepts. Certain modifications or options to the unshielded machine cooling systems will also be discussed.

1. The shielded FHM will weigh in the order of 150 tons, which is approximately 7 times the unshielded machine weight. This weight requires a much stronger supporting foundation and framework. However, the heavier machine is well within the state-of-art without excessive development. This weight difference affects trolley and tilting mechanisms and the structures to contain the equipment. The speed of travel must be more controlled and the indexing requires more care than a lighter machine. These items all indicate a somewhat greater reliability for the lighter machine.
2. The grapple system of the shielded machine is made capable of both push and pull by use of an endless chain design; whereas the unshielded machine has only pull capability. The unshielded machine has dual drives, each capable of the full load. The shielded uses only a single drive. The redundancy of drives increases the grapple reliability for pull capability. The FHM uses grapple weight for push.
3. The shielded machine uses rods to actuate the "wet" valve, but the guide tube of the unshielded machine is moved to actuate the valve. This change should produce some increase in valve operational reliability due to simpler operation and elimination of four very long small diameter rods.

4. The cooling of the shielded machine is accomplished by use of NaK systems. The unshielded machine uses a NaK system for the freeze seal on the "wet" valve and to cool the snorkel while the cask cooling is accomplished by a forced gas system in the normal cooling mode and a natural convective method for emergency conditions. The blower and heater of the gas system are "off-the-shelf" equipment with much smaller failure rates than the NaK pump, NaK-air heat exchanger, heater, compensator and cold trap. A leakage in the air system is of small concern whereas a NaK leakage could cause fire, and/or loss of cooling capability. In addition, a NaK leak in one of the tubes inside the shielded machine could result in a large outage time.

The NaK cooling lines for the "wet" valve on the shielded machine are routed down through the hot Na adjacent to the element thus resulting in a decrease of cooling capability and increasing the probability of failure of the cooling to the valve and snorkel. The NaK cooling lines to the valve and snorkel are routed through the gas annulus on the unshielded machine concept improving reliability and decreasing size of system required.

5. There are several modifications or options in the unshielded concept: one moves the cask up and down through a seal (the same as in the shielded machine) to raise and lower the snorkel; a second uses a long (4 ft stroke) bellows at the bottom of the cask which is a probable source of failures, manufacturing troubles, etc.; a third eliminates the gas recirculating duct and simplifies the cooling systems (forced and emergency). An increase in the reliability of the forced cooling system and heating could be obtained by use of redundant blowers and heaters at a very small cost. The size is such that there would probably be no change in the machine configuration for one setup or for two setups.

The second method which uses the bellows, moves the entire forced gas cooling system and ducting up and down, creates design and actuation problems, and must be assumed to reduce the reliability of the cooling system.

6. One possible failure mode on the secondary gas cooled-unshielded machine, which could cause loss of Na and uncovering of the element, is leakage external from the cask. The shielded machine would require a double failure for this to occur. Which failure has the highest probability of occurrence is dependent upon the design, amount of welding, etc., on the lower portion of the machine. The single tube of the unshielded may be of higher

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reliability even though only a single failure is required. The penalty from a heat transfer consideration for a multi-layer tube might be small and be worthy of tradeoff for greater reliability due to increased strength and decrease in the probability of a single crack or a leak through one layer causing a meltdown.

A perusal of the above six items will disclose the reason for stating that most of the improvements are applicable to both types of machines. For example, the use of the simpler "pull only" grapple with the weight used for push can be used in either concept. The reliability improvement due to variance in weight is not considered to be of major significance and would require design details for evaluation. The failure rates of the equipment may be greater for the heavy shielded machine for certain functions, but the ability to make contact with the machine, with an irradiated element inside, would allow repair of certain equipment involved and definitely could reduce unavailability of the machine. Therefore, the major reliability/availability comparison must be based on the differences in the cooling systems.

The cooling approaches are illustrated by the following block diagrams and the accompanying failure rates allows calculation of the reliability of each cooling function. The average failure rates of similar equipment used in power plants and presented in the references will be assigned for calculation of reliability. The values will be varied by engineering judgment where conditions or knowledge warrants judgment in such a preliminary evaluation.

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SHIELDED MACHINE COOLING

BLOCK DIAGRAMS

NORMAL OR EMERGENCY COOLING

WET VALVE AND SNORKEL COOLING SHIELDED MACHINE

UNSHIELDED MACHINE COOLING
BLOCK DIAGRAMS

Reliability for normal cooling =

$$R_{NC} = \exp(-14.2 \times 10^{-6} \times 300) \approx .9957 \quad \text{One Blower and Heater}$$

$$R_{2NC} = 1 - (1 - .9957)^2 \approx .99998 \quad \text{Redundant Setups}$$

NOTE: Reliability of setup for heating will be approximately the same as for cooling (.996 for one and .99998 for redundant setups).

NORMAL COOLING

UNSHIELDED MACHINE EMERGENCY COOLING

Reliability of emergency cooling = R_E

$\exp(-30 \times 10^{-6} \times 100) \approx .997$ for estimated repair period of 100 hours

$R_E \approx .9997$ for 10 hours

$R_E \approx .985$ for 500 hours

WET VALVE AND SNORKEL COOLING

This cooling system is the same as the shielded machine system except a smaller pump should be required due to the lines being in the gas annulus. The estimated reliability =

$\exp(-45 \times 10^{-6} \times 300) \approx .986$

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A failure mode and effect evaluation is shown on the Table 1 for the two concepts.

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TABLE 1
FAILURE MODE AND EFFECT ANALYSIS

ITEM	COMPONENT	FAILURE MODE	CAUSE	EFFECT SINGLE SETUP (DUAL SETUP - 2 FAILURES REQUIRED)	ESTIMATED FAILURE RATE ($\lambda \times 10^6$)	*EST. AVG REPAIR TIME (HOURS)	ESTIMATED UNAVAILABILITY (%) IN 300 HOURS
1.	<u>UNSHIELDED MACHINE</u> Blower	Impeller failure	(a) Material flaw (b) Unbalance	Loss of forced cooling or heating	—	(Repair required during fuel handling period)	$\lambda \times R.T. \frac{100}{300} = \%$
		Shaft failure	(a) Material flaw (b) Manufacturing error (c) Vibration (d) Dirt in bearing	Loss of forced cooling or heating	—	—	—
		Bearing failure	(a) Improper lubrication (b) Misalignment (c) Vibration (d) Material flaw (e) Dirt (f) Excess temperature	Loss of forced cooling or heating	2.4	8	.0019
		Housing failure	(a) Improper mounting (b) Vibration (c) Material flaw (d) Manufacturing error (e) Damaged by external source (human error)	Loss of forced cooling if housing is ruptured on pressure side or if failure interferes with impeller. Same for heating.	—	—	—
		Inlet Damper Failure	(a) Vane bind (b) Linkage wear (c) Damage to linkage from external source (d) Actuator failure	Loss of forced cooling if in closed position or control if in open position. Same for heating.	—	—	—

* Spares or complete units assumed on hand, and modular design for remote replacement.

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TABLE 1 (CONT)
FAILURE MODE AND EFFECT ANALYSIS

ITEM	COMPONENT	FAILURE MODE	CAUSE	EFFECT SINGLE SETUP (DUAL SETUP - 2 FAILURES REQUIRED)	ESTIMATED FAILURE RATE ($\lambda \times 10^6$)	*EST. AVG REPAIR TIME (HOURS)	ESTIMATED UNAVAILABILITY (%) IN 300 HOURS
UNSHIELDED MACHINE (CONT)							
2.	Motor Blower	Wiring failure	(a) Electrical short (b) Mechanical failure (c) Material flaw (d) Cooling loss	Loss of forced cooling or heating	1.2	4	.0048
		Bearing failure	(a) Improper lubrication (b) Misalignment (c) Vibration (d) Material flaw (e) Dirt	Loss of forced cooling or heating			
3.	Connection Motor-Blower	Belt failure (Belt driven unit)	(a) Material flaw (b) Wearout - normal (c) Overload - improper adjustment (d) Misalignment - wearout (e) Over temperature exposure (f) Damage from external source	Loss of forced cooling or heating	3.6	4	.00144
4.	Duct Valves to Hot Cell	Valves fail open (Forced cooling in operation)	(a) Actuator fails (b) Mechanical failure (c) Operator error	Loss of forced cooling but emergency convective cooling would be operative less of heating capability.	2.0	4	.0008
		Valves fail closed	(a) Actuator fails (b) Mechanical failure (c) Operator error (d) Stick	No effect unless emergency cooling required. Then meltdown would occur if in cooling mode.			

*Spares or complete units assumed on hand. and modular design for remote replacement.

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TABLE 1 (CONT)
FAILURE MODE AND EFFECT ANALYSIS

ITEM	COMPONENT	FAILURE MODE	CAUSE	EFFECT SINGLE SETUP (DUAL SETUP - 2 FAILURES REQUIRED)	ESTIMATED FAILURE RATE ($\lambda \times 10^6$)	*EST. AVG REPAIR TIME (HOURS)	ESTIMATED UNAVAILABILITY (%) IN 300 HOURS
	UNSHIELDED MACHINE (CONT)						
5.	FHM Gas Annulus	Restricted flow area	(a) Blockage by foreign material (b) Collapse of walls	Less of cooling to a degree dependent on blockage of gas passage, especially bad for emergency. Same for heating.	.01	240	.0024
6.	Duct	Restricted flow area	(a) Crushed by external force (b) Blocked by foreign material	Less of normal cooling and if in certain areas less of emergency cooling or less of heating	.2	5	.0001
7.	Blower Motor Controls	Fails open	(a) Electrical (b) Mechanical (c) Operator error cause open condition	Less of forced cooling or heating	.5	4	.0002
		Fails closed	(a) Electrical (b) Mechanical (c) Operator error cause open condition	If variable, could cause less of experimental data by excess cooling			
8.	Heater	Fails open	(a) Electrical (b) Mechanical	All heating out. None on cooling	4.0	8	.0032
9.	Heater Control	Fails open	(a) Electrical (b) Mechanical	Loss of heating	.5	2	.0001
		Fails closed	(a) Electrical (b) Mechanical	Less of control. Crude control could be obtained by operating line CB or SW.			

*Spares or complete units assumed on hand, and modular design for remote replacement.

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TABLE 1 (CONT)
FAILURE MODE AND EFFECT ANALYSIS

ITEM	COMPONENT	FAILURE MODE	CAUSE	EFFECT SINGLE SETUP (DUAL SETUP - 2 FAILURES REQUIRED)	ESTIMATED FAILURE RATE ($\lambda \times 10^6$)	*EST. AVG REPAIR TIME (HOURS)	ESTIMATED UNAVAILABILITY (%) IN 300 HOURS
UNSHIELDED MACHINE (CONT)							
10.	Wiring to Heater Controls	Fails open	(a) Electrical (b) Mechanical	Loss of heating	.3	4	.00012
11.	Wiring to Blower Motor	Fails open	(a) Electrical (b) Mechanical	Loss of normal cooling and/ or heating	.3	4	.00012
							$\Sigma 0.00058 \%$
SHIELDED MACHINE HI Temp U-Tube NaK System							
1.	Surge Tank	Loss of gas charge	(a) Loss of gas system (b) Leak in gas area of tank	Loss of normal cooling and heating	.15	16	.00024
		NaK leak	(a) Weld flaw (b) Material flaw (c) Corrosion	Loss of normal cooling and heating	1	1	
2.	Pump	Impeller fails	(a) Corrosion (b) Material flaw (c) Vibration (d) Excess speed	Loss of normal cooling and heating	1	1	
		Bearing failure (if used)	(a) Dirt (b) Misalignment (c) Excess temperature (d) Material flaw (e) Vibration	Loss of normal cooling and heating	20.	16	.032

* Spares or complete units assumed on hand. and modular design for remote replacement.

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TABLE 1 (CONT)
FAILURE MODE AND EFFECT ANALYSIS

ITEM	COMPONENT	FAILURE MODE	CAUSE	EFFECT SINGLE SETUP (DUAL SETUP - 2 FAILURES REQUIRED)	ESTIMATED FAILURE RATE ($\lambda \times 10^6$)	*EST. AVG REPAIR TIME (HOURS)	ESTIMATED UNAVAILABILITY (%) IN 300 HOURS
	SHIELDED MACHINE (CONT) HI Temp U-Tube Mak System						
2.	Pump (Cont)	Housing fails	(a) Material flaw (b) Manufacturing error (c) Vibration (d) Corrosion (e) Over pressure (inner wall)	Loss of normal cooling and heating			
		Coil failure (helical induction pump)	(a) Excess temperature (b) Excess amps (c) Short (d) Open	Loss of normal cooling and heating			
3.	Motor - Pump	Wiring failure	(a) Short (b) Open (c) Mechanical flaw (d) Excess temperature	Loss of normal cooling and heating			
		Bearing failure	(a) Improper lubricant (b) Dirt (c) Vibration (d) Material flaw (e) Misalignment	Loss of normal cooling and heating	2.5	4	.001
		High Temperature SW Fails	(a) Excess amps (b) Mechanical failure	Loss of normal cooling and heating			

* Spares or complete units assumed on hand, and modular design for remote replacement.

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TABLE 1 (CONT)
FAILURE MODE AND EFFECT ANALYSIS

ITEM	COMPONENT	FAILURE MODE	CAUSE	EFFECT SINGLE SETUP (DUAL SETUP - 2 FAILURES REQUIRED)	ESTIMATED FAILURE RATE ($\lambda \times 10^6$)	*EST. AVG REPAIR TIME (HOURS)	ESTIMATED UNAVAILABILITY (%) IN 300 HOURS
SHIELDED MACHINE (CONT) Hi Temp U-Tube NaK System							
4.	Motor Controls	Fails open	(a) Electrical (b) Mechanical (c) Physical damage	Loss of normal cooling and heating	.5	2	.0001
		Fails at one location - no control	(a) Electrical (b) Mechanical fault (c) Damaged - external	Dependent on extent of failure			
5.	Wiring	Fails open	(a) Short (b) Mechanical break (c) External source caused failure	Loss of normal cooling and heating	.3	2	.00006
6.	Air-NaK HX	Leaks	(a) Corrosion (b) Material flaw (c) External damage	Loss of normal cooling and	8.0	300	.24
		Contamination of surfaces	(a) Oxides (inside) (b) Dirt or oil (outside)	Gradual loss of cooling			
7.	Blower-Motor	Impeller fails	(a) Corrosion (b) Material flaw (c) Excess speed (d) Vibration	Loss of cooling capacity	2.4	4	.00096
		Motor bearing fails	(a) Improper lubricant (b) Dirt (c) Vibration (d) Misalignment	Loss of cooling capacity			

* Spares or complete units assumed on hand, and modular design for remote replacement.

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TABLE 1 (CONT)
FAILURE MODE AND EFFECT ANALYSIS

ITEM	COMPONENT	FAILURE MODE	CAUSE	EFFECT SINGLE SETUP (DUAL SETUP - 2 FAILURES REQUIRED)	ESTIMATED FAILURE RATE ($\lambda \times 10^6$)	* EST. AVG REPAIR TIME (HOURS)	ESTIMATED UNAVAILABILITY (%) IN 300 HOURS
SHIELDED MACHINE (CONT) HI Temp U-Tube NaK System							
7.	Blower-Heater (Cont)	Motor fails	(a) Wiring short (b) Wiring open	Loss of cooling capacity	—	—	—
		Belt drive fails (if used)	(a) Overload (b) Wearout - normal (c) Misalignment (d) Material flaw (e) External damage	Loss of cooling capacity	—	—	—
8.	Valve (NaK) (Est. 5 required)	Fails open	(a) Corrosion of stem (b) Binding due to oxides (c) Damaged stem	No effect for continued operation	—	(Fix when not in use)	—
		Fails closed	(a) Corrosion of stem (b) Binding due to oxides (c) Damaged stem	Loss of cooling (normal)	5.0	8	.004
		Leakage (external)	(a) Seal fails	Dependent on amount of leakage, but would cause shutdown after transfer complete	—	—	—
9.	Piping	Leakage	(a) Corrosion (b) Material fault (c) External damage	Dependent on amount of leakage, but would cause shutdown after transfer complete	2.0	16	.0032

* Spares or complete units assumed on hand, and modular design for remote replacement.

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FAILURE MODE AND EFFECT ANALYSIS

ITEM	COMPONENT	FAILURE MODE	CAUSE	EFFECT SINGLE SETUP (DUAL SETUP - 2 FAILURES REQUIRED)	ESTIMATED FAILURE RATE ($\lambda \times 10^6$)	*EST. AVG REPAIR TIME (HOURS)	ESTIMATED UNAVAILABILITY (%) IN 300 HOURS
10.	SHIELDED MACHINE (CONT) HI Temp U-Tube NaK System Cold Trap	Leakage	(a) Corrosion (b) Material fault (c) External damage	Dependent on amount of leakage, but would cause shutdown after transfer complete	.3	16	.00048
		Loss of trapping	(a) Loss of or in- sufficient cooling (b) Full trap	No effect		(fix when not in use)	$\Sigma 0.28156 \%$ Shielded Machine

*Spares or complete units assumed on hand, and modular design for remote replacement.

NOTE: (1) The same failure modes and effects are prevalent in the 2nd or backup cooling system and failure rates and repair times are sufficiently close so that same data applies.

(2) Item 1 above is true also for the Wet Valve and Snorkel NaK cooling setup.

(3) Estimated repair times based on personal communication with J. Burton.

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The percent unavailability due to the cooling systems of the unshielded machine for a 300 hour period is the value in the table above (0.0058%) plus a value for the NaK system used for cooling the wet valve and the snorkel. The total FHM unavailability due to the cooling systems is estimated to be conservatively 10 times the value in the above table for a NaK cooling system or 2.81%. As would be expected, the NaK cooling system which cannot be easily repaired or replaced is the portion of the cooling system which would cause the greatest unavailability. The unavailability associated with the remote handling equipment failing or not having been designed for some failures cannot be estimated at this time. One failure mode overlooked and not prepared for in remote handling, including procedures, could negate all estimates of outage and unavailability.

The shielded machine has a total of approximately 3×0.281 or 0.843% unavailability for a 300 hour period.

The NaK system in both machines will be exposed to approximately the same radiation fields, but as they are secondary systems the radioactivity should not be excessive enough to cause long outage, when repair is required. However, the inaccessibility to portions of these systems can cause very long outages for repair. Again, it should be pointed out that the valve and snorkel cooling is not considered a critical item as it is backup to the mechanical sealing of the valve and loss would not necessarily cause a possible meltdown. A double failure is required to be damaging.

Conclusions and Summary

1. Both concepts are assumed capable of meeting the requirements for cooling in an emergency or in normal fuel transferring conditions.
2. The lower weight of an unshielded machine could improve the reliability of transportation, trolley operations, indexing, and alignment.
3. The various modifications on the grapple and wet valve actuation, for example, were not considered for comparison as they are feasible for both concepts.
4. The reliability estimates for the cooling system and certain modifications are shown in the table below. The FHM is assumed to be returned to "new" condition after each period of use.

TABLE 2

RELIABILITY OF COOLING SYSTEMS		
SYSTEM	*RELIABILITY	COMMENT
Shielded Machine - NaK Cooling of Na Cask 1. No redundancy Normal Emergency	 0.9755 0.9925	The value for emergency reliability varies from 0.99925 for 10 hours to 0.963 for 500 hours. The 100 hours used is an average repair time use of backup system. Normal refers to the U-tube HX system. Emergency refers to the shield HX system.
2. Redundant pumps Normal Emergency	 0.9866 0.9925	
3. Redundant pumps and air blast HX Normal Emergency	 0.991 0.9925	
4. Complete redundant systems Normal Emergency	 0.9994 0.9925	Normal here refers to two U-tube or one of each type capable of cooling as shown on SK-N68181103. Emergency refers to the 2nd system reliability for 100 hours after 1st failure
5. Wet valve and snorkel cooling	0.983	
Unshielded Machine - Forced Gas Cooling of Na Cask with Natural Convective Emergency Cooling 1. No redundancy Normal Emergency	 0.9957 0.997	Emergency reliability equals 0.9997 for 10 hours 0.985 for 500 hours Value shown for 100 hours average repair time assumed for comparison
* Based on 300 hours for refueling use of normal cooling, and 100 hours for use of emergency cooling.		

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TABLE 2 (CONT)

RELIABILITY OF COOLING SYSTEMS		
SYSTEM	*RELIABILITY	COMMENT
2. Redundant normal systems Normal Emergency	0.99998 0.997	
3. Wet valve and snorkel cooling	0.986	Smaller pump required due to lines in gas annulus

* Based on 300 hours for refueling use of normal cooling, and 100 hours for use of emergency cooling.

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Conclusion and Summary (Cont)

5. The estimated percentage of unavailability of the FHM for each 300 hour refueling period is as shown below.

TABLE 3

SYSTEM	ESTIMATED FHM UNAVAILABILITY - % Due to Cooling Systems for a 300 Hour Refueling Period
Shielded SK-N68181103	0.84
Unshielded	2.81

6. The problem area in the unshielded system cooling, which is indicative of requiring the major study and development, is the NaK cooling system repair or replacement. Development of a quick disconnect or some type of line separation device is needed.
7. The repair of NaK internal lines buried in behind the shielding and through the Na cask is the problem area of the shielded machine cooling.
8. Design and development of modular cooling units are necessary for either concept to achieve the lowest unavailability.
9. The concept of the unshielded machine with the long bellows at the bottom would add more failure modes to the FHM than the concept with the moving cask sealed at the top similar to the SK-N68181103 and therefore was not analyzed further. Its reliability will be lower than the concept without the bellows which was analyzed.
10. The cooling concept with the recirculating ducting removed would be more reliable for cooling, but the excessive amount of heat required for preheating would be dumped into the hot cell and overload the cell cooling capacity. Therefore, no further evaluation was made on this concept.

Conclusion and Summary (Cont)

11. The very great affect that the unknown remote handling equipment interface with the FHM and other machines in the hot cell could have on the selection of a machine tends to negate any small variance in FHM availability between the concepts evaluated in this report. The size and complexity of the undefined remote handling equipment required and the consequences of missed failure modes on the overall refueling system reliability cannot be quantitatively evaluated from the preliminary nature of the data available.

However, the values in Table 2 indicate the secondary gas cooling with full redundancy for normal cooling is a much more reliable system than the NaK system with full redundancy, 0.99998 to 0.9994. There is little difference indicated between the 2nd NaK system for emergency and the natural convective backup, 0.9925 to 0.997, respectively.

The unavailability difference is much more speculative and more greatly influenced by the remote handling equipment than the reliability values for the cooling system.

12. A requirement which does not affect the cooling system reliability but does affect the unavailability is the need for very skilled operators to operate the remote handling equipment. The estimated repair times can increase many fold when jobs must be done with lesser skilled operators. The time increase can be partially due to a cautious approach to new work and the much more serious increase due to errors in operation.
13. On the basis of this analysis and in consideration that system details are incomplete, it is concluded that the gas system of cooling with full redundancy is a more reliable method of cooling a FHM than a method using NaK systems. The gas concept combined with a shielded machine could be the most reliable and would have the least unavailability of any of the "Na Cooled" FHM concepts considered.

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References:

- (1) AI-67-TDR-15 "Failure Rate Estimates of Some Nuclear and Conventional Power Plant Concepts," I. Sexton
- (2) Failure Rates AVCO (Earles & Eddins) 1962
- (3) EEI No. 67-23 Issued August 1967
Report on Equipment Availability for the Seven Year Period 1960-1966
- (4) Farada Data (Failure Rates) Revised June 1967
SP63-70
- (5) SK-N68181103 Na Cooled - Shielded FHM
- (6) Sketches for Unshielded Na Cooled FHM with Secondary Gas Cooling

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INTERNAL LETTER

ATOMICS INTERNATIONAL
A Division of North American Aviation, Inc.

TO C. E. Jones, Jr.
Address D/731, C002

Date January 5, 1968

FROM J. V. Addison
Address D/732, C002

Phone 1356

Subject Reliability-"Na Cooled" Unshielded FHM Concepts

The preliminary sketches of the five natural convective heat transfer concepts without secondary cooling systems and the four concepts with secondary cooling (2 forced and 2 natural convections) have been reviewed for reliability of heat transfer sufficient to maintain a non-melt down condition. The concepts are shown on the attached sketch (data by G. P. Streechon) and are discussed below.

- a. The Bare Cask with natural convection, with a diameter of approximately 18 inches, is equivalent in heat rejection to the 12.75 diameter Finned Cask. If the extra volume of sodium does not add problems, and it does not appear to do so at present, then the Bare Cask should be the most reliable of all concepts shown from the standpoint of elimination of melt down. It allows easier manufacture, as all other concepts are basically the Bare Cask with additional construction.
- b. The Finned Cask does allow a lower sodium volume for the same heat rejection, however, it has added manufacturing problems, thermal stress and handling problems.
- c. The Chimney Cask and Finned Chimney Cask do not add anything to the reliability of the heat rejection as it would be possible to "choke" air circulation, and manufacturing and handling problems are added.
- d. The Adjustable Louver Cask could be worth-while where excess heat rejection is available and it is necessary to control the amount of heat rejection when handling a test specimen in order to preserve test data, otherwise, it does not add reliability to the heat rejection.
- e. The "hot cell" cooling system reliability controls the upper limit of the reliability of these natural convective methods of cooling.

Cold panels on the walls of the "hot cell" may be one way to add to the heat rejecting capability of the concepts by radiation from the FHM to the "cold walls." Calculations are necessary to determine effect of "cold walls." Provided control of the temperature is required to handle test elements, then a secondary cooling system such as the U-tube type would probably be necessary.

IL to: C. E. Jones, Jr.
From: J. V. Addison
Subject: Reliability "Na Cooled" Unshielded FHM Concepts

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The forced convective type #1 would be the most appropriate if a modular concept can be designed to reduce the maintenance and the downtime for repair in case of failure. The forced cooling type could be made smaller in size, which should be an advantage in design of modular, quick disconnect type units for repair or replacement by remote handling equipment. However, the insulation should probably not be used because it reduces the probability of sufficient heat rejection in an emergency situation caused by loss of the secondary cooling system. With a properly sized "Bare Cask," the size probably is determined by other factors than emergency cooling, loss of the secondary would not cause melt down. If several modular secondary systems were used, the probability of loss of test data could be made to fall within an acceptable risk assigned as part of the cooling requirement.

The natural convective secondary may be acceptable and may or may not be more reliable, depending upon the requirements set forth. It does lack the controllability of the forced secondary and the size may complicate the overall FHM design. Further design details are necessary for proper evaluation of these factors. The secondary cooling, if equal to or in excess of the minimum emergency cooling rate, could add to the reliability of non-melt down because it is in parallel with the "hot cell" cooling.

The natural convective method of cooling of a Bare Cask can only be improved upon from a reliability of heat rejection by use of a combination with the other two static heat removal methods (conduction and radiation). However, the rate of cooling can be improved by design, materials, coatings, etc. The items such as those mentioned should be evaluated by parametric studies to maximize the heat rejection capabilities within the constraints of the system and environs. The maximum heat rejection system may not be the most reliable because of manufacturing and maintainability problems, therefore, a trade off may be required.

If the static method of heat rejection will not remove the required amount of heat, then the secondary cooling is required and the first five concepts are not applicable. In this case, the forced cooling without insulation on the "Bare Cask" is recommended and the method that can be constructed to allow the easiest replacement of the modular cooling systems, whether internal or external to the cask, should be selected. Provided, of course, that other problems are not induced which lower the reliability of the cooling system or interfere with other aspects of fuel and test specimen handling.

After the most applicable systems of cooling are selected, further analyses of their reliability will be made as details become available.

All machines require remote handling and repair, so all aspects of these conditions were assumed the same. The other functions of the FHM were assumed

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From: J. V. Addison
Subject: Reliability "Na Cooled" Unshielded FHM Concepts

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identical for this preliminary evaluation and only cooling concepts considered based primarily on the supplied sketches.

J. V. Addison
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Product Effectiveness Unit
Engineering Systems Management

JVA:dc

Attachment as noted

cc: W. V. Haigler *WBA*

FFTF UNSHIELDED-SODIUM COOLED FHM CONCEPTS

I. NATURAL CONVECTION

#1 BARE CASK

#2 FINNED CASK

#3 CHIMNEY CASK

#4 FINNED CHIMNEY CASK

#5 ADJUSTABLE LOUVER CASK

II WITH SECONDARY COOLING

#1 FORCED - U TUBE

#2 FORCED CONVECTION - U TUBE

#3 NATURAL - HEADER TYPE

#4 NATURAL - HEADER TYPE

F F T F
UNSHIELDED FUEL HANDLING MACHINE
30 KWT DECAY HEAT REMOVAL SYSTEMS

CONCEPT II
 FFTF REACTOR REFUELING SYSTEM
 UNSHIELDED FUEL HANDLING MACHINE
 SODIUM GAS COOLING WITH GAS
 BARRIER BELLOWS & STEPPED INTERNAL
 ASSEMBLY 11 1/4 IN O.D. WALL

Drawing 4. Unshielded SCFHM,
 Concept II
 (SK-N68181146)

CONCEPT III

FFTF REACTOR REFUELING SYSTEM
UNSHIELDED FUEL HANDLING MACHINE
SODIUM & GAS COOLING WITH
GAS BARRIER TUBE & STRAIGHT
INTERNAL ASSEMBLY - 12 1/4 IN O.D. WALL

Drawing 5. Unshielded SCFHM,
Concept III
(SK-N68181147)
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CONCEPT 3
COOLING GAS ANNULUS ADJACENT TO GAS BARRIER TUBE. HELIUM ANNULUS BETWEEN INTERNAL ASSEMBLY AND GAS BARRIER TUBE.

CONCEPT 2
COOLING GAS ANNULUS ADJACENT TO STEPPED INTERNAL ASSEMBLY.

CONCEPT 1
COOLING GAS ANNULUS ADJACENT TO STRAIGHT INTERNAL ASSEMBLY

Drawing 6. Cooling System Comparison

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Drawing 7. Alternate Top
 Arrangement, Minimum
 Height Machine

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SECTION C-C
SCALE 1/4

SECTION B-B
SCALE 1/2

Drawing 8. Top Hat
(SK-N68181150)

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