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1000-MWe LMFBR ACCIDENT ANALYSIS
AND SAFETY SYSTEM DESIGN STUDY

— Topical Report —

Candidate Emergency Decay
Heat Removal Systems

by

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PREFACE

This report was originally prepared as a technical note to document the work performed in a specific contract activity as soon as the work was completed. The technical editing was limited in order to meet the objective of timely reporting. The report was issued for USAEC-ANL use only, and the intent was to update and consolidate the information from all technical notes in a comprehensive phase report before final publication for public distribution at the end of Phase II.

This plan was changed when the contract was terminated in October 1970 for the convenience of the government. Instead, a final summary report will be prepared, and the previously issued technical notes will be published as formal topical reports. In accordance with the modified plan, this technical note is being published in its original form without further editing or modification except for minor technical corrections and changes in the title and date of issue. Even without updating and technical editing, the report provides detailed information that should be helpful in evaluating and resolving LMFBR safety questions in related areas.

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1000-MWe LMFBR Accident Analysis and
Safety System Design Study
Candidate Emergency Decay
Heat Removal Systems

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Natural Circulation,
Na-Air Heat Exchangers

ABSTRACT

Candidate systems for emergency decay heat removal were identified and developed to the extent required for an initial screening of questionable systems. These systems were based on anticipated requirements which were arbitrarily imposed pending results from other activities which will establish the functional requirements for the emergency decay heat removal system.

The possibility of containing molten fuel was examined along with various ways of cooling it. This investigation covered: (a) meltdown pan features and requirements to determine the possibility of containing molten fuel from a hypothetical seven-fuel assembly meltdown inside the core vessel, (b) a sodium-cooled pan located outside the primary tank to accommodate the entire molten core as a last-ditch cooling system, and (c) characteristics governing the potential for natural circulation of primary sodium under a range of thermal duties.

Based on a simplified melt-through model, the results of a transient thermal analysis indicate that for a hypothetical seven-fuel assembly meltdown, melt-through can be reasonably precluded as long as the pony motors are operable and provide 5% of the total flow rate. In the event of a total core meltdown, the transient-temperature analysis indicate that natural convection cooling is a very effective means in preventing melt-through.

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1. INTRODUCTION

1.1. Background

Babcock & Wilcox is performing work on the Accident Analysis and Safety System design study under ANL Contract No. 31-109-38-2339. Various utility companies are participating in the work on a cost-sharing basis, under separate agreements with B&W. The Study is being conducted primarily to gain a better understanding of the influence of safety requirements on large LMFBR designs.

Although B&W's 1000-MWe Follow-On Study provided first-step information on conceptual LMFBR designs favored by the industry, the scope of the study was not sufficient to provide in-depth resolution of many safety-oriented problems or to provide detailed guidance for specific research and development requirements. Therefore, B&W is now analyzing the accidents that determine the design bases for certain protective systems and safety features and preparing conceptual designs for these protective systems and engineered safety features. The reference design of the Follow-On Study has been selected to form the basis for these studies. A comprehensive plan has been developed which divides the total effort into a series of parallel and sequential work activities. This activity is entitled, "The Identification of Candidate Emergency Decay Heat Removal Systems."

The general design criterion for the 1000-MWe reference design stipulates that systems and components essential to the prevention of accidents that could affect the public's health and safety or to the mitigation of their consequences shall be identified and then designed, fabricated, and erected to quality standards reflecting the importance of the safety function to be performed. Owing to the vital nature of these requirements, the reference concept must be examined closer. Although the design of the post-DBA decay heat removal system did incorporate some of the basic features known to be required at the

time, subsequent considerations indicate that certain deficiencies still exist. Therefore, under this activity, we have reexamined the reference design in an attempt to correct these deficiencies based on additionally assumed requirements.

1.2. Objective

The objective was to identify and develop possible features and systems that could remove fission-product decay heat from a portion or all of a disassembled core and transfer it to the ultimate sink. This is the first part of a series of activities. The subsequent effort will cover the development of functional requirements, the selection of reference systems from the candidate systems, the conceptual design of the reference systems, and the establishment of research and development requirements.

1.3. Reference Design

The emergency decay heat removal system of the reference design was coupled to the normal decay heat removal system. It consisted of two identical heat transport systems, each being capable of removing normal decay heat and post-accident decay heat. Normal decay heat was removed by an NaK circuit connected to a heat exchanger in the primary tank. The same NaK circuit was used with the post-accident decay heat removal system, but in conjunction with the cooling coils located outside the liner of the primary tank cavity. To switch from the normal decay heat removal mode to the post-accident mode required the actuation of appropriate valves to isolate the heat exchanger and place the cooling coils in the circuit. Because the primary system provides such a large heat sink, the time required to switch to the emergency conditions did not present a problem. The point of concern is whether or not the valves would operate properly when required.

It would have been better to separate the normal and the emergency decay heat removal functions and thus eliminate the need for switching operations. In addition, it would have been desirable to assign the emergency circuit the function of continuously removing heat from the biological shield. This would have ensured the capability

of the system to perform its function and would have eliminated the need for periodic testing.

The reference design included forced circulation of the NaK by electromagnetic pumps. Increased reliability should have been possible by designing this system to operate with natural circulation.

The considerations given to meltdown accommodations for the fuel were not adequate. Further examination of this problem should provide some insight into the provisions required to contain fuel melt.

Other areas in which the reference design was deficient include accommodations for bottom cooling of the primary tank and blast protection for the cooling coils behind the cavity liner.

2. SUMMARY

2.1. General

The study was primarily directed toward defining emergency decay heat removal systems that could remove decay heat from a portion or all of a disassembled core and transfer it to the ultimate sink. The scope of the effort is shown in Figure 1. To perform this task, it was necessary to (1) establish a range of accident conditions as a primary step in the design of the emergency cooling system, (2) establish major assumptions, and (3) survey what others have done relative to the objective.

2.2. Assumptions

The major assumptions were as follows:

1. An accident limited to seven fuel assemblies will not destroy the capabilities of the normal DHRS.
2. Meltdown accommodations for seven fuel assemblies must be provided inside the core vessel.
3. Meltdown accommodations for more than seven fuel assemblies will be provided outside the primary tank.
4. Under conditions requiring use of the outside meltdown accommodations, primary sodium will be present.
5. Pans or catchers fabricated from an appropriate material will be used to accommodate molten fuel outside the primary tank.

2.3. Post-DBA Cooling Survey

Emergency DHRSs of fast reactors (EBR-II, FERMI, PFR, and the proposed LMFBRs) were surveyed to determine new requirements, ideas, and design features that might be applicable. In general, there is not much information available. As an example, none of the older

fast reactor designs (EBR-II, FERMI, etc.) incorporate post-DBA cooling systems based on removing heat from large quantities of molten fuel. Among the later designs, the PFR has provisions for the use of sea water as a last-ditch means of cooling the primary tank complex. Some of the 1000-MWe studies mention cooling coils attached to the cavity liner surrounding the reactor vessel. One conceptual design had several layers of natural-convection-cooled meltdown trays below the core support structure. Details of how or why these systems are expected to work are not available. The FFTF has considered the effect of a blast on the reactor vessel, and some work has been done on meltdown, but it has not been decided whether an external cooling system is required.

2.4. Seven-Fuel-Assembly Meltdown

The possibility of containing molten fuel resulting from a hypothetical meltdown of seven fuel assemblies was examined along with various ways of cooling the fuel. A simplified model consisting of the meltdown pan and molten debris was set up for the analysis. The results of the calculations showed that it is reasonable to expect preclusion of melt-through as long as the pony motors are operable and can provide 5% of the total flow rate. Cases with poorer cooling capabilities, such as natural convection and radiation, were not considered.

2.5. Total Core Meltdown

In the event of a total core meltdown, a last-ditch cooling system consisting of a sodium-cooled pan with a large heat-transfer area will be provided outside the primary tank. The transient thermal analysis of the pan indicated that natural convection cooling provided at the upper and lower surfaces is effective in preventing melt-through.

2.6. Candidate Systems

Two candidate systems for a total core meltdown resulted from this study: Na-NaK-air, and Na-organic coolant-water. In the Na-NaK-air concept, the results indicated that natural circulation of the sodium and the NaK may be feasible, but that forced air flow may be essential to avoid excessively large NaK-to-air heat exchangers.

In the second concept, Biphenyl ($C_{12}H_{10}$) was considered at first because its physical and chemical properties appeared to be suitable as a heat transfer agent for cooling the sodium and transferring the heat to cooling water. A more promising organic fluid is Dowtherm A, which has a lower melting point than does Biphenyl (54 versus 160 F). A potential advantage lies in the possibility of using this system to cool the biological shield during normal operation.

Figure 1. Candidate Systems and Possible Alternates for Emergency Decay Heat Removal

3. DESCRIPTION OF WORK

3.1. Post-DBA Cooling Survey.

The problems associated with core cooling following a design basis accident were surveyed to reveal the philosophies of others on core meltdown and to extract solutions that were applicable to this activity. Both light water reactors and sodium-cooled fast breeders were examined.

The approach taken by the light water reactor industry seems to preclude core melting through the use of engineered safety systems. In 1967 an advisory task force¹ concluded as follows:

The description of the events that could take place subsequent to the postulated meltdown of large portions of a core is at present indeterminate and quite speculative. Reliable and practical methods of containing the large molten masses of fuel that would probably result from such a meltdown do not exist today.

The authors of the report supported the philosophy of emphasizing the integrity of the primary system and the availability of reliable, fast-acting, abundant supplies of emergency cooling water. In a later work conducted by BMI² (1969), the major conclusions were:

- "1. Crumbled cores are not always uncoolable, and core crumbling during a loss-of-coolant accident may not necessarily lead to more serious consequences such as pressure-vessel melt-through.
- "2. Quenching of a hot, dry, fixed bed may be possible."

Emergency cooling systems for existent and planned fast reactor plants were surveyed to determine what others have done to provide post-DBA core cooling. In general, not much information is available. None of the older fast reactor designs (such as FERMI, EBR-II, DOUNREAY, etc.) provide post-DBA cooling in the event that the geometry of the core were seriously disrupted. Among the later designs,

the PFR utilizes sea water as a last-ditch means of cooling the primary tank complex. Special provisions, in the form of a specially cooled structure below the core support plates, have been made to hold a disrupted or partly melted core within the primary system vessel in the unlikely event of the circumstance. In the PHENIX design, cooling tubes embedded in the concrete surrounding the reactor vessel would remove fission product decay heat over long periods of time.

Among the 1000-MWe studies, Atomics International proposed cooling coils attached to the cavity liner surrounding the reactor vessel. In a conceptual design with a pool-type primary system, General Electric proposed the use of several layers of natural-convection-cooled, stainless steel meltdown trays within the primary system's tank core support structure and the blast shield, but details on the use of this system are not available. The effect of a blast on the FFTF³ reactor vessel has been considered, and some work has been done on meltdown, but it has not been decided whether an external cooling system is required. Emergency cooling systems⁴ for several fast reactor designs are compared in Table 1.

Table 1. Comparison of Post-DBA Heat Removal for Several Reactor Designs

Reactor	Post-DBA decay heat removal
FERMI	None
EBR-II	None
DOUNREAY	None
BN 350	None
BOR	None
PHENIX	Cooling coils outside reactor tank
PFR	Specially cooled receptacle below core support plate but within reactor tank
SNR	Cooling of containment wall
CE	Not established
AI	Cavity liner cooling system
GE	None
W	Normal and/or auxiliary coolant loops
B&W	In the event of failure of the heat exchange equipment in the pool, heat is removed through coils in the biological shield

3.2. Analytical Studies

3.2.1. General

A study was undertaken to examine the problems of cooling and containing molten fuel in the event of a core meltdown. Because the physical state, geometry, and behavior of the molten fuel are not known, once melting has begun, it is necessary to establish some basic ground rules. The first and most obvious of these is that a bonafied candidate system must accommodate fuel from a portion of one element all the way up to and including fuel from a total core.

An examination of the reference design indicated that it would be difficult to ensure that heat removal equipment inside the primary tank would survive a disturbance resulting in a total core meltdown. As a result, the meltdown and cooling accommodations for the total core have been located outside the primary tank. Although this may be a satisfactory arrangement for a total core meltdown, it is not desirable for the meltdown of a single fuel assembly. For example, it would not be logical to allow the molten fuel to melt through the core vessel and the primary tank before it reached the area in which cooling would occur. The obvious solution to the total problem was to provide split accommodations for any eventuality; i.e. for minor accidents, retain the molten fuel inside the core vessel, and for larger accidents, retain the fuel outside the primary tank.

A meltdown of seven fuel assemblies was selected as the design criterion for the meltdown pan inside the core vessel. The selection was arbitrary but seemed reasonable on these bases: (1) if not more than seven assemblies melted, then the normal decay heat removal system probably would not be damaged; (2) the removal of heat from a seven-assembly accident did not appear to be formidable; and (3) if more than seven assemblies melted, then the whole core would probably be endangered. Based on this reasoning, two major assumptions were made:

1. For a hypothetical meltdown of seven fuel assemblies, the normal decay heat removal capability will not be incapacitated; therefore, accommodations will be provided inside the core vessel.

2. In the unlikely event of a total core meltdown, accommodations will be provided outside the primary tank.

3.2.2. Seven-Fuel-Assembly Meltdown

This investigation was primarily directed toward examining the problems of containing molten fuel resulting from a hypothetical meltdown of seven fuel assemblies. The molten fuel debris was assumed to be collected on the meltdown pan in a spread-out configuration. A debris layer with various heat sink and heat transfer mechanisms was considered. The melt-through model consisted of several layers as shown in Figure 2. The 2-inch-thick meltdown pan, which was arbitrarily selected, had thermal properties of stainless steel. The thickness of the debris layer was fixed so that the volume of the debris was equal to the volume of seven fuel assemblies. Because of a lack of better data, the thermal properties of the various layers were approximated and/or averaged in the temperature range under consideration.

Figure 2. Seven-Fuel Assembly Meltdown Model (Steady State)

3.2.2.1. Steady-State Analysis

Several assumptions were made for the steady-state analysis:

1. The upper surface of the debris layer was assumed to be in contact with a large volume of sodium. (Although boiling is likely to occur in the immediate vicinity of the surface, it was not considered in this study.)

2. The decay heat was assumed to be generated uniformly in the debris layer of the fuel.

3. The time variation of the decay heat source was assumed to be that for fission product decay;⁵ i.e., for any given time t (seconds),

$$Q = \{0.18t^{-0.8} - 0.07t^{-0.2} + 36.9[1 - \exp(-1.283 \times 10^{-5} t)] + 21\} \times 10^6 \text{ Btu.} \quad (1)$$

A composite slab of molten fuel is shown in Figure 2. Since the decay heat can be removed from either the top or the bottom of the slab, it follows that a plane must exist where the temperature gradient is zero, i.e., $dt/dx = 0$. Below this surface the heat is transferred to the sodium by conduction through the bottom of the steel pan. The heat transfer rate through the steel pan is

$$q_c'' = K_1 \frac{(T_1 - T_0)}{L_1} \quad (2)$$

where L_1 is the thickness of the pan. The decay heat generated above the zero-temperature-gradient surface goes to the upper heat sink by radiation at the top of the molten steel layer. The heat transfer rate by thermal radiation is

$$q_r'' = \sigma F_e F_A (T_4^4 - T_5^4). \quad (3)$$

The decay heat rate in Btu/h is obtained by differentiating equation 1 and applying the equation to seven fuel assemblies out of 288:

Figure 3. Seven-Fuel Assembly Meltdown Model
(Transient Case)

○ Bulk Sodium (800 F)

Case 1: Upper Surface Insulated;

Lower Boundary —
Free Convection.

Case 2: Upper Surface Heat Transfer Coefficient,

$H = 440 \text{ Btu/h-ft}^2 \cdot ^\circ\text{F};$

Lower Boundary —
Free Convection.

$$q = dQ/dt = (0.144t^{-0.2} + 0.014t^{-1.2}) \times 3600 \times 10^6 \times 7/288 \text{ Btu/h} \quad (4)$$

A balance of decay heat with the upper and lower heat sinks is tabulated as follows:

Location and heat transfer mechanism	Area, ft ²	Heat flux, Btu/h-ft ²	Heat balance, Btu/h	
			Approx rate capacity of heat sinks	Decay heat rate (7 fuel assy)
Bottom of debris; conduction through molten and solid fuel and steel slab	$\pi/4 (12.75)^2 = 127.67$	1.944×10^5	24.82×10^6	2.445×10^6 (1 h after shutdown)
Top of debris; radiation	$\pi/4 (12.75)^2 = 127.67$	0.296×10^5	3.78×10^6	
Total:			28.6×10^6	$> 2.445 \times 10^6$

The summation of heat dissipation through the heat sinks is greater than the decay heat generated by the fuel assemblies for a decay time of 1 hour after shutdown. This indicates that a debris up to seven fuel assemblies will not melt through the bottom of the pan.

3.2.2.2. Transient Heat Transfer Analysis

The information presented in the steady-state case study is incomplete in many aspects. To obtain more meaningful results, a transient-temperature analysis of the pan was performed using the TIGER heat transfer computer code.⁶ A model similar to the steady state model was set up, as shown in Figure 3, with the addition of two more composite slabs, i.e., sodium below the meltdown pan and the 1.5-inch steel core vessel. The fuel and the structural debris were assumed to be molten initially. Two cases were examined:

Case 1 — It was assumed that all the primary pumps were shut down and that the upper surface of the debris was not allowed to lose heat. Clearly, this situation does not reflect any real condition that could exist in the core vessel, for it would not be possible to insulate the top layer of debris, and design requirements in the 1000-MWe Follow-On study dictate that after shutdown the core would be cooled by operating the primary pumps with pony motors. The only reason for running this case was to determine whether melt-through was a possibility.

Figure 4. Transient-Temperature Response, Seven-Fuel-Assembly Meltdown (Case 2)

The model was based on pure conduction heat transfer through the sodium located between the pan and the core vessel. Making the same assumptions as in the steady-state case, it was then assumed that the core failure occurred instantaneously. This represents the worst condition that could be seen by the pan because the decay heat generation rate is at its maximum. The program was terminated when the sodium closest to the pan approached the boiling point. Information beyond this point would have no value.

The calculated steel temperatures at the end of 3 hours were about 2050 F, and they were still rising when the calculations were terminated. The temperature of the sodium closest to the pan (1524 F) was approaching the boiling point (1618 F at 1 atmosphere). Hence, the investigation was terminated at this point. It appears that melt-through would probably occur under these severe conditions.

Case 2 — It was assumed that the pony motors were in operation and capable of providing 5% of the total flow rate. This situation was simulated by assigning a heat transfer coefficient of 440 Btu/h-ft²-°F to the upper surface of the debris layer in contact with flowing sodium. The value of 440 Btu/h-ft²-°F was computed using heat transfer correlations for forced convection cooling with turbulent flow (see Appendix A). The transient-temperature results are shown in Figure 4. When the investigation was terminated (3 hours), the temperature profile of the pan was about 920 F and just starting to come to steady-state. Thus, it appears that the forced convection cooling with 5% of the total flow rate is sufficient to preclude melt-through.

3.2.2.3. Conclusion

The results of the seven-fuel-assembly melt-down study indicate that melt-through can be precluded as long as the pony motors are operable and capable of providing 5% of the total flow rate. Cases with poorer cooling capabilities, such as natural convection and radiation, were not considered.

Figure 5. Emergency Decay Heat Removal Concept

3.2.3. Total Core Meltdown

Under conditions resulting in a meltdown of more than seven fuel assemblies, an additional engineered safeguard system is required to accommodate the core debris and provide a means to cool it. Using natural convection cooling and a large surface-to-mass ratio as the design approach, we identified and evaluated a possible candidate system for containing and cooling the molten core.

The conceptual layout of the emergency decay heat removal system is shown in Figure 5. The concept provides a sodium-cooled pan with a large heat transfer area below the primary tank. The meltdown pan has sufficient thickness and thermal conductance to prevent melt-through as long as the subcritical accumulation is surrounded by the sodium coolant.

In general, the physical state and the geometric configuration of the core debris during and after core meltdown and migration are not known. In order to analyze the situation, we had to make assumptions and then proceed with the transient-temperature analysis of the pan. The assumptions are as follows:

1. All of the fuel and structural debris from the core melts and falls down into the pan, including all the materials below the core; i.e., the lower grid plate, the meltdown pan inside the core vessel, the bottom-head of the core vessel, and the bottom-head of the reactor vessel. The pan is located far enough below the reactor vessel to protect itself from the effects of any shock or blast energies associated with the DBA.

2. Since the time at which significant quantities of core material can reach the pan is unknown, a decay time of 800 seconds in one case and 20 seconds in the second case was arbitrarily assumed.

3. When all of the debris is collected in the pan, it will be distributed into a spread-out configuration forming two layers consisting of molten steel on top of the fuel. The distribution can probably be aided by providing an inverted funnel at the midportion of the pan similar in construction to that used in FERMI (see Figure 5).

4. The decay heat is generated uniformly in the debris layer. The time variation of the decay heat source is that for fission product decay⁵ as given by

$$q = (0.144t^{-0.2} + 0.014t^{-1.2}) \times 3600 \times 10^6 \text{ Btu/h,}$$

where t = seconds. This assumption is made on the basis that the stored energy and the excursion energy associated with the initial accident have already been dissipated to the sodium, and that the ^{24}Na decay heat generation is insignificant in relation to the fission-product decay heat generation.

5. Heat transfer in the axial direction represents only a fair approximation of the true situation.

6. The following thermal properties⁷⁻⁹ of the fuel debris and molten steel are valid estimates:

	<u>Fuel</u>	<u>Steel</u>
Melting temp, F	5080	2600
Boiling temp, F	6200	5500
Conductivity, Btu/h-ft-°F	2.9 (molten) 2 (solid)	12 (800 °F) 18 (2300 °F)
Specific heat, Btu/lb-°F	0.10545	0.17
Density, lb/in. ³	0.3334	0.276

Since the TIGER code has no provision for varying the thermal conductivity as a function of temperature, a constant value of 2.45 Btu/h-ft²-°F is used. This value is probably low and should provide a certain degree of conservatism in the calculations. Decreasing the debris conductivity decreases the capability of diffusing heat within the debris layer, resulting in a higher maximum temperature in the debris. This would represent a worse condition than a higher debris conductivity.

The following procedure was used in the transient-temperature analysis of the pan: A simplified model consisting of three slabs was set up. The lowest slab represents the meltdown pan, which

was assumed to be 40 feet in diameter and 1-foot thick. The middle portion represents a layer of molten fuel debris, and the upper slab represents a layer of structural debris (see Appendix B). The size and geometry of the fuel and structural debris were fixed so that the volumes of each were equal to the volume of the fuel in the core and all structural materials that melted with it as it flowed downward to the meltdown pan. The upper surface of the debris layer and the bottom surface of the pan were assumed to be in contact with sodium.

A series of transient conditions was analyzed using the TIGER computer code. Heat transfer coefficients at the upper and lower surfaces were varied for each case. The analysis was divided into four cases; the values assigned for the coefficients are as follows:

Case No.	Heat transfer coefficient, Btu/h-ft ² -°F		Heat transfer mechanism at surface
	h_{upper}	h_{lower}	
1	733	183	Natural convection ($\Delta T = 20^\circ\text{F}$)
2	600	150	Natural convection ($\Delta T = 10^\circ\text{F}$)
3	60	15	Arbitrarily assigned, which may represent radiation
4.1	30 ($0 \leq t \leq 20$ min)	1.3 ($0 \leq t \leq 20$ min)	1. Radiation from the upper surface, free convection for the lower surface for $0 \leq t \leq 20$ min
4.2	733 ($t > 20$ min)	183 ($t > 20$ min)	2. Natural convection ($\Delta T = 20^\circ\text{F}$) for $t > 20$ min

In the first three cases a decay time of 800 seconds was used as the time at which significant quantities of core material could reach the pan, and in the fourth case a decay time of 20 seconds was used.

The results of calculations for cases 1 through 4 are shown in Figures 6 through 9, respectively. Cases 1 and 2 simulate conditions under which the core debris is cooled by natural convection, depending on the ΔT , while transferring heat to an isothermal sink.

The heat transfer coefficients for case 3 were arbitrarily assigned and would probably include the effect of radiation. The cooling coefficients used in case 4 would represent radiation from the top surface of the debris, and free convection at the bottom of the pan facing downward; after 20 minutes, it was assumed that both surfaces were cooled by natural convection of sodium.

Figure 6 is the result of a typical transient response for case 1. Upon contact with the hot molten fuel, the temperature of the steel pan closest to the fuel-pan interface increases to a maximum temperature of 2400 F at 1200 seconds. The temperature at the bottom of the steel pan increases slightly up to 360 seconds. At this time, sodium is available to cool the external surfaces by natural convection. In this way the lower surface of the pan is cooled down to a steady-state value. In like manner, the temperature of the molten structural debris, which is directly in contact with sodium, slightly increases at first. After 360 seconds, the temperature drops rapidly and the structural debris solidifies owing to the effective cooling at its upper surface. Since the heat transfer at the upper surface is greater than that at the lower surface, the temperature of the structural debris drops below the temperature at the bottom of the pan at 3400 seconds. The temperature at the center of the molten fuel increases slightly at first. Because of the decreasing temperatures of the structural debris and the pan, the fuel debris freezes at 700 seconds.

For all cases, the results show that natural-convection cooling at the external surfaces is a very effective means of retarding or preventing melt-through. It seems likely that the pan will not fail even with low heat-transfer coefficients (i.e., case 3 with 60 and 15 Btu/h-ft²-°F) and delayed natural convection cooling (case 4).

Figure 6. External Meltdown Pan Transient-Temperature Response (Case 1)

Figure 7. External Meltdown Pan Transient-Temperature Response (Case 2)

Figure 8. External Meltdown Pan Transient-Temperature Response (Case 3)

Figure 9. External Meltdown Pan Transient-Temperature Response (Case 4)

3.3. System Requirements

3.3.1. Identification of Follow-On Reference Requirements

The primary function of the emergency DHRS is to remove fission-product decay heat from the reactor after any accident up to and including a design basis accident (DBA). During post-DBA decay heat removal operations, the decay heat loop should be capable of transferring and rejecting the heat generated by the damaged core. Additional requirements are as follows:

1. After a DBA, the system should be capable of providing sufficient coolant flow in the decay heat loop to permit heat exchange.
2. The heat rejection system should be arranged so that no sodium leak, including leaks resulting from the DBA, will make emergency cooling impossible.
3. The system must be completely reliable and should not require expensive installation that is useless during normal operation of the reactor.
4. Provisions should be included for testing the full operational sequence that would bring the emergency heat removal mechanisms into operation.
5. The system should be designed so that the components, including heat exchangers, pumps, fans, valves, and interconnecting piping, can be removed and replaced.
6. The primary system components, such as pipes and heat exchangers, should be protected from radiation during normal operation and from possible damage resulting from a vessel rupture.
7. The volume of the primary decay heat loop should be chosen so that, if it is filled with sodium, the level in primary tank will not fall below the top of the core.

3.3.1.1. Identification of Important Features

In the reference Follow-On design, the emergency DHRS removes decay heat after a DBA. The important features associated with the design are summarized as follows:

1. The system contains two separate and similar decay heat removal loops which can be operated independently.
2. The system shares the same components with the normal decay heat removal system.
3. Electromagnetic pumps circulate the NaK through the circumferential biological shield cooling coils.
4. In the NaK-to-air heat exchanger, forced-air cooling with fans is used.
5. If the reactor vessel does not fail after a DBA, action will be taken to dump sodium from the intermediate loop into this void. This ensures thermal communication between the cooling coils and the decay heat source.
6. When the reactor is on line, the system is in a standby condition.

3.3.1.2. Identification of Reference Design Limitations

In the Follow-On design described in section 2.2, the decay heat is removed through NaK cooling coils in the biological shield. Some of the disadvantages associated with this design are:

1. There is no provision, except perhaps the reactor pit liner, to protect the coils after a DBA.
2. The system has added complications because the normal and post-DBA cooling are combined.
3. There is no post-DBA cooling under the reactor.
4. The entire system cannot be operated periodically to ensure its operability when the need arises.

5. There is no insulation between the reactor vessel and the concrete shielding. Therefore, a considerable amount of heat has to be removed to cool the concrete during normal operation.

3.3.2. Identification of Potential Requirements

In addition to the requirements developed during the Follow-On Studies, the following requirements and conditions are assumed:

1. Use natural circulation throughout.
2. Separate the post-DBA system from the normal decay heat removal system.
3. Protect the system from the effects of nuclear accidents.
4. Design so that an accident limited to seven fuel assemblies will not destroy the capabilities of the normal DHRS.
5. Provide meltdown accommodations for seven assemblies inside the core vessel.
6. Provide meltdown accommodations for more than seven fuel assemblies outside the primary tank.
7. Have primary sodium available under conditions requiring use of the outside meltdown accommodations.
8. Use pans or catchers fabricated from an appropriate material to accommodate molten fuel outside the primary tank.

3.4. Candidate Emergency Decay Heat Removal Systems

3.4.1. General

Based on the requirements and conditions delineated in section 3.3, candidate systems were developed to meet these requirements. The emergency DHRS has been divided into three subsystems as follows:

1. Primary Decay Heat Removal Subsystem (PDHRS)—covers features that are needed to remove heat from the disassembled core and transfer it to the primary sodium.

Figure 10. Primary Sodium Flow Vs Hot-Leg Temperature

2. Secondary Decay Heat Removal Subsystem (SDHRS)—covers features that are needed to remove heat from the primary sodium and transfer it to the secondary heat transfer fluid.

3. Heat Sink Subsystem (HSS)—covers features considered necessary to transfer heat to the final heat sink.

The results of investigations on these subsystems are discussed in the following sections.

3.4.2. Primary Decay Heat Removal Subsystem

Figure 5 shows a section of a conceptual layout of the channels connecting the annulus with the heat sink, the seven-fuel-assembly meltdown pan inside the core vessel, and the core catcher for total core meltdown outside the primary tank. In this concept, sodium flows upward as it is being heated and circulates naturally through the channels leading to a heat exchanger in the biological shield. Heat from the sodium is transferred to the secondary fluid flowing countercurrent in the tubeside of the heat exchanger. The cooled sodium then flows by gravity through passageways leading to the bottom of the annulus surrounding the reactor vessel, thereby completing the loop.

3.4.2.1. Natural Circulation of Primary Sodium After DBA

The path for natural circulation is shown in Figure 10. The head for natural circulation is provided by the difference in height between the center of the active zone and the heat exchanger, and the difference in density between the heat source (in this case, the fuel debris) and the heat exchanger.

Using assumed values for the dimensions of the pipes and channels, the flow rate resulting from natural circulation may be expressed as a function of the difference in density between the hot and cold legs. Since neither hot- nor cold-leg temperatures were known, a parametric analysis was made to determine the minimum hot-leg temperature that would initiate natural circulation for different internal generation levels, holding the cold-leg temperature constant (see Appendix C). Figure 10 shows the effects of these parameters on the primary system flow rate. Thus, for a decay heat rate of 136×10^6

Btu/h (corresponding to decay heat level 800 seconds after reactor shutdown), the hot-leg temperature must be at least 1140 F in order to initiate natural circulation with the cold-leg temperature at 450 F.

As a result of this investigation, one can reasonably conclude that natural circulation of primary sodium can reliably provide emergency cooling of the core debris collected at the bottom of the external meltdown pan. It is recognized that some thermal stress problems could arise in the heat exchanger equipment.

3.4.2.2. Volume of Primary Decay Heat Removal Subsystem

Calculations were made to determine the volume of the emergency decay heat removal loop, i.e., the volumes of the annular region, the heat exchangers, interconnecting pipes, and channels. The length, size, number, and geometry of connecting channels were assumed in order to make pressure-drop calculations. The results indicate that this volume can be filled without uncovering the core.

3.4.2.3. Possible Alternate

As an alternate to active systems that will mitigate the effects of a core meltdown, BNWL is performing an analysis of the "China Syndrome." The history of the fuel, core, and structural material after a meltdown is being estimated with special emphasis on the downward progress of the molten material and on the heat transfer to the concrete floor. The results of this study will determine the size of the molten pool formed by dissolution of the concrete floor in contact with the molten core as a function of time. This approach may be applicable to power plants of larger size.

3.4.3. Secondary Decay Heat Removal Subsystem

This subsystem covers features that are needed to remove heat from the primary sodium and transfer it to the secondary heat transfer fluid. B&W's reference design provided circumferential biological shield cooling coils to remove heat from the primary sodium following a DBA. This feature has an inherent weakness: it would be difficult to ensure that the coils were protected after a core disturbance,

and that a heat transfer path existed between the primary sodium and the NaK in the coils.

An alternate concept that would overcome some of the difficulty was investigated. Here, the heat exchangers that will remove heat from the primary sodium can be positioned deep inside the biological shield, and the connecting channels between the heat exchanger and the annulus can be offset and redundant to virtually ensure that shearing or blockage does not interfere with their intended operation.

The primary sodium on the shell side of the heat exchanger gives up its heat to the countercurrent secondary fluid in the tubes. The heat is transported to an ultimate sink located outside the reactor containment. Given an effective heat sink, natural circulation of the secondary fluid is essentially assured, since the difference in height between the heat addition regions in the heat exchanger and ultimate heat sink is about 100 feet. The piping can be made large enough so that the flow resistance will be small. The general considerations for the secondary heat transfer fluids include:

1. Compatibility with sodium and heat sink fluid.
2. Design approach, i.e., single or multi-purpose system.

Two candidate heat exchanger concepts were considered:

(1) Na-to-NaK heat exchanger, and (2) Na-to-organic coolant.

3.4.3.1. Na-NaK Heat Exchanger

A simple shell-and-tube heat exchanger with counterflow and single-pass arrangement was selected. Typical values taken from the 1000-MWe reference design were used in the heat transfer and pressure drop calculations (see Appendix D). In the design studies, minimizing the size of the component was emphasized by assuming a larger temperature rise in the primary side and by minimizing the flow rates. Table 2 shows the results of the Na-NaK heat exchanger investigations.

Table 2. Comparison of Na-NaK and Na-C₁₂H₁₀ Heat Exchangers

	Na-NaK	Na-C ₁₂ H ₁₀
Temperature, F	Na: $t_{in} = 800^{(a)}$ $t_{out} = 450$ NaK: $t_{in} = 400^{(b)}$ $t_{out} = 700$	Na: $t_{in} = 800^{(a)}$ $t_{out} = 450$ C ₁₂ H ₁₀ : $t_{in} = 200^{(b)}$ $t_{out} = 450$
Flow rate, lb/h	$w_{Na} = 0.788 \times 10^6$ $w_{NaK} = 1.113 \times 10^6$	$w_{Na} = 0.788 \times 10^6$ $w_{C_{12}H_{10}} = 0.72 \times 10^6$
Heat transfer coefficient, Btu/h-ft ² -°F	$h_{Na} = 4737$ $h_{NaK} = 2481$ $h_m = 2477$ $U = 983$	$h_{Na} = 4953$ $h_{C_{12}H_{10}} = 129$ $h_m = 2477$ $U = 119$
LMTD, °F	72.2	297
Heat transfer area, ft ²	A = 1196	A = 2407
Effective length, ft	L = 6.2	L = 12.5

(a) Shell side.

(b) Tube side.

3.4.3.2. Na-Organic Coolant Heat Exchanger

A secondary system using Biphenyl (C₁₂H₁₀) as the heat transfer medium was examined. Table 2 compares the Na-Biphenyl and the Na-NaK heat exchangers.

The physical and chemical properties of Biphenyl¹⁰ indicate that it is suitable as a heat transfer agent for cooling the sodium and transferring the heat to cooling water. However, keeping in mind that the post-DBA heat removal system might be operated on a continuous basis (i.e., the system removes heat from the biological shield under normal operating conditions), the high freezing

point of Biphenyl (156 F) makes it unsuitable as a heat transfer medium because of the danger of freezing. Hence, the physical and chemical properties of various fluids were investigated briefly. The results of the survey seem to suggest that Dowtherm A is the best candidate. It has about the same characteristics as Biphenyl, but in addition it freezes at a lower temperature (56 F) and can be operated over a wider range of temperatures. Some of the important properties of NaK, Biphenyl, and Dowtherm A are compared in Table 3.

Table 3. Comparison of Secondary Heat Transfer Fluids¹¹

	<u>NaK</u>	<u>Biphenyl (C₁₂H₁₀)</u>	<u>Dowtherm A</u>
Melting point, F	66.2	160	53.6
Boiling point, F	1518	489	495.8
Relative capital cost	2.35	0.11	0.23
Specific heat, Btu/lb-°F	0.28	0.40 - 0.56 (liquid) (150 - 500 F)	0.63 - 0.69 (liquid) (500 - 750 F)
Decomposition	Stable	Stable up to approx 700 F	Stable up to 705 F

3.4.4. Heat Sink Subsystem

This subsystem covers the features considered necessary to transfer heat to the final heat sink. Some of the considerations and assumptions established for the system are as follows:

1. Compatability of the heat transfer fluid with both the sodium and the heat sink fluid.
2. Natural circulation in all circuits with an option to provide forced circulation as indicated by more detailed evaluations.
3. Separate fluid systems from those involved with normal decay heat, if possible.
4. Possibility of using heat removal capabilities to cool the biological shield during normal operation.
5. Other functional requirements as listed in section 3.3.1.

Table 4. Comparison of Forced-Convection and Free-Convection NaK-Air Heat Exchangers

NaK Flow (two passes unmixed);
Air Crossflow (mixed)

	Forced convection	Natural convection
Tubing OD, in.	1.024	1.024
Tubing wall thickness, in.	0.049	0.049
No. of cooling fins per inch of tubing length	8.8	8.8
Cooling fin diameter, in.	1.737	1.737
Material of construction	304 SS	304 SS
Total air flow rate, cfm	414.300	--
Approximate NaK ΔP , psi	0.779	--
Shaft hp	322	--
Tube array dimensions (length/ width), ft	20/12	--
No. of tube rows	8	--
Air side heat transfer coefficient based on fin side, Btu/h-ft ² -°F	20.3	5
Air flow frontal area, ft ² (a)	240	2177

(a) For the same size tubes and cooling fins, as well as inlet and outlet temperatures, the natural-convection scheme would require an air frontal area of 2177 ft², while forced convection would require 240 ft²—a factor of 9 difference. The obvious conclusion is that it may be difficult and expensive to obtain enough heat transfer surface

Two candidate systems were evaluated in an effort to determine the magnitude of the problem involved in meeting the requirements for an ultimate heat sink.

3.4.4.1. Na-NaK-Air System

In the Na-NaK natural convection system, both free and forced convection of air were considered. Preliminary results are shown in Table 4 for the free-convection and forced-convection NaK-air heat exchanger concepts. The results show that forced air flow utilizing motor-driven fans is essential to avoid excessively large heat exchangers. Heat transfer and pressure drop calculations are shown in Appendix E.

3.4.4.2. Na-Organic Coolant-Water System

The two different configurations of heat exchangers were considered for the organic coolant-water system: submerged pipe coil; and bundle-in-column.¹² The submerged pipe coil is one of the simplest and cheapest methods of obtaining cooling surface. A series of pipes is connected by standard fittings and submerged in a trough with water circulating about the pipes. The organic coolant in the tube side can be arranged for a single pass or for a multiple pass through pipes that are connected by return elbows. The results of calculations for the latter arrangement show that approximately 7563 ft² of heat transfer area is needed to remove 85.5×10^6 lb/h.

The bundle-in-column heat exchanger consists of a bundle of tubes submerged in a column of water. The tubes, arranged for two passes, have headers attached at both ends. From a heat-transfer standpoint, approximately 7600 ft² of heat-transfer area is needed to remove 85.5×10^6 Btu/h.

Table 5 shows some pertinent results for the organic coolant-to-water heat exchangers. No attempt was made to compare the individual concepts on the basis of economics.

The bundle-in-column heat exchanger is not practical in size because the tubes are too long. To decrease the length of the tubes, the diameter of the bundle, and consequently the heat transfer area, has to be increased. Hence, from a practical viewpoint, the submerged pipe coil exchanger is better than the bundle-in-column exchanger.

Table 5. Comparison of Biphenyl-to-Water Heat Exchangers

	<u>Submerged pipe coil</u>	<u>Bundle-in-column</u>
Temperature, F		
Biphenyl, t_{in}	450	450
Biphenyl, t_{out}	200	200
Water, t_{in}	80	80
Water, t_{out}	150	150
Tube diameter, in.	6	2
Overall heat transfer coefficient (U), Btu/h-ft ² -°F	62	56.3
Heat transfer area (A), ft ²	7010	7723
Length of tubes, ft	24	97
No. of tubes	182	152

3.4.5. Additional Alternate Systems

One important consideration in selecting potential candidates for the emergency decay heat removal system is that the system must be completely reliable and should not require an expensive installation that is useless during normal operation of the reactor. This brings up the possibility of using the DHRS to remove heat from the biological shield during normal operation of the plant.

A brief study was conducted to determine the feasibility of coupling the biological shield's normal heat removal functions with

functions of the standby emergency decay heat removal equipment.

Some of the considerations that were evaluated are as follows:

1. Examination of the primary tank cavity for insulation requirements during normal operation relative to the location and characteristics of the insulation.
2. Circulation of argon gas through the primary decay heat loop.
3. Addition of extended surfaces to the heat exchanger for heat removal from the biological shield during normal operation.

3. 4. 5. 1. Insulation Requirements for Primary
Tank Cavity During Normal Operating
Conditions

To prevent the biological shield from being exposed to high temperatures for prolonged periods of time without removing excessive amounts of heat, it was necessary to install insulation between the primary tank and the shield's liner. Mirror insulation was selected from a series of candidates. The choice and location of insulation were based on the following requirements:

1. It should be located away from the primary tank to allow for possible inspection requirements of the vessel.
2. Its properties should permit it to perform as required during normal operation, but offer little resistance to heat transfer to permit emergency core cooling when the annulus is filled with sodium.
3. It should have good structural integrity to prevent slumping.

Mirror insulation is a thermal reflective material consisting of concentric sheets of stainless steel spaced to allow for a gas gap between the sheets. During normal operation, the insulation is effective to yield a desired heat loss when the inside surface temperature and the outside gas temperature are known. Past experience has indicated that a heat loss of approximately 80 Btu/h-ft² is not unreasonable for temperature drops of five- to six-hundred degrees.

To provide for emergency core cooling where the annulus is filled with sodium, offset holes are punched in the sheets.

These holes allow the sodium to circulate through the concentric gas spaces to the outer surface with only slight heat loss penalties during normal operation.

3.4.5.2. Argon Cooling System

By providing insulation between the primary tank and the biological shield, the heat removal rate to cool the biological shield is reduced to approximately 5.0×10^5 Btu/h. This heat loss can be removed by circulating 100,800 lb/h of argon gas through the primary decay heat loop with hot- and cold-leg temperatures of 150 F and 110 F, respectively. Heat transfer calculations are shown in Appendix F.

3.4.5.3. Argon-NaK-Air System

The possibility of using an argon-NaK heat exchanger with extended surfaces was examined. Heat transfer calculations were performed using the Na-NaK heat exchanger and incorporating extended surfaces. The results indicate that a heat transfer area of 3100 ft² is required, a factor of 2.25 times the heat transfer area required for the Na-NaK heat exchanger without extended surfaces. It appears that a heat exchanger of this size could be accommodated in the biological shield.

Table 6 compares the emergency DHRS operating as a standby unit with that operating under normal conditions with argon gas to cool the biological shield.

The potential for natural circulation in both primary and secondary loops was not examined. However, it seems likely that forced circulation of the argon will be required in the primary loop.

Table 6. Comparison of Na-NaK-Air and Argon-NaK-Air Systems

<u>Heat exchanger</u>	<u>System operating as standby unit</u>	<u>System operating under normal conditions</u>
Na-NaK	$A_{HT} = 1375 \text{ ft}^2$	$A_{HT} = 3100 \text{ ft}^2$ (with extended surfaces and argon in the primary side)
NaK-air	$A_{HT} = 1480 \text{ ft}^2$	$A_{HT} = 1480 \text{ ft}^2$ (requires only 582 ft^2 of surface area, during normal operation with argon-NaK-air concept)

4. RESULTS AND CONCLUSIONS

The systems required to remove heat from the primary sodium following an accident in the core depend on the character and magnitude of the accident. The mechanisms that describe the consequences of the accidents for which candidate systems are provided have not been fully explored.

The major problem areas considered at the outset of this activity were:

1. Transport of core debris from its initial location to its final destination.
2. Core debris configuration at the location where it is to be cooled.
3. Mechanisms and systems for cooling the core debris.
4. Systems for rejecting the heat to the ultimate heat sink.

Although it was recognized that items one and two are of major significance to the development of satisfactory candidate systems, these points could only be treated lightly because of a lack of quantitative information. The majority of the effort for this activity was focused on items three and four.

In the investigation of the Primary Decay Heat Removal Subsystem (PDHRS), two major assumptions were established as a starting point:

1. For a hypothetical meltdown of seven fuel assemblies, accommodations will be provided inside the core vessel; the premise here is that the consequences of such an accident will not incapacitate normal decay heat removal systems.

2. In the event of a total core meltdown the same premise cannot be made. Therefore, accommodations will be provided outside the primary tank.

The major limitations associated with the analysis of the PDHRS are as follows:

1. The models used for the heat transfer analysis of the meltdown pans were simplified one-dimensional representations of the processes involved. The physical properties of the materials involved did not change as a function of temperature. In some cases heat transfer coefficients were approximated and allowed to remain constant over a selected time interval.

2. In the present analysis, no attempt was made to determine the effects of varying the depth and conductivity of the debris or the effects of varying the thickness of the meltdown pan.

3. Internal convection and mass transfer within the molten debris were not considered.

4. The total core meltdown analysis was centered around one ideal case assumption: that an inverted funnel compelled all of the molten materials in the core to spread uniformly throughout the bottom surface of the pan. The possibility that molten debris could solidify upon contact with the cold surface of the funnel, thus tending to accumulate larger and larger amounts of fuel in a configuration that yields an increasing heat flux, has not been eliminated. This possibility could lead to temperatures that might cause melt-through of the pan. No attempt was made to treat this condition.

Based on the foregoing assumptions and limitations, the following conclusions were made:

1. For the case of seven fuel assemblies melting down, it appears that melt-through can be precluded if sufficient flow (approximately 5% of the total) is provided by the pony motors on the primary pumps. Cases with poorer cooling capabilities, such as natural convection, were not considered.

2. For the total core meltdown, natural-convection cooling provided at the upper surface of the debris and the bottom surface of the pan appeared to be very effective in preventing melt-through. The sodium-cooled pan consisted of a large heat transfer area and an inverted

funnel at the center of the pan to prevent a supercritical configuration from forming following a core meltdown.

Candidate systems for emergency decay heat removal were identified and developed to the extent required for an initial screening of questionable systems. These systems were based on "candidate" requirements, which were arbitrarily imposed pending the results from Activity 232.

Some of the important features incorporated with the candidate systems are summarized as follows:

1. Circulation by natural convection in both the PDHRS and the SDHRS.
2. Separation of the post-DBA system from the normal decay heat removal system.
3. Relocation of the heat exchange equipment that will remove the heat from the primary systems to better protect them from core disturbances.
4. Incorporation of redundant and offset primary coolant channels to the heat exchangers located within the biological shields to ensure that blocking or shearing will not interfere with the heat removal operation.
5. Combination of the post-DBA heat removal system with a normal operating heat removal function (shield cooling) to ensure availability.
6. Incorporation of bottom cooling for the primary tank to prevent breeching of the secondary containment by core debris.

APPENDIX A
Meltdown of Seven Fuel Assemblies
Transient Thermal Analysis

The magnitude of the heat transfer coefficient for the condition where the flow is 5% of the total flow rate was obtained by considering the relationships for forced-convection cooling along a heated plate. An approximate relationship for the Nusselt's number is given by Yevick¹³ as follows:

$$Nu = 0.38 Pe^{0.65} \text{ for turbulent flow,}$$

$$Nu = 1.1[(1 - Pr^{0.333})Pe]^{0.5} \text{ for laminar flow,}$$

where

$$Pe \text{ (Peclet No.)} = Pr \times Re,$$

$$Pr \text{ (Prandtl No.)} = \frac{C_p \mu}{k}.$$

The heat transfer coefficient was then calculated from the relation

$$h = \frac{Nu k}{D}.$$

The Reynolds and Nusselt numbers are based on plate diameter.

Calculation of Heat Transfer Coefficient

All thermal properties of sodium¹⁴ were evaluated at 800 °F.

$$\rho = 53.05 \text{ lb/ft}^3$$

$$\mu = 0.6437 \text{ lb/ft-h}$$

$$k = 40.6 \text{ Btu/h-ft-}^\circ\text{F}$$

$$Pr = 0.00482$$

$$w = 4.6 \times 10^6 \text{ lb/h (5\% of the total flow rate)}$$

$$D = \text{diameter of plate} = 12.75 \text{ ft}$$

$$A = \text{free-flow area} = 49.46 \text{ ft}^2.$$

Reynolds No.:

$$Re = \frac{VD\rho}{\mu} = \frac{\omega D}{A\mu} = 1.842 \times 10^6.$$

We can therefore say that the flow is turbulent.

$$Pe = Pr \times Re = 8879,$$

$$Nu = 0.38(Pe)^{0.65} = 140.6,$$

$$h = \frac{Nuk}{D} = 447.9 \text{ Btu/h-ft}^2\text{-}^\circ\text{F}.$$

Use

$$h = 440 \text{ Btu/h-ft}^2\text{-}^\circ\text{F}.$$

APPENDIX B
Total Core Meltdown Transient
Thermal Analysis

● 16 (Sodium)

13

12

11

III

10

9

8

7

II

6

5

4

3

I

2

1

14

15 (Sodium)

Structural Steel-to-Fuel Interface

Fuel-to-Pan Interface

Both Sides Insulated

One-Dim. Unit Depth

3.2"

2.4"

12"

$$\begin{aligned}C_p &= 0.17 \text{ Btu/lb-}^\circ\text{F} \\ \rho &= 0.276 \text{ lb/in.}^3 \\ k &= 18 \text{ Btu/h-ft-}^\circ\text{F}\end{aligned}$$
$$\begin{aligned}C_p &= 0.1054 \\ \rho &= 0.3334 \\ k &= 2.45\end{aligned}$$
$$\begin{aligned}C_p &= 0.17 \\ \rho &= 0.276 \\ k &= 18\end{aligned}$$

Internal Generation: All Fuel Nodes
(i. e. Nodes 7 - 10)

Example: Case No. 1 — Total Core Meltdown

For this case it was assumed that the earliest time at which significant quantities of core material can reach the pan is 800 seconds. During this time, the sodium surrounding the pan would be heated to approximately 1140 F. Hence, the initial temperature of the meltdown pan was assumed to be 1140 F. The initial temperature of the fuel nodes was set at 5640 F, which is the average temperature of boiling and melting fuel (6200 F and 5080 F, respectively). For the molten structural debris, the node closest to the fuel interface was arbitrarily set at

5080 F (near the boiling temperature of steel, which is 5500 F), and the middle node at 4050 F (average of melting and boiling temperatures). The surface node exposed to sodium was arbitrarily set at 2600 F (melting temperature of steel).

2. Internal Heat Generation Library

The total volume of fuel in the core is 248 ft³. The internal heat generation in Btu/h-in.³ is expressed as a function of time after shutdown:

$$q''' = (0.144t^{-0.2} + 0.014t^{-1.2}) \times \frac{3600 \times 10^6}{248 \times 1728} \text{ Btu/h-in.}^3$$

where t is time, in seconds, after reactor shutdown.

The initial internal generation level at $t = 800$ seconds is

$$q''' = [0.144(800)^{-0.2} + 0.014(800)^{-1.2}] \frac{3600 \times 10^6}{248 \times 1728} = 317 \text{ Btu/h-in.}^3$$

3. Boundary Temperature Library

The initial temperature of the sodium at 800 seconds after shutdown, is 1140 F. There is a certain delay time for the sodium to naturally circulate. Since this is not known, the time to initiate natural circulation of the sodium from the primary tank annulus through the biological shield channels and heat exchanger, and then back to the primary tank, was assumed to be 5 minutes. Hence, the temperature of the sodium surrounding the core debris was allowed to decrease linearly from 1140 F to 450 F at a real time of 5 minutes. Then, the inlet temperature was held constant at 450 F after 5 minutes.

4. Heat Transfer Coefficient at Surface

For the cooling of a hot plate of diameter D on the bottom of a pool facing up,¹³ the following equation is applicable:

$$Nu = 0.0785 (Gr \times Pr)^{0.32}$$

where the diameter of the cold spot is the characteristic length. Thermal properties of sodium will be evaluated at 800 F.

$$Pr = 0.00482$$

$$\rho = 53.05 \text{ lb/ft}^3$$

$$\beta = 1.5634 \times 10^{-4} / ^\circ\text{F}$$

$$\mu = 0.6437 \text{ lb/ft-h}$$

$$g = 32.2 \text{ ft/s}^2 = 417.3 \times 10^6 \text{ ft/h}^2$$

$$D = \text{diameter of plate} = 40 \text{ ft.}$$

Grashop's No.:

$$Gr = \frac{L^3 \rho^2 g \beta \Delta T}{\mu^2} = 2.836 \times 10^{13} \Delta T.$$

$$Nu = 0.0785 (Gr \times Pr)^{0.32} = 286.9 (\Delta T)^{0.32}$$

$$h = \frac{Nu k}{D} = 286.9 (\Delta T)^{0.32}$$

where ΔT = difference between the coolant temperature at the wall and far from the wall.

If $\Delta T = 1000 \text{ F}$, then

$$h = 286.9 (1000)^{0.32} = 2619.4 \text{ Btu/h-ft}^2\text{-}^\circ\text{F}.$$

If $\Delta T = 20 \text{ F}$, then

$$h = 286.9 (20)^{0.32} = 748.$$

If $\Delta T = 10 \text{ F}$, then

$$h = 286.9 (10)^{0.32} = 600.$$

Arbitrarily choose $h = 733 \text{ Btu/h-ft}^2\text{-}^\circ\text{F}$ (conservative assumption) for $\Delta T \approx 20 \text{ F}$.

The heat transfer coefficient at the lower surface of the pan was assumed to be approximately 24.9% of the coefficient at the upper surface, based on the flow geometry in the plenum surrounding the pan and core debris. Hence,

$$h_{\text{lower}} = 733 (0.249) = 183 \text{ Btu/h-ft}^2\text{-}^\circ\text{F}.$$

The investigation was started at 0.1 second (corresponding to 800 seconds after reactor shutdown) and terminated at 180 minutes. Printout times were selected arbitrarily.

The temperature distribution solution by the TIGER program is shown below for Case No. 1. The pertinent results are plotted in Figure 6.

THE INITIAL TEMPERATURE DISTRIBUTION

NODE	TEMP	NODE	TEMP	NODE	TEMP	NODE	TEMP
1	1140.00	2	1140.00	3	1140.00	4	1140.00
5	1140.00	6	1140.00	7	5460.00	8	5460.00
9	5460.00	11	5460.00	11	5080.00	12	4050.00
13	2000.00	14	1140.00	15	1140.00	16	1140.00

METAL MATERIAL PROPERTIES

METAL NO.	HEAT CAP.	DENSITY	CONDUCTIVITY
1	.1700	.2760	13.0000
2	.1054	.3334	2.4500
3	.1700	.2760	18.0000

INTERNAL NODE VOLUMES AND BASE GENERATION RATES

NODE NUMBER	MATERIAL	NODE LENGTH	NODE WIDTH	NODE DEPTH	NODE GENERATION
1	1	2.0000	1.0000	1.0000	0.
2	1	2.0000	1.0000	1.0000	0.
3	1	2.0000	1.0000	1.0000	0.
4	1	2.0000	1.0000	1.0000	0.
5	1	2.0000	1.0000	1.0000	0.
6	1	2.0000	1.0000	1.0000	0.
7	2	.6000	1.0000	1.0000	3.173E+02
8	2	.6000	1.0000	1.0000	3.173E+02
9	2	.6000	1.0000	1.0000	3.173E+02
10	2	.6000	1.0000	1.0000	3.173E+02
11	3	1.6000	1.0000	1.0000	0.
12	3	1.6000	1.0000	1.0000	0.

THE INTERNAL GENERATION MULTIPLIER LIBRARY

TIME	FACTOR	TIME	FACTOR	TIME	FACTOR	TIME	FACTOR
.0166	1.0000	.1166	.9990	1.0000	.9870	2.0000	.9740
5.0000	.9390	6.6000	.9230	20.0000	.8330	30.0000	.7910
60.0000	.7110	90.0000	.6640	120.0000	.6310	180.0000	.5940

THE BOUNDARY TEMPERATURE LIBRARY

NODE	TIME	TEMP	TIME	TEMP	TIME	TEMP
15	.0166	1140.00	5.0000	450.00	180.0000	450.00
16	.0166	1140.00	5.0000	450.00	180.0000	450.00

CONDITIONS EMPLOYED TO DETERMINE THE SURFACE RESISTORS

NODES CONNECTED	HEAT TRANSFER MECHANISM	SURFACE WIDTH	SURFACE DEPTH	INITIAL FILM COEF
13 16	CONST COEF.	1.0000	1.0000	733.0000
14 15	CONST COEF.	1.0000	1.0000	183.0000

THE TIME IN MINUTES 1.0166

TEMPERATURES OF INTERNAL NODES

NODE	TEMP	NODE	TEMP	NODE	TEMP	NODE	TEMP
1	1140.00	2	1140.00	3	1140.00	4	1140.00
5	1140.00	6	1499.20	7	4012.49	8	5610.42
9	5610.42	10	5460.50	11	4907.75	12	3660.79

CONDITION OF SURFACE NODES

SURFACE NODE	TEMPERATURE	FILM COEF.	SURFACE FLUX	SINK NODE
13	1818.58	733.000	5.9889E+05	16
14	1140.00	183.000	2.5338E+04	15

TEMPERATURES OF BOUNDARY NODES

NODE	TEMP	NODE	TEMP
15	1001.54	16	1001.54

THE TIME IN MINUTES 4.0166

TEMPERATURES OF INTERNAL NODES

NODE	TEMP	NODE	TEMP	NODE	TEMP	NODE	TEMP
1	1093.57	2	1137.75	3	1140.05	4	1158.58
5	1300.53	6	1840.24	7	3446.98	8	4990.33
9	5595.49	10	5242.18	11	4223.95	12	2568.51

CONDITION OF SURFACE NODES

SURFACE NODE	TEMPERATURE	FILM COEF.	SURFACE FLUX	SINK NODE
13	1220.98	733.000	4.6532E+05	16
14	924.35	183.000	6.1889E+04	15

TEMPERATURES OF BOUNDARY NODES

NODE	TEMP	NODE	TEMP
15	586.16	16	586.16

THE TIME IN MINUTES 19.0166

TEMPERATURES OF INTERNAL NODES

NODE	TEMP	NODE	TEMP	NODE	TEMP	NODE	TEMP
1	746.04	2	982.06	3	1195.74	4	1446.58
5	1802.05	6	2286.18	7	3176.08	8	3856.11
9	3856.13	10	3089.08	11	2037.76	12	1158.09

CONDITION OF SURFACE NODES

SURFACE NODE	TEMPERATURE	FILM COEF.	SURFACE FLUX	SINK NODE
13	640.61	733.000	1.3972E+05	16
14	610.26	183.000	2.9328E+04	15

TEMPERATURES OF BOUNDARY NODES

NODE	TEMP	NODE	TEMP
15	450.00	16	450.00

THE TIME IN MINUTES 79.0166

TEMPERATURES OF INTERNAL NODES

NODE	TEMP	NODE	TEMP	NODE	TEMP	NODE	TEMP
1	766.64	2	1058.21	3	1350.52	4	1640.95
5	1924.33	6	2193.54	7	2589.56	8	2735.85
9	2482.77	10	1828.01	11	1112.26	12	720.82

CONDITION OF SURFACE NODES

SURFACE NODE	TEMPERATURE	FILM COEF.	SURFACE FLUX	SINK NODE
13	522.90	735.000	5.3438E+04	16
14	621.42	183.000	3.1369E+04	15

TEMPERATURES OF BOUNDARY NODES

NODE	TEMP	NODE	TEMP
15	450.00	16	450.00

THIS INVESTIGATION IS 99.4536 PERCENT COMPLETE

PRESENT TIME = 179.0166 MINUTES

TEMPERATURE CHANGE RATE OF EACH INTERNAL NODE, DEG/MIN

NODE	RATE	NODE	RATE	NODE	RATE	NODE	RATE	NODE	RATE
1	-.40	2	-.75	3	-1.09	4	-1.40	5	-1.68
6	-1.92	7	-2.23	8	-2.30	9	-1.99	10	-1.33
11	-.64	12	-.26						

TEMPERATURE OF EACH NODE

NODE	TEMP	NODE	TEMP	NODE	TEMP	NODE	TEMP
1	736.27	2	995.91	3	1249.92	4	1495.78
5	1731.15	6	1953.91	7	2287.74	8	2406.05
9	2183.17	10	1620.22	11	1006.50	12	676.58
13	510.99	14	604.97	15	450.00	16	450.00

APPENDIX C
Potential for Natural Circulation
in the Primary Loop

A schematic diagram of the natural circulation path is shown below.

1. The driving head for natural circulation is

$$\Delta P_{N.C.} = \oint \rho dx = h(\rho_C - \rho_H).$$

2. The total pressure drop losses are due to friction in the flow area of the primary tank's annulus, the interconnecting pipes and channels, contraction and expansion losses, and heat exchanger pressure drop losses.

- a. Annulus

$$\Delta P_a = \frac{fL}{\rho D_h A_f^2} \left(\frac{\omega}{1 \times 10^5} \right)^2.$$

$$A_f = \frac{\pi}{4} [54^2 - 52^2] = 166.5 \text{ ft}^2$$

$$D_h = \frac{4 \times A_f}{W.P.} = 2t = 2 \text{ ft} \quad \text{or} \quad D_h = 24 \text{ inches.}$$

$$L \cong 33 \text{ ft}$$

Assume $f = 0.029$, then

$$\Delta P_a = 1.43 \times 10^{-16} \frac{\omega^2}{\rho_H}.$$

b. Receptacle and Eight Pipes Below Primary Tank

98.6% of the total flow rate flows through the receptacle, and the remaining 1.4% flows through eight pipes, 6 inches in diameter and 3 feet long. The receptacle is assumed to be 12 feet in diameter and $L = 3$ ft.

$$A_f = \frac{\pi}{4} (12)^2.$$

$$D_h = \frac{4A_f}{W.P.} = 12 \text{ ft} = 144 \text{ inches.}$$

Assume $f = 0.029$, then

$$\Delta P_r = 4.59 \times 10^{-19} \frac{\omega^2}{\rho_H}.$$

The pressure drop losses for the eight 6-inch-diameter pipes are as follows:

$$A_f = \frac{\pi}{4} (0.5)^2.$$

$$D_h = 6 \text{ in.}$$

$$L = 3 \text{ ft}$$

Assume $f = 0.029$, then

$$\Delta P_a = 7.04 \times 10^{-15} \frac{\omega^2}{\rho_H}.$$

Other pipe losses consist of a 6-inch-diameter, 7-foot pipe in the hot leg; two 6-inch-diameter, 2-foot pipes in the cold leg; and 6-inch-diameter, 31-foot-long pipe in the cold leg. Assume $f = 0.026$:

$$\Delta P = \left[0.1967 \frac{\omega^2}{\rho_H} + 0.1124 \frac{\omega^2}{\rho_C} + 0.8711 \frac{\omega^2}{\rho_C} \right] \times 10^{-10}.$$

c. Other Losses

From this it was determined that contraction and expansion losses and bend losses can be neglected.

d. Heat Exchanger Losses

The pressure drop losses will consist of entrance and exit losses and friction in the flow area between the tubes and the inside shell diameter:

$$\Delta P_{Hx} = \Delta P_{in} + \Delta P_{fr} + \Delta P_{out} + \Delta P_{other}.$$

$$\Delta P_{in} = \frac{k_{in} \omega^2}{12 \rho A_f^2 \times 10^{10}}.$$

$$k_{in} = 0.5.$$

Assume a 6-inch-diameter inlet pipe:

$$A_f = \frac{\pi}{4} (0.5)^2.$$

$$\Delta P_{in} = 0.27 \times 10^{-10} \frac{\omega^2}{\rho_H}.$$

$$k_{out} = 0.8.$$

Assume a 6-inch-diameter outlet pipe:

$$\Delta P_{out} = 0.432 \times 10^{-10} \frac{\omega^2}{\rho_C}.$$

$$\Delta P_{\text{friction}} = \frac{fL\omega^2}{\bar{\rho} D_h A_f^2 \times 10^{10}}.$$

Assume

$$f = 0.028,$$

$$L_{\text{eff}} = 6.2 \text{ ft},$$

$$A_f = \frac{\pi}{4} \left[3^2 - (0.04391)^2 \right] = 6.414 \text{ ft}^2$$

$$D_h = \frac{4 \times A_f}{W.P.} = 1.57 \text{ inches}.$$

Detailed information on the heat exchanger is given in Table 2.

$$\Delta P_{\text{fr}} = 0.000672 \times 10^{-10} \frac{\omega^2}{\bar{\rho}}.$$

Other losses are assumed to be negligible.

$$\text{Total } \Delta P_{\text{Hx}} = \left(\frac{0.27}{\rho_H} + \frac{0.000672}{\bar{\rho}} + \frac{0.432}{\rho_C} \right) \frac{\omega^2}{10^{10}}.$$

Combining like terms and neglecting higher-order terms, we get

$$\text{Total } \Delta P = 0.4667 \times 10^{-10} \frac{\omega^2}{\rho_H} + 1.4155 \times 10^{-10} \frac{\omega^2}{\rho_C}.$$

Equating driving head to ΔP_{losses} ,

$$h(\rho_C - \rho_H) = \left(\frac{0.4667}{\rho_H} + \frac{1.4155}{\rho_C} \right) \times 10^{-10} \omega^2,$$

$$h \approx 40 \text{ ft}.$$

If we assume a constant cold-leg temperature of 450 F ($\rho_C = 55.93 \text{ lb/ft}^3$), and solving for the flow rate, we obtain,

$$\omega = \sqrt{\frac{0.2777(55.93 - \rho_H)}{\frac{0.4667}{\rho_H} + 0.0253}} \times 10^5 \text{ lb/h.}$$

Figure 10 shows the effect of varying the hot-leg temperature on the primary system flow rate.

APPENDIX D
Na-NaK Heat Exchanger Design

Assume a simple shell-and-tube heat exchanger with counterflow and single-pass arrangement. The basic steps in the design are as follows:

1. Given a heat load ($Q = 85.5 \times 10^6 \text{ Btu/h}^*$); assume inlet and outlet temperatures of both fluids in the shell side and the tube side. The flow rates are then calculated from the heat balance equation.

Assume Na in the shell side with

$$T_{\text{in}} = 800 \text{ F}$$

$$T_{\text{out}} = 450 \text{ F}$$

and NaK in the tube side with

$$T_{\text{in}} = 400 \text{ F}$$

$$T_{\text{out}} = 700 \text{ F.}$$

$$\omega_{\text{NaK}} = \frac{Q}{\bar{c}_p \Delta T} = 1.113 \times 10^6 \text{ lb/h,}$$

$$\omega_{\text{Na}} = 0.788 \times 10^6 \text{ lb/h,}$$

where

$$\bar{c}_p = 0.2559 \text{ for NaK at } 550 \text{ F,}$$

$$\bar{c}_p = 0.31 \text{ for Na at } 625 \text{ F.}$$

2. Select tube size, pitch (triangular or square), wall thickness and BWG number.¹⁵ From available tables, select

*Value taken from B&W 1000-MWe Reference Design.

Tube OD = 0.625 inch,

Wall thickness = 0.049 inch,

Tube ID = 0.527 inch,

BWG = 18

Triangular pitch = 7/8 inch.

3. Assume an approximate shell diameter, and use empirical equations to calculate the number of tubes, or vice versa.

Say that the shell diameter = 3 ft (ID). From the empirical equation, approximate tube sheet ID = $1.055 \sqrt{N_T} \times \text{pitch} + \text{tube OD} + 1.5$, solve for the number of tubes:

$$N_T = \left[\frac{(\text{ID})_{\text{shell}} - (\text{OD})_{\text{tube}} - 1.5}{1.055 \times \text{pitch}} \right]^2,$$

$$N_T = 1346.59 \approx 1347.$$

4. Calculate the flow areas for both the tube and shell sides.

Tube side flow area:

$$a_{\text{NaK}} = \frac{\pi}{4} (\text{ID})^2 N_T = 2.039 \text{ ft}^2.$$

Shell side flow area:

$$a_{\text{Na}} = \frac{\pi}{4} (\text{ID})_{\text{shell}}^2 - \frac{\pi}{4} (\text{OD})_{\text{tubes}} N_T = 5.268 \text{ ft}^2.$$

5. Calculate the mass velocities, G_{NaK} and G_{Na} :

$$G_{\text{NaK}} = \left(\frac{\omega}{a} \right)_{\text{NaK}} = 618,330.$$

$$G_{Na} = \left(\frac{\omega}{a} \right)_{Na} = 149,580.$$

6. Calculate the tube and shell side film coefficients, ¹⁶ h:

a. For the tube side:

$$Pe = Re \times Pr = \frac{DGC_p}{k}$$

$$Pe = 444.6$$

where $C_p = 0.2559$ for NaK at 550 F,

$k = 15.625$ for NaK at 550 F,

$$Nu = 5 + (0.025)^{0.8} = 8.27.$$

The heat transfer coefficient based on tube OD is

$$h_{NaK} = \frac{Nu k}{L} \left(\frac{ID}{OD} \right)_{tube} = 2481.3 \text{ Btu/h-ft}^2\text{-}^\circ\text{F}$$

where Nu and L are based on the equivalent diameter.

b. For the shell side:

$$\text{Equivalent diameter, } D_e = \frac{4 \times \text{flow area}}{\text{wetted perimeter}} = 0.09169 \text{ ft.}$$

$$Pe = 98.87.$$

$$Nu = 7 + 3.8 \left(\frac{P}{D} \right)^{1.52} + 0.027 \left(\frac{P}{D} \right)^{0.27} (Pe)^{0.8} = 14.43.$$

Applying a correction factor of 0.7, $Nu = 10.1$. Hence,

$$h_{Na} = \frac{Nu k}{L} = 4737 \text{ Btu/h-ft}^2\text{-}^\circ\text{F}.$$

7. Calculate tube metal coefficient:

a. Calculate tube wall temperature.

b. Calculate equivalent wall thickness and determine thermal conductivity for a specified tube material at the tube wall temperature.

The temperature of the wall can be calculated as follows:

$$T_m = \bar{T}_{NaK} + \frac{h_{Na}}{h_{NaK} + h_{Na}} (\bar{T}_{Na} - \bar{T}_{NaK}) = 599.2 \text{ F},$$

$k_m \cong 11$ at 599.2 F for stainless steel,

$$t_e = \frac{1}{2} (OD) \ln \left(\frac{OD}{ID} \right) = 0.05328 \text{ inch};$$

$$\therefore h_m = \frac{k_m}{t_e} = 2477 \text{ Btu/h-ft}^2\text{-}^\circ\text{F}.$$

8. Determine overall coefficient of heat transfer:

$$\frac{1}{U} = \frac{1}{h_{NaK}} + \frac{1}{h_{Na}} + \frac{1}{h_m},$$

$$U = 892.8 \text{ Btu/h-ft}^2\text{-}^\circ\text{F}.$$

9. Determine LMTD and heat transfer area A: For counterflow, single-pass arrangement,

$$\text{LMTD} = 72.2 \text{ F},$$

$$A = \frac{Q}{U(\text{LMTD})} = 1196 \text{ ft}^2.$$

Allowing a factor of safety = 1.15,

$$A = 1375.4 \text{ ft}^2.$$

10. Determine the effective length of tubes:

$$L_e = \frac{A}{\text{circumference}} = 6.2 \text{ ft.}$$

11. Calculate pressure drops. Pressure losses include friction, entrance and exit losses, contraction and expansion losses, and other losses.

a. Tube side:

$$\Delta P = \Delta P_{\text{in}} + \Delta P_{\text{fr}} + \Delta P_{\text{out}}.$$

The inlet and outlet losses are computed from

$$\Delta P = \frac{kv}{12} \left(\frac{G}{1 \times 10^6} \right)^2$$

where k = velocity-head coefficient,
 v = specific volume.

b. The frictional pressure drop is computed from

$$\Delta P = \frac{fL}{D_p} \left(\frac{G}{1 \times 10^6} \right)^2.$$

The same procedure is used for the shell side, keeping in mind to use the equivalent diameter.

APPENDIX E
NaK-Air Heat Exchanger Design

1. Free-Convection of Air

This concept utilizes free convection for the air outside the finned-tubes. For free convection of air,¹⁷

$$h = 1 - 5 \text{ Btu/h-ft}^2\text{-}^\circ\text{F}.$$

Try $h = 5$.

For air outside finned tubes in a staggered close-pitch formation,¹⁸

$$h = 0.28 \frac{k}{d} \left(\frac{Gd}{\mu} \right)^{0.6} \left(\frac{C_p \mu}{k} \right)^{0.33} = 0.28 \frac{G^{0.6} k^{0.67} C_p^{0.33}}{d^{0.4} \mu^{0.27}}.$$

Assume, air

$$t_{in} = 100 \text{ F},$$

$$t_{out} = 300 \text{ F},$$

$$\text{Tube ID} = 1 \text{ inch}.$$

Thermal properties of air at 200 F are:

$$k = 0.0185,$$

$$C_p = 0.241,$$

$$\mu = 0.052.$$

Solve for the mass velocity G :

$$G^{0.6} = \frac{hd^{0.4}\mu^{0.27}}{0.28k^{0.67}C_p^{0.33}},$$

$$G = 1260 \text{ lb/h-ft}^2.$$

The flow rate required to remove 85.5×10^6 Btu/h is

$$\dot{w}_a = \frac{Q}{C_p \Delta T} = 1.765 \times 10^6 \text{ lb/h},$$

$$G_a = \left(\frac{\dot{w}}{A} \right)_a,$$

where A_a = free flow area outside tubes.

$$A_a = \left(\frac{\dot{w}}{G} \right)_a = 1400 \text{ ft}^2,$$

free flow area/frontal area = 0.643;

$$\therefore \text{air frontal area} = \frac{1400}{0.643} = 2177 \text{ ft}^2.$$

These results show that the size of the NaK-air heat exchanger with free convection of air is not practical. If a square air duct is assumed, then the air frontal dimensions would have to be 46.7 ft $\times$ 46.7 ft. For a circular duct, the diameter would have to be 52.7 ft.

The obvious conclusion is that it would be difficult and expensive to obtain enough heat transfer surface.

2. Forced-Convection of Air

Assume an NaK-air heat exchanger of the type shown in Table 4.

a. Heat balance:

$$\frac{\dot{w}_{\text{air}}}{\dot{w}_{\text{NaK}}} = \frac{Q}{C_p \Delta T} = 1.765 \times 10^6 \text{ lb/h}.$$

NaK — The results obtained from the Na-NaK heat exchanger calculations will be used; i. e.

$$W_{\text{NaK}} = 1.113 \times 10^6 \text{ lb/h},$$

$$t_{\text{in}} = 700 \text{ F},$$

$$t_{\text{out}} = 300 \text{ F}.$$

b. Assume finned circular tubes with dimensions obtained from Kays and London,¹⁹ Figure 99, p 116.

Assume

$$\text{frontal area} = 240 \text{ ft}^2.$$

Hence,

$$\text{air free flow area} = 240 \times 0.643 = 154.32 \text{ ft}^2.$$

c. Mass velocity, G_a :

$$G_a = \left(\frac{\dot{w}}{A} \right)_{\text{air}} = 11,430.$$

For air outside finned tubes in a staggered close-pitch formation

$$h = 0.28 \frac{k}{d} \left(\frac{Gd}{\mu} \right)^{0.6} \left(\frac{C_p \mu}{k} \right)^{0.33} = 0.28 \frac{G^{0.6} k^{0.67} C_p^{0.33}}{d^{0.4} \mu^{0.27}}.$$

Thermal properties for air are evaluated at 200 F.

$$h = 20.36 \text{ Btu/h-ft}^2\text{-}^\circ\text{F}$$

where h is the heat transfer coefficient on the fin side of the tube.

d. Fin effectiveness (n_f):

$$m = \sqrt{\frac{2h}{k\delta}}$$

where

$$h = 20.36,$$

$$\delta = 0.012 \text{ inch},$$

$$k = 218.4 \text{ Btu/h-ft-}^\circ\text{F, for copper, at 200 F assuming that the fin material is made of copper,}$$

$$m = 3.9.$$

From Figure 1, p 31, of Kays and London,¹⁹ $n_f = 0.98$ with $m = 3.9$ and $r_o/r_i = 1.695$.

e. Air heat transfer coefficient based on the inner surface of tube:

$$h_a = (n_f \times A_f + A_o) \frac{h}{A_i}.$$

$$\text{Fin area, } A_f = 2.26 \text{ ft}^2/\text{ft}.$$

$$\text{Bare tube area, } A_o = 0.214 \text{ ft}^2/\text{ft}.$$

$$\text{Inside surface per lineal ft, } A_i = \pi \times 0.926 \times 1/12 = 0.242 \text{ ft}^2/\text{ft}.$$

$$h_a = 204.9 \text{ Btu/h-ft}^2\text{-}^\circ\text{F}.$$

f. On the NaK (tube) side:

Assume length of tube = 20 ft,

transverse length = 12 ft.

Approximate number of tubes (transverse):

$$N_T = \frac{12 \text{ ft}}{\frac{3.079}{12}} = 46.7$$

where tube spacing = 3.079 inches, 47 tubes may be fit in one bank;
46 tubes in alternating banks for triangular pitch.

g. Flow area:

Assume eight banks, four banks upflow, and four banks downflow.

Total number of tubes = 372.

$$a_{\text{NaK}} = 1.733 \text{ ft}^2.$$

h. Mass velocity, G_{NaK} :

$$G_{\text{NaK}} = \left(\frac{\omega}{a} \right)_{\text{NaK}} = 0.642 \times 10^6.$$

i. NaK heat transfer coefficient:

$$Pe = \frac{D_e G C_p}{k} = 811.4$$

where the thermal properties of NaK are evaluated at 550 F. Using the relationship

$$Nu = 5 + 0.025(Pe)^{0.8} = 10.3,$$

$$h_{\text{NaK}} = \frac{Nu k}{D_e} = 2085.3 \text{ Btu/h-ft}^2\text{-}^\circ\text{F}$$

based on the inside diameter of the tube.

j. Tube metal coefficient: To evaluate the thermal conductivity of the metal,

$$T_m = \bar{T}_{\text{NaK}} + \frac{h_a}{h_{\text{NaK}} + h_a} (\bar{T}_a - T_{\text{NaK}}) = 546 \text{ F.}$$

Assuming stainless steel tubes, $k_m = 10.7$ at 546 F. The equivalent thickness,

$$t_e = \frac{1}{2} D_o \ln \frac{D_o}{D_i} = 0.05109 \text{ inch.}$$

Hence,

$$h_m = \frac{k_m}{t_e} = 2513 \text{ Btu/h-ft}^2\text{-}^\circ\text{F}.$$

k. Overall heat transfer coefficient:

$$\frac{1}{U} = \frac{1}{h_a} + \frac{1}{h_m} + \frac{1}{h_{\text{NaK}}},$$

$$U = 174.2 \text{ Btu/h-ft}^2\text{-}^\circ\text{F}.$$

l. Heat transfer area based on inside diameter of tube:

$$A_i = \frac{Q}{U\Delta t}$$

where

$$\Delta t = (\text{LMTD}) F_t.$$

$$\text{LMTD} = 347.5.$$

F_t is a correction factor based on two-pass, tube fluid unmixed and crossflow, shell fluid mixed: $F_t = 0.95$. Hence,

$$A_i = 1480 \text{ ft}^2.$$

m. Check number of banks and length of tubes: Inside surface/
bank = 227.4 ft²/bank.

$$n = \frac{1480 \text{ ft}^2}{227.4 \text{ ft}^2/\text{bank}} = 6.5 \text{ banks}.$$

$$L = \frac{A_i}{\text{circumference}} = 16.4 \text{ ft}.$$

These results are reasonably close to the assumed values.

n. Pressure drop calculations (air side):

$$\Delta P = \frac{f G^2 L_p}{5.22 \times 10^{10} \times D'_{e_v} S \phi_S} \left(\frac{D'_{e_v}}{S_T} \right)^{0.4} \left(\frac{S_L}{S_T} \right)^{0.6}$$

$$D'_{e_v} = \text{equivalent volumetric diameter} = \frac{4 \times \text{net free volume}}{\text{frictional surface}}$$

where the net free volume is the volume between the center lines of two vertical banks of tubes less the volumes of the half tubes and fins within the center line.

The detailed calculations are not shown here. The reader is referred to Kern, Process Heat Transfer.

$$\Delta P = 0.07 \text{ psi.}$$

o. NaK pressure drop:

$$\Delta P = \frac{f G^2 L n}{5.22 \times 10^{10} D S \phi_t}$$

where

$$\phi_t = 1,$$

$$f = 0.00016,$$

$$n = 2,$$

$$L = 20 \text{ ft,}$$

$$D = 0.0771,$$

$$S = \frac{52.5}{62.5} = 0.84.$$

$$(\Delta P)_{\text{NaK}} = 0.779 \text{ psi.}$$

p. Fan capacity:

$$\text{Total air hp} = 0.0001573 Q \Delta P_t$$

where

Q = air flow, cfm,

ΔP_t = total pressure = dynamic head + static pressure,

$Q = 414,310$ cfm,

$\Delta P_t = 4.9439$ inches of water,

$$\text{air hp} = 322.19 \text{ hp},$$

$$\text{Bhp} = \frac{322.19}{0.65} = 495 \text{ hp}$$

assuming 65% fan efficiency.

APPENDIX F
Biological Shield Heat Removal Calculations

For the mirror insulation, past experience has indicated that a heat loss of 80 Btu/h-ft² is not unreasonable for temperature drops of 5 to 600 degrees. The outside heat transfer area of the primary tank, including the bottom-head, is 3336 ft². Therefore, the heat loss is

$$80 \text{ Btu/h-ft}^2 \times 3336 \text{ ft}^2 = 0.27 \times 10^6 \text{ Btu/h.}$$

Say,

$$Q = 0.5 \times 10^6 \text{ Btu/h.}$$

The outlet argon gas temperature is set at 150 F. In designing the argon-NaK-air concept of biological shield heat removal, the temperature difference is limited since the air inlet temperature is 100 F. Hence, the possible combination of process temperatures would have to be such that the inlet and outlet temperatures for each system fall between 100 and 150 F. Based on this requirement, the combination of temperatures for each system were established as follows:

The flow rates can be calculated from the usual heat balance equations. In the design calculations for the argon-NaK heat exchanger with extended

surfaces and for the NaK-air heat exchanger, the same procedure was taken as in Appendix D and E.

The heat transfer correlations for argon gas flow is

$$\text{Nu} = \frac{hD_i}{k} = 0.023 \text{ Re}^{0.8} \text{ Pr}^{0.4}.$$

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ARGONNE NATIONAL LABORATORY

February 19, 1971

PRO:K:029

Mr. Robert L. Shannon, Director
Division of Technical Information Extension
U.S. Atomic Energy Commission
P.O. Box 62
Oak Ridge, Tennessee 27830

Subject: 1000-MWe LMFBR Safety Studies -
Publication of Babcock & Wilcox Topical Reports

Reference: Letter, L. W. Fromm to R. L. Shannon, "1000-MWe LMFBR
Safety Studies - Publication of Contractors' Phase and
Topical Reports," October 16, 1970

Dear Mr. Shannon:

In the reference letter I advised you that we would be transmitting to you for publication a total of twelve Babcock & Wilcox Company Phase and Topical Reports, and possibly three reports from other contractors, generated under the AEC-sponsored 1000-MWe LMFBR Safety Analysis Studies program. With that letter I enclosed one B&W report (BAW-1344, which you have since published), and advised that the remainder would be transmitted to you for publication when received and patent-cleared.

I am enclosing herewith one copy of each of the eight B&W Topical Reports listed below, all of which are now patent-cleared and ready for publication. The covers for these reports should be that used for the previously-issued BAW-1344, except for the changes noted in the table below. The letters heading the columns of the table are keyed to the markings on the attached xerox copy of the cover for BAW-1344.

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BAW-1349	TOPICAL REPORT	Candidate Secondary Containment Support Systems
BAW-1350	TOPICAL REPORT	Accident Initiating Conditions Part 1 - Flow Abnormalities
BAW-1351	TOPICAL REPORT	Candidate Emergency Decay Heat Removal Systems
BAW-1352	TOPICAL REPORT	Candidate Primary Containment Safety Features
BAW-1354	TOPICAL REPORT	Candidate Protective Features
BAW-1355	TOPICAL REPORT	Effects of Irradiation-Induced Metal Swelling on the Reference Design
BAW-1360	TOPICAL REPORT	Accident Initiating Conditions Part 2 - Reactivity Insertions

All other parts of the front covers for these reports should remain the same as the cover for BAW-1344.

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BAW-1360	1000-MWe LMFBR Safety Studies	B&W	Init. Cond. - 2. Reactivity	USAEC

Mr. R. L. Shannon, Director
February 19, 1971

3

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The distribution of all of these reports should be our "Distribution A" plus Category UC-80, Reactor Technology, as before. For your convenience I am enclosing another copy of the "Distribution A" list previously supplied to you.

In the reference letter I stated that there would be twelve B&W reports, and possibly three from other contractors. This has now been revised downward to eleven B&W reports and one report from Atomics International. The single remaining B&W report and the AI report will be transmitted to you when received and patent-cleared.

Thank you again for your excellent cooperation in publishing these reports. If there are any questions, please contact me on FTS extension 312/739-2971 or 312/739-4844.

Very truly yours,

L. W. Fromm, Manager
1000-MWe Studies
LMFBR Program Office

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