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THERMAL ASPECTS OF THE FFTF
REACTOR REFUELING SYSTEM

December 1969

AEC RESEARCH &
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BNWL-1235
UC-80, Reactor
Technology

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REACTOR REFUELING SYSTEM

A. F. Lillie
Reactor and Plant Technology Department
FFTF Division

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BNWL-1235
UC-80, Reactor
Technology

Printed in the United States of America
Available from
Clearinghouse for Federal Scientific and Technical Information
National Bureau of Standards, U.S. Department of Commerce
Springfield, Virginia 22151
Price: Printed Copy \$3.00; Microfiche \$0.65

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REACTOR REFUELING SYSTEM

A. F. Lillie

ABSTRACT

Thermal analyses of three potential fuel handling schemes for the FTR refueling subsystem are described in this report. The handling schemes considered were (1) indirect gas cooling of driver fuel, (2) indirect gas cooling of closed loop test fuel, and (3) direct gas cooling of closed loop and open test assemblies. The analysis is restricted to normal fuel handling operations involving undamaged fuel. Results are presented in terms of decay heat loads and limiting temperatures for each handling method.

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THERMAL ASPECTS OF THE FFTF REACTOR REFUELING SYSTEM

INTRODUCTION

The Fast Flux Test Facility (FFTF) fuel handling system is comprised of the Reactor Refueling System (RRS), the non-irradiated fuel handling system, and the irradiated fuel handling system. Basically, RRS takes fresh driver fuel from the nonirradiated fuel handling system, delivers it to and positions it within the reactor, and subsequently delivers spent driver fuel from the reactor to the irradiated fuel handling system. The RRS also handles other routinely removable reactor components such as control rods, reflector and shield assemblies, and closed loop and open test assemblies.

Several prime considerations involved in the conceptual design of the fuel handling system, and in particular the RRS revolve around the thermal aspects of handling the irradiated fuel. Fission product decay heat in the irradiated fuel requires that provisions be made in the design of the RRS to adequately cool the fuel assemblies. Thermal analyses of the RRS are required to provide bases for conceptual design selection of the system. This report describes the thermal analyses and presents the salient results.

OBJECTIVES AND PURPOSE OF THE STUDY

A thermal analysis of the RRS was performed. The objectives of the analysis were:

- To determine the thermal performance characteristics of an indirect gas cooled - finned pot driver fuel handling approach.
- To determine the thermal performance characteristics of an indirect gas cooled closed loop test assembly

handling approach (wherein a closed loop test assembly is handled while remaining in the closed loop in-reactor tube).

- To determine the thermal performance characteristics of a direct gas cooled handling approach for use with closed loop test assemblies and open test assemblies.

The analyses were confined to the above items. Direct gas cooling of driver fuel and direct sodium cooling of test assemblies were not considered, per se, but are discussed briefly in Section 4.3. References 1 and 2 contain results of analyses of such approaches.

The purpose of the analyses was to provide calculated thermal performance data for the above mentioned RRS design approaches in order to:

- Assess the capability of the design approach(es) to meet the system thermal design requirements, and
- Identify any inherent thermal limitations of the design approach(es).

SUMMARY AND CONCLUSIONS

Thermal analyses were made of three fuel handling schemes. These were (1) indirect gas cooling of driver fuel, (2) indirect gas cooling of closed loop test fuel, and (3) direct gas cooling of closed loop and open test assemblies. The analyses considered only normal fuel handling operations involving undamaged fuel.

The analyses were performed to determine the thermal performance characteristics of the three fuel handling schemes in order to:

- Assess the capability of the schemes to meet the RRS thermal requirements (in particular, the capability of the schemes to maintain the fuel cladding maximum temperature to acceptable levels), and to

- Identify any inherent thermal limitations of the handling schemes.

Based on the results of the analyses, the following conclusions are in order:

- (a) Using an indirect gas cooling scheme for handling driver fuel (i.e., employing a sodium filled finned pot as a container for an irradiated driver fuel assembly, a 30 kWt decay heat load driver can be handled without exceeding a maximum temperature on the fuel cladding of 1000 °F. Assuming normal operations handling undamaged fuel, approximately 10 minutes is available for the uncooled transition period when the fuel is lifted from the reactor into the ex-vessel handling machine (EVHM) or when the fuel is lowered from the EVHM into the interim decay storage (IDS) facility. The adiabatic heating rate of the 30 kWt fuel during this uncooled transition is about 30 °F/min.
- (b) Using an indirect gas cooling scheme for handling closed loop test assemblies (i.e., employing the sodium filled closed loop tube as a container for the irradiated test fuel), a 17 kWt decay heat load test can be handled without exceeding a fuel cladding maximum temperature of 1000 °F. The adiabatic heating rate of the fuel during uncooled transition from the reactor into the gas cooled loop handling machine (GCLHM) or from the GCLHM into the IDS is about 5 °F/min (which will allow ample time for handling fuel out of the reactor and into the IDS). The loop tube topworks can be used as a heat exchanger for rejecting the fuel decay heat to the GCLHM argon coolant.
- (c) Using a direct gas cooling scheme for handling closed loop and open test assemblies, test fuel may require striking a compromise between allowable test fuel peak operating power and in-reactor cooling time.

In the present analysis, a 1000 °F maximum temperature limit on the test fuel cladding cannot be maintained (if the fuel must be handled 24 hours after reactor shutdown) using uncooled transition times of two minutes and three minutes for closed loop and open test assemblies, respectively, because of the high adiabatic heating rates in the test fuel, for fuel operating peak powers which would be anticipated for such test fuel. The results presented herein can be used to determine the interrelationships among peak operating test fuel powers, in-reactor cooling time, and maximum allowable test fuel cladding temperatures.

- (d) While somewhat exacting heat transfer performance will be required of the argon cooling system using the direct gas cooling scheme for handling test fuel, the approach is feasible. As noted above (see item c above), some compromises among operating fuel power, in-reactor cooling time, and maximum fuel cladding temperatures might be required since the present design requirements of (a) 1000 °F maximum cladding temperature and (b) handling of fuel 24 hours after shutdown are incompatible using the transfer times and fuel power densities assumed in the present analyses.

With regard to the three fuel handling schemes considered herein, conclusions are as follows:

- (1) Using indirect gas cooling of driver fuel, it appears that fuel decay heat loads of the order of 50 kWt can be handled (both in the in-reactor storage positions during power operation and during fuel handling operations) using an optimized fin pot design.
- (2) Using indirect cooling of a closed loop test assembly (i.e., handling the fuel within the sodium filled closed loop in-reactor tube), it appears that the test

fuel operating power densities of present and near-term interest will present no thermal limitations on handling the test fuel 24 hours after reactor shutdown. It is imperative that a natural circulation sodium circuit be established within the tube containing the fuel for this judgment to be valid.

- (3) Direct gas cooling of test assemblies is technically feasible. It will be necessary to decide whether the compromises which will probably be required among test assembly operating peak powers, maximum allowable cladding temperatures, and in-reactor cooling times are consistent with project goals before proceeding with such a handling scheme. If the compromises are acceptable with respect to the project goals, it is recommended that future analyses of the scheme concentrate on the thermal aspects of off-normal (or emergency) handling operations. The thermal considerations involved in handling damaged test assemblies should be given strong emphasis.

I DESIGN CONSIDERATIONS

A. GENERAL SYSTEM DESCRIPTION

The FIR is a sodium cooled fast test reactor rated at 400 MWt. The vertical core, comprised of 91 core lattice positions, is arranged as shown in Figures 1.A and 1.B. Referring to Figure 1.A, the core is subdivided into 3 sectors and the testing facilities are placed along the radial lines forming the sector boundaries. Each sector, containing fuel, control, reflector and shield assemblies in appropriate locations is serviced by an in-vessel handling machine (IVHM) which rides on a rotating plug affixed to the reactor cover. A plan view of the reactor cover is shown in Figure 1.C.

Briefly, a driver fuel assembly is removed from its core location after being grappled by the IVHM by a vertical lift of about 14 to 15 feet. After the assembly is clear of the top of the core structures, it is moved under sodium by suitable manipulation of the IVHM mechanism to a storage location (see Figure 1.C) located outboard of the radial shield boundary. The fuel assembly is lowered into an empty finned pot stationed at the appropriate storage location. Subsequent removal of the assembly from the reactor vessel is accomplished by using the IVHM to transfer the fuel assembly from a storage position to a finned pot located at an exit port location (see Figure 1.C). The out of vessel handling machine (EVHM) is positioned on the top face of the reactor cover at the exit port location and grapples the finned pot, raises it into the EVHM, and transports it away from the reactor to appropriate storage facilities in the containment building. The EVHM is equipped with suitable argon gas cooling equipment to cool the fuel being carried in the machine. Subsequent transfer of fuel out of

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FIGURE 1.A. Reference Core Map

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containment is accomplished using a fuel transfer machine (FTM). This operation of the RRS, i.e., transfer of fuel out of containment, was not considered in the present study.

Other routinely removable core components, such as control, reflector, shield assemblies, etc., are handled in much the same manner as driver fuel. Owing to the significantly lower decay heat levels in such components, as compared to fuel assemblies, it probably would not be necessary to use a finned pot transfer device for such items from a thermal standpoint alone. From the standpoint of standardizing the handling mechanisms/operations of the EVHM, it might be desirable to use the finned pot transfer device for handling such items. In any event, the handling of core components other than fuel does not involve thermal design considerations to the extent that fuel handling does. Handling of core components other than fuel, therefore, was not considered in the present study.

A test assembly is handled somewhat differently than a driver assembly. Access to test assembly positions is provided through individual nozzle access ports in the reactor cover (see Figures 1.B and 1.C). Removal of an open test assembly proceeds as follows. After preparation of the test position nozzle for refueling (using a special machine known as the Loop Preparation Cask-LPC), the loop handling machine (LHM) is sealed to the nozzle and the test fuel hanger bar is grappled. If a sodium cooled LHM is employed, reactor sodium is raised into the barrel of the LHM to a suitable level using either machine suction or reactor pressurization (or a combination thereof), and the test fuel is then withdrawn into the LHM. A valve on the bottom of the barrel is then closed and made secure, excess sodium is returned to the reactor pool, and the

test fuel is carried away from the reactor cover region to a suitable storage location in the containment building. Discharge of the test assembly from the LHM into the storage location is accomplished by reversing the above procedure, always being careful to maintain the test assembly immersed in sodium.

If a gas cooled LHM is employed, the test assembly is withdrawn directly into the dry barrel of the machine, the bottom valve is closed, and argon gas cooling of the test assembly within the LHM is started. Discharge of the test assembly into a storage location is accomplished by reversing the above procedure.

A prime difference, from a thermal standpoint, between a sodium cooled LHM (a so-called "wet LHM") and a gas cooled LHM (GCLHM) is that an uncooled transition (from sodium to gas cooling modes and vice-versa) is experienced by the test assembly using the GCLHM approach. The wet LHM approach does not subject the test assembly to this uncooled transition, and the attendant thermal shocks, since the test assembly is always submerged in sodium during normal handling operations.

Handling of a closed loop test assembly can be accomplished in a manner essentially identical to that just described for an open test assembly. Closed loop system sodium would be used in the wet LHM, of course, instead of the reactor sodium used when handling open test assemblies.

Closed loop test assemblies might also be handled in a different manner. The entire closed loop assembly could be removed into the LHM while remaining in the closed loop in-reactor tube. The closed loop in-reactor tube design could provide a natural circulation path between the loop downcomer

and riser legs. The closed loop in-reactor tube would, then, function in much the same manner as the finned pot device used for handling driver fuel. Argon gas cooling of the exterior topworks of the closed loop in-reactor tube would remove the test assembly decay heat.

B. DESIGN REQUIREMENTS AND INTERFACES

The design requirements and interfaces for the FFTF fuel handling system are listed in References 3 and 4. Specifications which have a direct bearing on the thermal aspects of the fuel handling system, and in particular the RRS, are reiterated below for ease of reference.

1. Design Requirements

The design requirements which have a bearing on the thermal aspects of the RRS are (from References 3 and 4):

- a. The fuel handling system shall be designed to maintain the driver fuel cladding temperature below the peak in-reactor operating temperature under normal conditions.
- b. The fuel handling system shall be capable of removing core components and/or test assemblies from the reactor 24 hours after reactor shutdown.
- c. Direct fuel withdrawal shall be utilized for refueling. Fuel handling machines which are gas cooled will be utilized in the designs unless concept studies indicate that this mode of cooling is unworkable.
- d. Transfer of core components and/or test assemblies from the reactor shall be performed using a shielded cask operating in air.
- e. Provision of a capability for in-vessel decay storage is considered to have substantial merit and will be investigated during the current concept development period.

- f. Routine capability shall be provided for direct refueling of closed loops without closed loop in-reactor tube removal from the reactor.

2. Interfaces

The key physical interfaces associated with the reactor refueling system, from a thermal standpoint, are outlined as follows:

For driver fuel handling,

- One interface is between the in-vessel storage position and the ex-vessel handling machine (VHM). During transfer of spent driver fuel from the in-vessel storage to the EVHM, the fuel undergoes an uncooled transition period.
- Another interface is between the EVHM and the interim decay storage (IDS) area. During transfer of spent driver fuel from the EVHM to the IDS, the fuel undergoes an uncooled transition period.

For closed loop assemblies (assuming discharge of the fuel contained within the closed loop in-reactor tube),

An interface exists between the loop handling machine (LHM) and the in-reactor tube. When the in-reactor tube (with fuel installed) is removed from the reactor into the LHM the fuel undergoes an uncooled transition period. Another interface is between the LHM and the IDS. When the closed loop tube (with fuel installed) is lowered from the LHM into the IDS, the fuel undergoes an uncooled transition period.

For test assemblies (either closed loop or open test) using direct gas cooling,

- An interface exists between the LHM and the reactor cover test nozzle. When the test assembly is retracted directly into a GCLHM, the fuel undergoes an uncooled transition period.

Another interface is between the LHM and IDS. When the test assembly is lowered from a GCLHM into the IDS, the test assembly undergoes an uncooled transition period.

Other interfaces exist which could be considered from a thermal standpoint; examples are storage of driver fuel in the finned pots within the reactor during power operation, and transfer of fuel out of containment through the transfer tunnel. The analyses did not consider the thermal aspects of these interfaces.

C. TYPES OF COOLING SCHEMES

Three types of cooling schemes have been considered for use in RRS. These are direct gas cooling, indirect gas cooling, and "wet" (or sodium) cooling.

Direct gas cooling involves removing the decay heat from a core component or test assembly by forced convection of gas. The gas is passed directly over the surface of the cladding using axial forced flow.

Indirect gas cooling involves removing the decay heat from the fuel by forced convection of gas. The gas is passed over the surface of a sodium filled component which contains the fuel (e.g., a finned pot or a closed loop, in-reactor tube).

Wet cooling involves removing the decay heat from the fuel by either natural or forced convection of sodium passed by the fuel. The heat is subsequently removed from the sodium by external heat removal systems.

Direct gas cooling involves a transition from sodium cooling of the fuel (i.e., in the reactor or closed loop in-reactor tube) to gas cooling of the fuel. Two methods have

been proposed for accomplishing this transition. The first method involves "blowdown" of the cooling gas before an assembly is lifted clear of the sodium. The cooling gas is injected into the sodium using this method. The second method involves the full retraction of an assembly from the sodium into the handling machine before initiating gas cooling. The assembly undergoes an uncooled transition period and the cooling gas is not injected into the sodium using this method.

The first method was analyzed by AI (Reference 1) and was rejected because of the large quantities of cooling gas introduced into the sodium. The second method is considered herein for the case of direct gas cooling of core components and/or test assemblies.

The indirect gas cooling method uses an interrupted cooling cycle similar to that employed in the direct gas cooling method. The sodium filled finned pot containing an assembly (e.g., a finned pot containing a driver fuel assembly or a closed loop in-reactor tube containing a test assembly) is raised fully from the reactor pool into a fuel handling machine before flow of cooling gas is initiated. Similarly, gas flow is stopped before the sodium filled component containing the fuel is lowered from the handling machine into the IDS.

The wet fuel handling method always maintains the fuel immersed in sodium. Reactor pool (or closed loop) sodium is raised into the handling machine prior to withdrawal of the assembly from the reactor to the machine. A snorkel device used in conjunction with suction/pressurization operations is used to raise the sodium into the machine. The assembly is then removed from the reactor and transported to the IDS where it is lowered into the IDS and stored under sodium. Analyses of this approach have been made by AI and are reported in Reference 2. The wet handling approach was not considered in the present analyses.

D. DRIVER FUEL HANDLING

For the present analyses, indirect cooling of driver fuel handling in a finned pot was considered. Direct gas cooling and wet handling of driver fuel were not considered.

E. TEST ASSEMBLY HANDLING

Two cooling schemes were considered for test assembly handling in the present analyses. Scheme 1 considered an indirect cooling scheme of a closed loop test assembly wherein the cooling gas was passed over the exterior surface of the closed loop in-reactor tube. The tube containing the test fuel was filled with loop sodium.

Scheme 2 considered direct gas cooling of both open and closed loop test assemblies. The test assembly was withdrawn directly from the reactor (or closed loop in-reactor tube) into the handling machine using an interrupted cooling sequence (i.e., cooling gas flow was initiated after the test assembly had been fully retracted into the machine). Indirect gas cooling of open test assemblies (e.g., using a finned pot), wet fuel handling of test assemblies, and direct gas cooling using the blowdown approach were not considered.

II THERMAL ANALYSES

The thermal analyses will be discussed in three parts:

- Indirect cooling of driver fuel
- Indirect cooling of closed loop assemblies
- Direct cooling of closed loop and open test assemblies

The distinction among the cases will be maintained throughout the remaining discussions.

A. ASSUMPTIONS

1. Indirect Gas Cooling of Driver Fuel,

The following assumptions were made for the thermal analyses of the indirect gas cooling of driver fuel:

- Reactor refueling temperature is 450 °F.
- Argon cooling gas is used.
- The argon cooling gas is assumed to be incompressible with physical properties evaluated at a suitable reference temperature.
- The maximum decay heat load from a driver fuel assembly is 30 kWt.
- The driver fuel assembly conforms to the present reference design (see Reference 5 and Table I).
- Natural convection of the sodium within the finned pot removes heat from the fuel and subsequently delivers it to the surface of the pot for rejection to the argon. Design provisions will be included to preclude "short circuiting" of the sodium convection loop.
- The finned pot is constructed of stainless steel.
- The finned pot - driver fuel assembly model shown in Figure 2 will be employed.

2. Indirect Gas Cooling of a Closed Loop Test Assembly

The following assumptions were made for the thermal analyses of the indirect gas cooling of closed loop test assemblies :

FIGURE 2. *Finned Pot - Driver Fuel Assembly Model Used in Analysis*

- Reactor refueling temperature is 450 °F.
- Argon cooling gas is used.
- The argon cooling gas is assumed to be incompressible with physical properties evaluated at a suitable reference temperature.
- The maximum decay heat load from the test assembly is 17 kWt.
- The test assembly used in the analysis conforms to the specifications listed in Table I.
- Natural convection of the sodium inside the closed loop in-reactor tube removes the decay heat from the test assembly and delivers it to the upper topworks of loop tube for rejection to the argon cooling gas. Design provisions will be included to preclude "short circuiting" of the sodium convection loop.
- The closed loop in-reactor tube is constructed of stainless steel.
- The closed loop in-reactor tube - test fuel model shown in Figure 3 will be used in analysis.

3. Direct Gas Cooling of Closed Loop and Open Test Assemblies,

The following assumptions were made for the thermal analysis of the direct gas cooling of closed loop and open test assemblies.

- Reactor refueling temperature is 450 °F.
- Argon cooling gas is used.
- The argon cooling gas is assumed to be incompressible with physical properties evaluated at a suitable reference temperature.
- Two closed loop test assemblies will be used in the analysis; a reference oxide test assembly and a reference carbide test assembly. The design specifications for these test assemblies will be in accordance with Table I.

CLOSED LOOP TUBE ELEVATION

FIGURE 3. *Closed Loop Tube - Test Fuel Assembly Model Used in Analysis of Indirect Gas Cooling Scheme for Handling Closed Loop Test Fuel*

***TABLE I. Driver Fuel, Closed Loop Fuel and
Open Test Position Fuel Specifications
Used in the Analyses.***

Fuel and Cooling Scheme	Item	Value	Remarks
Driver fuel - indirect gas cooling scheme	Fuel configuration	Spiral wire wrapped pins contained in hexagonal flow duct	Reference fuel assembly design, see Reference 5
	Fuel system	Stainless steel clad (Pu,U)O ₂	Reference fuel assembly design, see Reference 5
	Fuel pin characteristics		
	total length (in.)	84	Nominal dimension used in analysis
	cladding OD (in.)	0.230	Nominal dimension used in analysis
	cladding ID (in.)	0.200	nominal dimension used in analysis
	fuel column length (in.)	36.0	Fuel is positioned in lower end of cladding tube
	wire wrap OD (in.)	0.056	Wire is stainless steel, spiral wrapped on a 1 ft pitch
	number of pins per assy.	217	Reference fuel assembly design, see Reference 5
	Duct characteristics		
	total length (ft)	14.0	Nominal dimension used in analysis
	outside dimension across flats (in.)	4.615	Sominal dimension used in analysis
	across flats (in.)		
	inside dimension across flats (in.)	4.335	
	Fuel Assembly		
	Material weights		
	total fuel (lb)	80.0	Nominal weight used in analysis
	total steel (lb)	232.0	Nominal weight used in analysis
	total sodium (lb)	54.0	Nominal weight used in analysis; includes only the sodium interior to the duct (i.e., does not include sodium between duct and finned pot)

TABLE I (contd)

Fuel and cooling Scheme	Item	Value	Remarks
Driver fuel - indirect gas cooling scheme (contd)	Peak operating power (MWt)	6.42	Includes only the fuel power; based on reference core design and a 1.4 radial peaking factor
	Peak decay power (kWt)	5.5	This is the decay power after the reactor has been shut down for 1 day for conservatism. 30 kW was used in analysis.
Closed loop test fuel-indirect gas cooling scheme	Fuel configuration	spiral wire wrapped pins contained in hexagonal flow duct	Filler bars are used to fill the gaps between the hexagonal flow duct OD and the closed loop test section liner tube.
	Fuel system	Stainless steel clad (Pu,U)C	A carbide fuel assembly was assumed for this case.
	Fuel pin characteristics		
	Total length (in.)	84.0	Nominal dimension used in analysis
	Cladding OD (in.)	0.280	Nominal dimension used in analysis
	Cladding ID (in.)	0.244	Nominal dimension used in analysis
	Fuel column length (in.)	36.0	Nominal dimension used in analysis
	Wire wrap OD (in.)	0.042	Nominal dimension used in analysis
	Number of pins per assy	37	This is the maximum number of pins in a triangular pitch lattice which can be installed in a 2.5 in. ID closed loop tube test section.
	Duct characteristics		
	Total length (ft)	14.0	Nominal dimension used in analysis see Figure 3
	Outside dimension across flats (in.)	2.12	Duct assembly must fit into a 2.5 in. ID closed loop test section liner tube
	Inside dimension across flats (in.)	2.02	Duct wall thickness of 0.050 in. assumed to be adequate

TABLE I. (contd)

Fuel and Cooling Scheme	Item	Value	
Closed loop test fuel-indirect gas cooling scheme (contd)	Test section		
	Material weights		
	total fuel (lb)	27.0	Based on fuel smear density of 88% and a theoretical density of 13.6 g/cm ³
	Total steel (lb)	67.0	Nominal weight used in analysis (includes 14 ft of filler bars)
	Total sodium (lb)	10.0	Includes obly the sodium interior to the duct
Closed loop test fuel-direct gas cooling scheme reference oxide test assy	Peak operating power (MWt)	4.0	Corresponds to a peak pin linear heat rating of ~45 kW/ft
	Peak decay power (kWt)	15.2	This is the decay power after the reactor has been shutdown for 1 day; for conservatism, 17 kWt was used in ch ₂ analysis
	Fuel Configuration	Spiral wire wrapped pins contained in hexagonal flow duct	Filler bars used to fill the gap between the hexagonal flow duct OD and the closed loop test section liner tube
	Fuel system	Stainless steel cladding (Pu,U)O ₂	This is the reference oxide test assembly
	Fuel pin characteristics		
	Total length (in.)	84	Nominal dimension used in analysis
	Cladding OD (in.)	0.230	Nominal dimension used in analysis
	Cladding ID (in.)	0.200	Nominal dimension used in analysis
	Fuel column length (in.)	36.0	Nominal dimension used in analysis
	Wire wrap OD (in.)	0.056	Nominal dimension used in analysis
	Number of pins per assy	37	This is the maximum number of pins on a triangular pitch which can be installed in a 2.5 in ID closed loop test section liner tube

TABLE 1. (contd)

Fuel and Cooling Scheme	Item	Value	Remarks
Closed loop test fuel direct gas cooling scheme Reference oxide test assy (contd)	Duct characteristics		
	Total length (ft)	14.0	
	Outside dimension across flats (in.)	1.93	Duct assembly must fit into a 2.5 in. ID closed loop test section liner tube
	Inside dimension across flats (in.)	1.83	Duct wall thickness of 0.050 in. is assumed to be adequate
	Test Section		
	Material weights		
	Total fuel (lb)	13.6	Based on a fuel smear density of 33% (same as driver fuel)
	Total steel (lb)	97.0	Includes filler bars (14 ft long) between hex duct OD and test section liner tube ID
	Total sodium (lb)	9.0	
	Peak operating power (MWt)	Variable parameter	The test fuel power was carried as a variable parameter (see Table III)
Reference carbide test assy	Peak decay power (MWt)	Variable parameter	The test fuel decay power was carried as a variable parameter (see Table III)
	See remarks	See remarks	The reference carbide test assy was assumed to be of the same configuration at the carbide test assembly used in the analysis of the indirect gas cooling scheme for closed loop test fuel (see above) with the exception that the test fuel peak operating power (and, hence, the test fuel decay power) was carried as a variable parameter-see Table III
Open Test Position-direct gas cooling scheme			
	Reference oxide test assy	See remarks	See remarks
			the reference oxide test assembly for the analysis of the direct gas cooling of open test position fuel was assumed to be identical in configuration with the fuel assembly design used in the analysis of indirect gas cooling of driver fuel with the exception that the test fuel peak operating power (and, hence, the test fuel decay power) was carried as a variable parameter-see Table III).

- One open test assembly configuration will be used in the analysis and it will be equivalent to the peak driver fuel assembly. The design specifications for the reference open test assembly will be in accordance with Table I.
- The uncooled transition periods will be
 - 2 min. for closed loop test fuel
 - 3 min. for open test assembly

4. Other Assumptions

It was assumed throughout the analyses that the argon cooling systems of the EVHM and/or GCLHM presented no design constraints on the analyses. That is, the cooling system gas circulators could be designed to furnish the required argon flowrates and head, and that the heat exchangers could be designed to provide the required heat rejection capabilities.

The argon coolant inlet temperatures to the EVHM and/or GCLHM barrel containing the fuel was assumed to be 300 °F throughout the analyses. This temperature was selected to provide an adequate log mean temperature difference (LMTD) for the argon-to-heat dump heat exchangers, and to lessen the possibility of freezing the sodium in the handling machines.

As will be seen later, the required argon coolant velocities using the direct gas cooling scheme can reach fairly high values under certain conditions (in the range of 500 to 700 ft/sec). Compressibility effects were ignored and the results are assumed valid as long as the argon velocities are maintained below about $0.4 \times$ sonic velocity in the argon at the operating temperatures. The sonic velocity in argon is about 1500 ft/sec at 500 °F.

Throughout the analyses, attention was directed only to normal fuel handling operations involving undamaged driver assemblies. Abnormal operations such as stuck driver assemblies, loss of handling machine coolant circulation, etc.

were not considered. Irradiated driver and test assemblies were assumed to be in the as-built condition. Damaged fuel e.g., blocked subchannels; bowed, warped, or fused pins, etc. were not considered.

B. FIXED AND VARIABLE PARAMETERS

The fixed parameters employed in the thermal analyses of (1) indirect gas cooling of driver assemblies, and (2) indirect gas cooling of closed loop test assemblies, and (3) direct gas cooling of closed loop and open test assemblies are listed in Table II. The variable parameters are listed in Table III.

Cases (1) and (2) employ fixed values of the fuel operating and decay powers since it was desired to obtain results which would indicate the general effectiveness of the indirect gas cooling scheme in handling fuel assemblies with maximum anticipated decay heat loads. Case (3) fuels, however, employ test fuel operating and decay powers as a variable parameter inasmuch as the decay heat load from the test fuel has a strong influence on required in-reactor cooling times and argon cooling gas system performance requirements.

C. ANALYTICAL APPROACH

1. Indirect Gas Cooling of Driver Fuel Assemblies

Indirect gas cooling of driver assemblies involves handling of the assembly inside a sodium filled finned pot (see Figure 2). Decay heat is removed from the assembly by natural convection circulation of the sodium flowing upward through the assembly, past the fuel, and existing from the top of the fuel duct. Argon cooling gas passes by the exterior of the finned pot (down flow forced convection) and removes the heat from the sodium. The cooled sodium flows downward between the outside of the hexagonal fuel duct and the inside of the finned pot, thence returning upward through the fuel assembly through the flow holes located in the lower extension tube of the fuel assembly.

TABLE II. Fixed Parameters for Thermal Analysis

	Fuel and Cooling Scheme	Item	Value	Remarks
	Driver Fuel - indirect cooling scheme	Fuel configuration	Standard driver assy	See Table I and Reference 5 for details; also see Figure 2
		Finned pot configuration		<div> <div> <div>see figure</div> <div>1</div> </div> </div>
		Length (ft)	15	
		Pot ID (in.)	5.75	
		Wall thickness (in.)	0.125	
		Fin height (in.)	0.5	
		Pot OD over fins (in.)	7.0	
		Fin width (in.)	0.2	
		Number of fins on pot	36	Fins run longitudinally along full length pot
		Fin length	Full length of pot	
		Argon physical properties	See Figure 4	Argon inlet to handling machine assumed to be at 300 °F (See Section 5.1)
		Sodium Physical properties	See ANL-7223	
		Fuel decay power (kWt)	30	See Table I
		Maximum allowable fuel cladding temperature (°F)	1000	Design requirement for normal handling of driver fuel (See Section 4.2)
		Refueling temperature (°F)	450	See Section 5.1
29	Closed loop test fuel - indirect gas cooling scheme	Fuel configuration	Carbide 0210 fuel	See Table I and Figure 3
		Closed loop tube configuration	Reentrant oxide	See Figure 3
		Argon physical properties	See Figure 4	Argon inlet to handling machine assumed
		Sodium physical properties	See ANL-7323	
		Fuel decay power (kWt)	17	See Table I
		Maximum allowable fuel cladding temperature (°F)	1000	Assumed design requirement for normal handling of test fuel (see Section 4.2)
		Refueling temperature (°F)	450	See Section 5.1

TABLE II. (contd)

Fuel and Cooling Scheme	Item	Value	Remarks
Closed loop test fuel-indirect gas cooling scheme	Fuel configuration	Carbide test fuel	See Table I and Figure 3
	Closed loop tube configuration	Reentrant type	See Figure 3
	Argon physical properties	See Figure 4	Argon inlet to handling machine assumed to be at 300 °F (see Section 5.1)
	Sodium physical properties	See ANL-7323	
	Fuel decay power (kWt)	17	See Table I
	Maximum allowable fuel cladding temperature (°F)	1000	Assumed design requirement for normal handling of test fuel (see Section 4.2)
	Refueling temperature (°F)	450	See Section 5.1
Closed loop test fuel-direct gas cooling scheme			
	Reference oxide test assembly		
	Fuel configuration	Oxide test assy	See Table I
	Argon physical properties	See Figure 3	Argon inlet to handling machine assumed to be at 300 °F (see Section 5.1)
	Sodium physical properties	See ANL-7323	
	Maximum allowable fuel cladding temperature (°F)	1000	Assumed design requirement for normal handling of test fuel (see Section 4.2)
	Duration of uncooled transition period (min)	2	Based on a lifting/lowering speed of 12 ft/min and time required to close/open bottom valve and start/stop argon blowers of 30 seconds.
	Refueling temperature (°F)	450	See Section 5.1

TABLE II ntd)

Fuel and Cooling Scheme	Item	Value	Remarks
Closed loop test fuel direct gas cooling scheme (contd)			
Reference carbide test assembly	Fuel configuration	Carbide test assy	See Table I
	Argon physical properties	See Figure 4	Argon inlet to handling machine assumed to be at 300 °F (See Section 5.1)
	Sodium physical properties	See ANL-7323	
	Maximum allowable fuel cladding temperatures	1000	Assumed design requirement for normal handling of test fuel (See Section 4.2)
	Duration of uncooled transition period (min)	2	Based on a lifting/lowering speed of 12 ft/min and time required to close/open bottom valve and start/stop argon blowers of 30 seconds
	Refueling temperature (°F)	450	See Section 5.1
Open test position fuel - direct gas cooling scheme	Fuel configuration	Same as driver fuel assembly	See Table I, Reference 5, and Figure
Reference oxide test assembly	Argon physical properties	See figure 4	Argon inlet to handling machine assumed to be at 300 °F (See Section 5.1)
	Sodium physical properties	See ANL-732	
	Maximum allowable fuel cladding temperature (°F)	1000	Assumed design requirement for normal handling of test fuel (See Section 4.2)
	Duration of uncooled transition period (min.)	3	Based on a lifting speed of 12 ft/min and time required to close/open bottom valve on handling machine and start/stop argon blowers of 30 seconds. Duration of uncooled transition period for open test assembly is one minute longer than for closed loop assembly since open test must traverse reactor top cover region in an uncooled mode whereas closed loop test is still immersed in loop tube sodium in this region.

TABLE II. (contd)

Fuel and Cooling Scheme	Item	Value	Remarks
Note: The following physical properties were used throughout the analyses	Fuel Specific Heat, C_p (Btu/lb-°F)		
	for oxide fuel	0.07	
	for carbide fuel	0.035	
	Steel specific heat (Btu/lb-°F)	0.12	

TABLE III. *Variable Parameters for Thermal Analysis*

Fuel and Cooling Scheme	Item	Value	Pemarks
Driver Fuel - Indirect Cooling Scheme	See remarks	See remarks	A fixed fuel configuration - finned pot designs were employed (see Table II, Reference 5, and Figure 2); the maximum decay heat level was set at 30 kWt. The thermal performance of the finned pot (i.e., internal sodium natural circulation loop) and argon circulation system was calculated in order to provide results to assess the thermal performance of the indirect gas cooling scheme for handling driver fuel.
Closed loop test fuel - indirect pas coolinp scheme	See remarks	See remarks	A fixed fuel configuration - closed loop tube model was employed (see Table II and Figure 2); the maximum decay heat level was set at 17 kWt. The thermal performance of the closed loop tube (i.e., internal sodium natural circulation loop) and argon circulation system was calculated in order to provide results to assess the thermal performance of the indirect gas cooling scheme for handling closed loop test fuel.
Closed loop test fuel-direct gas cooling scheme Reference oxide test assembly	Peah fuel operating power - kW/ft of fuel pin - kW/kg of fuel	10 to 35 200 to 600	Peak fuel power was carried as a variable parameter in order to illustrate the effect of this variable on required in-reactor cooling time prior to handling, and on required arpon coolant flow velocities in the GCLHM. Where a set value of peak fuel power was required to illustrate the inter-relationship of other variables, a base case fuel power of 25 kW/ft of pin (peak) was used. This value was assumed to represent the upper hound of allowable J_{kd0} for oxide fuel.

TABLE III *contd*

Fuel and Cooling Scheme	Item	Value	Remarks
Closed loop test fuel direct gas cooling scheme Reference oxide test assembly (contd)	Argon coolant velocity in GCHM (ft/sec)	~100 to ~600	Upper limit is established to avoid the necessity of considering compressibility effects in calculating the thermal-hydraulics of the argon coolant
	In-reactor coding time (days)	1 to 30	A key independent variable related to maximum allowable cladding temperature during handling operations
	Maximum allowable cladding temperature (°F)	1000, 1200 400	Although 1000 °F was assumed to be a design requirement on maximum cladding temperature this item was carried as a variable parameter to illustrate its effect on the thermal results of the analysis.
Reference carbide test assembly	Peak fuel operating power		
	- kW/ft of fuel pin	~10 to 55	See above remarks for reference oxide test assembly; when required to use a set value of peak fuel power, 40 kW/ft of fuel pin was used - this value was assumed to represent the upper bound of carbide fuel powers of present interest in LMFBR's.
	- kW/kg of fuel	~100 to 500	
	Argon coolant velocity in GCHM (ft/sec)	~100 to ~600	See remarks above for reference oxide test assembly
	In-reactor cooling time (days)	1 to 30	See remarks above for reference oxide test assembly
	Maximum allowable cladding temperature (°F)	1000, 1200, 1400	See remarks above for reference oxide test assembly

TABLE III. (contd)

Fuel and Cooling Scheme	Item	Value	Remarks
Open test position fuel - direct gas cooling scheme	Peak fuel operating power		
	- kW/ft of fuel pin	~10 to 30	See foregoing remarks for oxide test fuel; when required to use a set value of peak fuel power, 12.7 kW/ft of fuel pin was used - this value is about the same as the peak fuel power in a standard driver fuel assembly
	- kW/kg of fuel	~100 to 500	
	Argon coolant velocity in GCLHM (ft sec)	~100 to ~600	See foregoing remarks for reference oxide test assembly
	In-reactor cooling time (days)	1 to 30	See foregoing remarks for the reference oxide test assembly
	Maximum allowable cladding temperature (°F)	1000, 1200, 1400	See foregoing remarks for reference oxide test assembly

The calculation of the sodium circulation inside the finned pot involves equating the flow friction ΔP around the circuit to the available driving head supplied by the differences in the sodium density around the circuit. Reference 6 discusses the calculational technique in detail.

The argon cooling gas flowing downward past the exterior surface of the finned pot removes the heat from the sodium by forced convection. For purposes of the analysis, it was assumed that the argon flow path past the finned pot was comparable to the finned pot residing in an 8 in. ID flow tube. The argon heat transfer coefficient on the OD of the finned pot was calculated using the Dittus-Boelter equation (Reference 7). The fin efficiency was taken as being 1.0 and the argon physical properties (Figure 4) were evaluated at the film temperature existing at the point where the axial temperature rise of the coolant was one-half of the total axial temperature rise. The total temperature rise was calculated using the standard heat balance equation.

Figure 5.A is a plot of the argon axial ΔT (as a function of argon temperature as a parameter) versus argon flow velocity for a 30 kWt fuel decay power. Figure 5.B relates the argon heat transfer coefficient as a function of argon film temperature to the argon flow velocity. Using the model illustrated in Figure 2 and the data presented in Figure 5.A and 5.B, Figure 6 can be generated.

Figure 6 summarizes the thermal performance characteristics of the indirect gas cooling scheme for handling driver fuel assemblies, subject to the conditions listed in Tables I, II, and III for this case. The hyperbolic curves represent the

FIGURE 4. Argon Physical Properties

FIGURE 5.A Argon Flow Velocity Versus
Argon ΔT 30 kW Rejected to Argon

FIGURE 5.B. Argon Heat Transfer Coefficient
Versus Argon Velocity

FIGURE 6. *Sodium Natural Convection Circuit Thermal Head Characteristics - Driver Fuel Indirect Gas Cooling*

"demand" curves for the sodium circuit flow, i.e., to obtain a given circuit ΔT the required thermal driving head can be read directly. The straight lines represent the "supply" curves for the sodium circuit, i.e., the driving head available as a function of the cooling characteristics of the argon coolant. For example, if the argon coolant flow is sufficient to remove the fuel decay heat from the sodium over the top 1 ft of the pot, the curve designated would be used in Figure 6.

The intersection of the appropriate supply and demand curves determines the sodium circuit ΔT which will be obtained when handling a driver fuel assembly producing 30 kWt of decay heat. The sodium circulation rate can also be determined using Figure 6.

It is anticipated that, using the indirect gas cooling scheme for handling driver fuel, the finned pot sodium circuit ΔT will be of the order of 150 to 250 °F. This is based upon estimates of the argon cooling gas heat transfer characteristics using Figure 5.A and 5.B. If the finned pot is immersed in sodium, however, it is anticipated that the sodium circuit ΔT would be of the order of 100 to 150 °F (see Figure 6) because of the effectiveness of the exterior sodium in removing the decay heat from the top of finned pot over a very short length (probably 1 ft or less). As a result of the analysis, then, the following conditions were assumed.

- The sodium circuit ΔT inside the finned pot is 130 °F when the pot is immersed in sodium
- The sodium circuit ΔT inside the finned pot is 200 °F when the pot is inside the EVHM and is being cooled by downflow forced convection of argon.

Having determined the steady state performance of the indirect gas cooling of driver fuel handling scheme, it was required to determine the adiabatic temperature rise of the sodium filled finned pot - driver fuel assembly combination.

It is necessary to know the rate of adiabatic temperature rise to determine the minimum allowable time increment available for uncooled transfer of the pot-fuel from the reactor sodium into the EVHM to the IDS.

Using the heat balance equation and allowing the driver fuel assembly and contained sodium to heat adiabatically (no credit was taken for heat up of the finned pot), the adiabatic heating rate was calculated to be about 30 °F/minute.

Using the above results, Figure 7 was constructed. Figure 7 illustrates the thermal aspects of using an indirect gas cooling scheme for handling driver fuel assemblies (generating a decay heat load of 30 kWt). See Section 6.1 for a discussion of Figure 7.

2. Indirect Gas Cooling of Closed Loop Test Fuel

The thermal analysis of the indirect gas cooling scheme for closed loop test fuel proceeds along the lines discussed in the foregoing section C.1. The analysis consists of equating the available thermal driving head in the sodium circuit (because of fluid density differences at various locations around in the circuit) to the friction ΔP of the sodium flowing in the circuit. Figure 8 shows the characteristics of the closed loop tube natural convection circuit. It is interesting to note the differences between the sodium circuit characteristics of the finned pot-drives fuel combination and the closed loop tube-carbide test fuel combination. The closed loop system, owing to its much longer length coupled with the use of the loop topworks as the decay heat rejection region, is much more insensitive to sodium temperature than is the finned pot-driver fuel assembly system. The finned pot sodium circuit is sensitive to both the effective cooling length of the pot for heat rejection to the argon and the bulk sodium temperature

FIGURE 7. Thermal Aspects of Using Indirect Gas Cooling to Handle Driver Fuel

FIGURE 8. *Sodium Natural Convection Circuit
Thermal Head Characteristics - Closed
Loop Test Fuel Indirect Gas Cooling*

in the circuit because the system works on a much smaller available thermal driving head (i.e., 4 to 8 lb/ft² for the finned pot versus about 30 lb/ft² for the closed loop system).

Assuming that the maximum allowable closed loop test fuel cladding temperature is 1000 °F, and that the argon coolant inlet temperature is 300 °F, it is possible to determine several design characteristics required of the topworks heat exchanger section of the closed loop tube. The interrelationships of some of these pertinent design features are illustrated in Figure 9. For a fixed maximum cladding temperature and argon inlet temperature, the required argon velocity increases with increasing argon outlet temperature. While the argon mass flowrate decreases for this situation, the argon annular flow passage thickness in the topworks decreases in order to provide the required higher argon velocities. With increasing argon velocities, of course, the flow ΔP across the topworks increases. A reasonable design course is to increase the clearance between the loop topworks OD and the stationary flow guide tube ID in the GCLHM to ~1.0 in. The argon mass flowrate would then be ~3500 lb/hr at a velocity of ~150 ft/sec past the topworks section (resulting in a coolant ΔP for the topworks of ~2-5 in. of H₂O).

3. Direct Gas Cooling of Test Assemblies

The analysis of direct gas cooling of test fuel involved a determination of several values including :

- (a) The required in-reactor cooling time prior to handling the test assembly and still maintain the maximum cladding temperature(s) to specified limits.
- (b) The required argon flow velocities through the bundle of test pins to maintain the specified maximum cladding temperature limits as a function of in-reactor cooling time for the base case maximum fuel power level.

- (c) The required argon flow velocities through the bundle of test pins to maintain a maximum cladding temperature of 1000 °F as a function of maximum fuel test power and in-reactor cooling time
- (d) The required argon flow velocities through the bundle of test pins to obtain a specified steady state maximum cladding temperature with the fuel in the GCLHM for the base case fuel power as a function of in-reactor cooling time.

The test fuel characteristics and range of variables are listed in Tables I, II, and III. Item A (above) is calculated using the adiabatic heating rate in the fuel (as determined by a standard heat balance) and fuel cladding as a function of decay power level. Only the fuel and fuel cladding were assumed to be available for absorbing the fuel decay power during the uncooled transition period; the adiabatic heating rates for the base case fuel powers are shown in Figure 10. Using Figure 10, with suitable adjustments for fuel power (as compared to the base case fuel powers used in Figure 10), along with the appropriate durations for the uncooled transition periods, Figures 11, 12, and 13 were generated. These figures illustrate the interrelationships of cooling time to peak allowable fuel operating power as a function of the specified maximum allowable cladding temperature (which occurs at the time the test fuel has been fully retracted into the GCLHM and the argon blowers are just being energized).

Item B (in the foregoing series) is calculated using the standard Dittus-Boelter equation (Reference 7) to evaluate the argon-cladding interface heat transfer coefficient (see Figure 5.B). Upflow of the argon was assumed and the maximum cladding temperature occurs at the top of the test fuel region,

FIGURE 9 Closed Loop Topworks Heat Exchanger Characteristics

FIGURE 10. *Adiabatic Heating Rates in Test Fuel Assemblies Versus Fuel Cooling Time*

FIGURE 11. Closed Loop Reference Oxide Test Assembly Required Cooling Time for Test Assembly in Closed Loop Prior to Removal to GCFHM Versus Fuel Operating Peak Power Density for Various Maximum Cladding Temperatures

FIGURE 12. *Closed Loop Reference Carbide Test Assembly Required Cooling Time for Test Assembly in Closed Loop Prior to Removal to GCLHM Versus Fuel Operating Peak Power Density for Various Maximum Allowable Cladding Temperatures*

FIGURE 13. *Open Test Position Reference Test Assembly Required Cooling Time for Test Assembly in Reactor Prior to Removal to GCLHM Versus Fuel Operating Peak Power Density for various Maximum Allowable Cladding Temperatures*

where the local argon bulk temperature is calculated by the standard heat balance equation. Using the base case test fuel powers (see Table II and III, viz, 25 kW/ft of pin for the closed loop reference oxide test assembly, 40 kW/ft of pin for the closed loop reference carbide test assembly, and 12.7 kW/ft of pin for the open test position reference (i.e., oxide test assembly), the argon velocity required to maintain specified maximum cladding temperatures (as a function of fuel cooling time) was determined. The results are shown in Figures 14, 15, and 16.

Item C was calculated in the same manner as Item 2. Item C however, is for a constant maximum allowable cladding temperature of 1000 °F but variable test fuel power levels. The results are shown in Figures 17, 18, and 19.

Item D was calculated in the same manner as Items B and C. Figures 20, 21, and 22 present the results which illustrate the maximum test fuel cladding temperatures (obtained with the fuel in the GCLHM) as a function of argon flow velocity and cooling time for the base case test fuel powers listed in Table III.

D. ASSESSMENT OF UNCERTAINTIES

It is difficult to assess the uncertainties of the overall results since the handling facilities (e.g., finned pot) design, the uncooled transition times, and even the fuel configurations employed in the analyses are nothing more than conceptual design assumptions at this point in time. Uncertainties in the analyses, then, are not of prime consideration. What is of importance, however, are some of the general observations and trends which can be determined from the results. Some of these observations and trends are discussed in Section 6.0.

FIGURE 14. *Closed Loop Reference Oxide Test Assembly Argon Flow Velocity Required in GCLHM Versus Cooling Time for Various Maximum Allowable Cladding Temperatures*

FIGURE 15. Closed Loop Reference Carbide Test Assembly with Argon Flow Velocity Required in GCLHM Versus Cooling Time for Various Maximum Allowable Cladding Temperatures

FIGURE 16. *Open Test Position Reference Assembly Argon Flow Velocity Required in GCFHM Versus Cooling Time for Various Maximum Cladding Temperatures*

FIGURE 17. Closed Loop Reference Oxide Test Power Density Versus Cooling Time for Various Argon Coolant Velocities Past Fuel Pin Bundle

FIGURE 18. Closed Loop Reference Carbide Test Assembly Power Density Versus Cooling Time for Various Argon Coolant Velocities Past Fuel Pin Bundle

FIGURE 19. *Open Test Position Reference Assembly Power Density Versus Cooling Time for Various Argon Coolant Velocities Past Fuel Pin Bundle*

FIGURE 20. *Closed Loop Reference Oxide Test Assembly
Maximum Steady State Cladding Temperatures
With Test Fuel in GCFHM Versus Argon
Coolant Velocities Through Pin Bundle for
Various Decay Times*

FIGURE 21. *Closed Loop Reference Carbide Test Assembly
 Maximum Steady State Cladding Temperatures
 With Test Fuel in GCLHM Versus Argon Coolant
 Velocities Through Pin Bundle for Various
 Decay Times*

FIGURE 22. *Open Test Position Reference Assembly
 Maximum Steady State Cladding
 Temperatures with Test Fuel in GCLHM
 Versus Argon Coolant Velocities Through
 Pin Bundle for Various Decay Times*

For benchmark reference by the reader some general assessments of the uncertainties in the results include:

- (1) Indirect gas cooling of driver fuel
 - overall sodium circuit ΔT - $\pm 20\%$ from values indicated in Figure 6
 - argon ΔT - $\pm 10\%$ from values indicated in Figure 5.A
 - argon heat transfer coefficient - $\pm 30\%$ from values indicated in Figure 5.B
- (2) Indirect gas cooling of closed loop test fuel
 - overall sodium circuit ΔT - $\pm 15\%$ from values indicated in Figure 8
 - argon ΔT argon heat transfer coefficients - uncertainty about the same as quoted for Item 1 in the foregoing.
- (3) Direct gas cooling of closed loop test fuel
 - adiabatic heat rates - uncertainty of the order of that used to predict decay power - versus - cooling time (see Figure 23); probably of the order of - $\pm 15\%$.
 - argon ΔT and argon heat transfer coefficients uncertainties as noted under Item 1 above.

FIGURE 23 Fuel Decay Power Versus Decay Time, 1 Year Operating Time

• III DISCUSSION OF RESULTS

A. DRIVER FUEL HANDLING USING THE INDIRECT GAS COOLING APPROACH

Figure 7 illustrates a typical cladding temperature history of a 30 kWt driver fuel assembly during removal of the assembly from the reactor into the EVHM, transportation in the IDS, and deposition into the IDS. Figure 7 was constructed as described in Section 5.3.1.

Figure 7 reveals that about 10 minutes are available for the uncooled transition period. This long transition period results from the extensive thermal inertia present in the sodium-filled finned pot handling scheme, and represents one of the (if not the most) important benefits obtained from this particular handling scheme. If one inspects Figure 10, it becomes immediately apparent that the adiabatic heat rates using the direct gas cooling approach are of an order of magnitude greater than those associated with the indirect gas cooling scheme. For off-normal (or emergency) handling conditions, then, the indirect gas cooling scheme is far and away preferred to the direct gas cooling scheme.

The results of the analysis indicate that an indirect gas cooling scheme can be used for handling driver fuel assemblies generating up to 30 kWt decay heat without imposing any severe thermal restrictions.

B. TEST ASSEMBLY HANDLING

1. Indirect Gas Cooling of Closed Loop Test Assembly

The thermal performance characteristics of this scheme (Figures 8 and 9) are quite acceptable. Adiabatic heat rates during uncooled periods are estimated to be of the order of 5 °F/min or less when handling a 17 kW test assembly. This low heating rate evolves from the substantial thermal inertia associated with the sodium-finned closed loop in-reactor tube which is used as a handling container for the test assembly. The 5 °F/min heat rate using indirect gas cooling of closed loop fuel is about two orders of magnitude lower than the corresponding adiabatic heating rates associated with the direct gas cooling scheme (see Figure 10), again illustrating the desirability of indirect gas cooling over direct gas cooling.

2. Direct Gas Cooling of Closed Loop and Open Test Position Assemblies

The results of the analysis of using a direct gas cooling scheme for handling test assemblies indicate that:

- Operating test fuel power can require cooling times in excess of one day before the assembly can be removed from the reactor.
- Conversely, if it is necessary to handle test fuel within one day after shutdown it will be necessary either to reduce the uncooled transition time from reactor-to-GCLHM, and/or restrict the peak operating test fuel power to levels compatible with the one day handling time restriction, and/or increase the maximum allowable temperature which the test fuel cladding can attain during handling operations.

- Significant argon cooling velocities (i.e., 500 ft/sec and greater) can be anticipated when using direct gas cooling of high-power density, short cooling time, test assemblies

Although direct gas cooling of test assemblies requires exacting thermal performance and close attention to handling operations, under normal conditions such a cooling scheme should perform satisfactorily. During off-normal operations, however, test fuel temperatures can rise rapidly. This can lead to destruction of test data and, under some circumstances, melt-down of the test assembly. Off-normal conditions should be considered in detail if a direct gas cooling scheme is desired for the FFTF.

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