SUBASSEMBLY TEMPERATURES DURING
POSTIRRADIATION TRANSFER
FROM THE EBR-II PRIMARY TANK

by

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ABSTRACT

The cooling capability of the fuel-transfer system was determined for the types of subassemblies now in use at EBR-II. This was done to provide expected subassembly temperatures during transfer from the primary tank and to allow a more flexible transfer schedule than the 15-day holding period initially set.

It was found that there is a wide variation in heat-transfer characteristics of subassemblies because of differences in element or capsule configuration and flow orificing. To maintain cladding surface temperatures within the desired range, the allowable decay-heat generation is generally well below 1.0 kW. The temperature rise on loss of cooling also varies significantly with subassembly configuration and composition, and may be the limiting factor in determining the holding period for some subassemblies.

A recently developed computer program, DECAY, provides curves of maximum temperatures during transfer vs postirradiation holding time, for fueled subassemblies. The tables and nomograms that have been developed from these results give holding-time requirements of subassemblies as a function of their power generation while in the core.

Structural subassemblies have also been examined. Most structural materials cause no serious heating problems during transfer. A few, however, have significant decay-heat production that must be considered carefully during design.

I. INTRODUCTION

A wide variety of experimental subassemblies is in use at EBR-II (Table I). These subassemblies have heat-transfer characteristics that are in most cases quite different from those for which the fuel-transfer system was designed. These differences arise from restricted flow orificing and the use of fewer fuel pins, resulting in higher temperatures during transfer than would be associated with the same heat output for driver subassemblies. It is important to be able to determine maximum temperatures to ensure safe transfer of subassemblies and integrity of postirradiation data. The ability to easily calculate these temperatures also allows a more flexible transfer schedule than the 15-day delay initially set for EBR-II.

To accomplish these objectives, the fuel-transfer process was analyzed and the computer program DECAY written to produce temperature-vs-cooling-time curves with a minimum input. The necessary data include subassembly history, subassembly power production when in core, and argon-cooling flowrates throughout the fuel-transfer process. On the basis of conservative values for these parameters, nomograms have been developed that list the maximum temperatures encountered in various subassembly types for a variety of transfer schedules (Appendix A).

II. FUEL HANDLING

Subassembly transfers are done in two phases. The first, unrestricted fuel handling, is done after the reactor has been shut down and involves the interchange of subassemblies between the reactor and storage basket.^{1,2,3} Both the reactor and the storage basket are submerged in primary bulk sodium, as shown in Fig. 1. The subassemblies remain below the bulk-sodium level during transfer and are therefore cooled adequately by the sodium. No special cooling is needed for the subassemblies within the storage basket.

After the spent subassemblies are loaded into the storage basket, they remain there for a holding period. This holding period allows sufficient decay of fission-heat generation to enable the subassemblies to be safely gas-cooled during subsequent transfer operations. It is necessary to remove spent subassemblies from the storage basket at the earliest

TABLE I. Summary of Design Features of Capsules or Elements for EBR-II Experimental Subassemblies ^a

<u>Capsule or Element</u>		<u>Spacer Wire</u>		<u>Subassembly Type</u>
<u>OD,</u> <u>in.</u>	<u>Length,</u> <u>in.</u>	<u>Dia,</u> <u>in.</u>	<u>Normal Pitch,^b</u> <u>in.</u>	
0.174	18.1	0.049	6	E-61A
0.220	60.9	0.051	6	B-61
0.023	40	0.042	12	B-61B; E-37A
0.230	40	None	None	L-61
0.230	60.9	0.040	12	B-61A; E-74A; E-19C
0.250	40	0.040	12	N-37; E-19E; E-37B; J-37A
0.250	60.9	0.062	6	F-37; E-7; E-19A; E-19D
			12	F-37A; E-7; E-19A; E-19D
0.250	60.9	0.040	6	H-37
			12	H-37A
0.290	60.9	0.056	6	B-37; E-7B
0.310	40	0.080	6	N-19; E-19B
0.375	40	None	None	A-19A
0.375	40	0.030	6 or 12	J-19A
0.375	40	0.097	6	B-19
0.778	57.8	0.020	6	B-7B
0.805	57.9	None	None	B-7A
Ring material, variable OD		None	None	K-1; P-1
Unit Assembly		None	None	M-1

^a From "Guide For Irradiation Experiments in EBR-II"

^b Most of the subassembly types will accept a complete bundle of elements of any uniform pitch.

Fig. 1. Fuel-handling Mechanisms in Primary Tank

possible time for two reasons. First, the storage basket can store only a limited number of subassemblies. A large portion of the space is needed for storing fresh subassemblies to be used in refueling the reactor. Second, the irradiated subassemblies must be moved to the Fuels and Examination Facility (FEF) as quickly as possible for postirradiation examination. Lengthy delays could affect the postirradiation data and reduce the value of the information.

Following the holding period, the subassemblies are transferred from the primary tank in the second phase of fuel handling. The second phase, restricted fuel handling, involves the interchange of subassemblies between the storage basket and FEF. Restricted fuel handling is normally done with the reactor operating, and an interchange is performed almost daily, with one fresh subassembly loaded into the storage basket and a spent subassembly returned to the FEF.

In restricted fuel handling, a spent subassembly is removed from the primary bulk sodium and transferred into the fuel unloading machine (FUM) through the primary-tank fuel-transfer port.³⁴ Mounted on rails, the FUM is a self-propelled lead-shielded cask equipped with a retractable gripper. An automatic argon-circulating system (Fig. 2) provides subassembly cooling and sodium-blow-off capabilities while the spent subassembly is being handled by the FUM. The FUM is driven to a pit where the subassembly is lowered into one of the two interbuilding coffins (IBC's). Each IBC is a 20-ton portable lead-shielded coffin with a gas-circulating system driven by an attached battery-powered blower (Fig. 3). After the FUM is moved, the IBC is picked up by the reactor-building crane and placed in the equipment airlock for transfer into the FEF. Once in the IBC, the subassembly remains there until it is removed within the FEF. Fresh subassemblies are returned to the reactor in a reverse sequence.

III. ARGON COOLING SYSTEM FOR THE FUEL UNLOADING MACHINE (FUM)

A. Description

The FUM argon cooling system (FUM-ACS) is designed to furnish uninterrupted argon flow through subassemblies during transfers between the primary tank and the IBC. More specifically, cooling is provided by this system when (a) the subassembly is raised from the primary bulk sodium and

Fig. 2. Argon-circulating-system Loop

Fig. 3. Interbuilding Coffin for Subassembly Transfers

is in the fuel-transfer port prior to loading into the FUM, (b) the subassembly is in the FUM, and (c) the subassembly is in the IBC in the FUM pit.

Operation of the argon system is essentially automatic. As shown in Fig. 4, the system is designed with argon loops in the IBC, FUM, and fuel-transfer port. These loops are connected together so that opening or closing air-operated valves in the loops will divert the argon flow through the subassembly at each stage of the transfer operations.

Flow is supplied by two argon turbine blowers mounted in parallel. A 10-hp ac turbine blower is used for normal operation, supplying 60 scfm at a 4-psi ΔP across the turbine. Upon failure of the ac turbine, a 5-hp dc turbine starts automatically and supplies two-thirds of the flow of the ac turbine. Emergency batteries will run the dc turbine for approximately 60 min on loss of normal power.

Although the normal flow is 60 scfm, the FUM-ACS is susceptible to reduced flow because of the system design. Plugging by sodium aerosol can occur in the FUM vapor trap and molecular sieve and in the ACS vapor trap and two molecular sieves. This plugging can cause a decrease in flow and reduce the cooling capabilities of the ACS. A low-flow alarm at 30 scfm is provided to warn the operating personnel of a low-flow condition.

There is no direct way to measure the temperature of a subassembly being cooled by the FUM-ACS. Instruments in the system allow measurements of the inlet and outlet temperatures, the inlet pressure for the FUM, and the total system flow. With a subassembly in the FUM, an approximation of the subassembly's temperature is provided by a thermocouple attached to the FUM hexagonal guide tube at approximately the level of the core section of a subassembly. Heat-transfer calculations must be made, however, to determine the temperature of a subassembly.

B. Argon Flow Through the FUM

The inside of the FUM is lined with a hexagonal guide tube of slightly larger diameter than a subassembly. Argon enters the FUM at the top of the hexagonal guide tube and flows downward. If the flow path is through the FUM only, the argon discharges through outlet piping just above the FUM shielding valve. A flow path through the FUM and fuel-transfer port directs the flow into the fuel-transfer port and then down into

Fig. 4. Argon Flow Paths

the primary cover gas.

Before entering the FUM, the argon is preheated to a temperature of 410°F . Once the hot argon enters the FUM, the argon flow is guided through the subassembly by the FUM gripper. The lower end of the gripper's outer shell consists of a 1- $\frac{1}{2}$ -ft-long hexagonal section.⁵ The hexagonal section fits closely in the FUM's hexagonal guide tube. The outer shell is spring loaded and mates to the subassembly top; the spring applies pressure on the outer shell and maintains the connection between the outer shell and the subassembly.

Most of the argon is forced into the gripper assembly through a number of access holes and then is blown through the inside of the subassembly. Leakage flow occurs, however, in the clearance space between the gripper's outer shell and the FUM's guide tube.

Figure 5 shows the clearance dimensions of the FUM's guide tube, the gripper's outer shell, and a subassembly. A smaller amount of leakage can also exist between the bottom of the gripper's outer shell and the rim of the subassembly top.

C. Argon Flow Through the Fuel-transfer Port

The fuel-transfer port (FTP) provides access into the primary tank for the removal and insertion of subassemblies. It is mounted in a nozzle in the primary-tank cover and consists of a shielding rotary valve with a hexagonal guide tube attached to the bottom of the valve. The hexagonal guide tube extends into the primary bulk sodium.

When the flow is through the FTP only, argon is drawn from the primary cover gas through the A-3 nozzle and discharged below the rotary valve into the hexagonal guide tube. Flow continues down the hexagonal guide tube and back into primary cover gas through a series of 1-in.-dia holes located above the bulk-sodium level.

The FTP loop of the FUM-ACS has two heaters that heat the argon to 610°F before it enters the FTP. The flow path through the FTP is used during the "blowing" cycle when a subassembly is being removed from the primary tank. The "blowing" operation blows hot argon into the FUM gripper and subassembly to remove most of the sodium.

Fig. 5. Argon Flow Path Through FUM Gripper and Subassembly

D. Argon Flow from the FUM-ACS to the Interbuilding Coffin (IBC)

Although the IBC has a self-contained cooling system, external cooling is provided from the FUM-ACS for the IBC during loading and unloading operations in the reactor building.⁶ While a spent subassembly is being lowered into the IBC, argon preheated to 410°F enters the top of the FUM and flows down through the IBC. After the FUM and IBC valves are closed, the argon flow is switched to the IBC only. The gas entering the IBC is preheated to 200°F by the gas-purifier heater.

IV. COOLING SYSTEM FOR THE IBC

A compact cooling loop is attached to the side of each IBC to provide cooling for subassemblies during transfer from the reactor building to the FEF. A blower circulates the coolant down through the subassembly and up past the inner surface of the lead shielding. The heat generated by the subassembly is transferred to the shielding.

A removable insert tube fits into the IBC for supporting the subassembly and establishing a gas seal to direct coolant flow through the inside of the subassembly. Three different insert tubes are used to accommodate the different types of subassemblies. Insert tube No. 1 accepts core, inner-blanket, and outer-blanket subassemblies, while insert tubes Nos. 2 and 3 accommodate control and safety subassemblies, respectively. All three insert tubes are used interchangeably in IBC-I, but IBC-II is fitted with an insert tube No. 1 only. The subassemblies are sealed in the insert tubes in a manner similar to that used in sealing subassemblies in the reactor grid. The subassembly ball seal (located at the bottom of the hex section) mates with a tapered sealing area of the insert tube. This arrangement provides a tight seal and results in negligible leakage of coolant gas through the seal. Drain holes are drilled above the insert-tube seal to prevent holdup of water in the insert tube. The insert tubes used for the core and safety subassemblies have one 3/16-in.-dia drain hole, and the insert tube for control subassemblies has two such drain holes. Calculations by the designers⁶ indicate that one hole will permit about 10% of the coolant gas to bypass the interior of a subassembly, while the two holes will allow about 25% of the coolant to bypass the interior of a control subassembly. These calculations were made for standard core, safety, and control

subassemblies. Subassemblies with low-flow orificing that are handled in insert tube No. 1 may have leakage of greater than 10%. However, the percentage of leakage will not be as large as occurs in the FUM (see Fig. 6).

The IBC coolant gas is driven by a rotary lobe-type positive-displacement blower. The blower maintains a fairly substantial flow even with a large increase in ΔP . The IBC is therefore able to handle subassemblies with low-flow orificing, since the greater pressure drop does not result in much decrease in coolant flow.

Instrumentation for the IBC includes gauges to measure inlet and outlet pressures on the rotary blower; a voltmeter across the motor to monitor the motor characteristics, and thermocouples to determine IBC cooling-loop temperatures. As in the FUM, there is no direct way to measure the temperature of a subassembly being cooled by the IBC cooling system.

V. TRANSFER OF IRRADIATED SUBASSEMBLIES

This section describes the gas cooling provided for an irradiated subassembly as it is removed from the primary bulk sodium and transferred to the FEF via the FUM and IBC. An uninterrupted flow of coolant gas is maintained through the subassembly during all phases of the operation.

When a subassembly is removed from the storage basket, it is placed on the transfer arm and positioned under the fuel-transfer port (FTP). The FUM gripper is lowered through the FTP into the bulk sodium and latched onto the subassembly. The subassembly is then raised into the primary-cover-gas region and stopped in the FTP at the "blowing" elevation. Hot argon is blown through the FUM gripper and subassembly for 15 min to remove most of the adherent sodium. Once the FUM gripper reaches the "blowing" elevation, argon at 410°F is directed through the subassembly for 7 min. The argon is cooling the subassembly, which is initially at 700°F , the temperature of the primary bulk sodium. After 7 min, the flow switches and 610°F argon enters the subassembly for the remaining 8 min of the "blowing" cycle. The subassembly will normally reach its highest temperature during the last phase of the "blowing" cycle.

The 410°F argon flow is again directed into the subassembly at the end of the "blowing" cycle. The next operations involve raising the subassembly into the FUM and closing the FUM shielding valve. The FUM is then moved into position over the IBC. The subassembly is lowered into the

IBC and released from the FUM gripper. Preheated argon at 410°F cools the subassembly from the end of the "blowing" cycle until the subassembly is released in the IBC. The hot argon maintains the residual sodium molten in the FUM gripper. This is necessary to prevent binding in the FUM gripper jaws when the subassembly is released in the IBC.

After the subassembly is released and the FUM gripper is raised, the IBC is isolated from the FUM and the argon flow is automatically changed to pass through the IBC only. The argon inlet temperature to the IBC is 200°F , which further cools the subassembly. The IBC blower is turned on and operates in parallel with the FUM-ACS. Valves on the IBC are then manually rotated to isolate the IBC from the FUM-ACS, and the subassembly cooling is maintained entirely by the IBC blower. The IBC is placed in the equipment airlock and transferred to a sodium-cleanup station in the FEF. At the cleanup station, the small amount of sodium still adhering to the subassembly is removed by circulation of water through the IBC. During the washing cycle, the IBC blower is shut off and isolated from the IBC. The cooling medium is then changed to air for drying the subassembly and IBC. When the drying is complete, the external air supply is isolated and the IBC blower is restarted. The IBC blower continues to provide cooling until the subassembly is transferred into the FEF air cell for disassembly.

VI. HEAT-TRANSFER ANALYSIS

The stages for which it is most important to determine subassembly temperatures during transfer are the "blowing" cycle in the FTP, the recirculating-argon cooling in the IBC, and the air-dry cycle in the IBC. The highest temperatures exist during the "blowing" cycle in the FTP, and these temperatures determine the minimum holding period before transfer of the subassembly from the primary bulk sodium.

The calculation of temperatures by the DECAY program depends on the assumptions and measurements described in this section.

A. Heat-transfer Coefficient

For temperature calculations at all positions, the heat-transfer coefficient is based on laminar flow. The Reynolds numbers encountered range from the laminar to the transition region, but the assumption of laminar flow will give a conservative answer in all cases. Nusselt numbers are calculated according to a derivation by Dryer and Barry.⁷ The derivation is appropriate for fully developed longitudinal laminar flow between cylinders with uniform heat flux axially and circumferentially. This gives a more conservative result than the boundary conditions of uniform heat flux axially and uniform temperature circumferentially,⁸ and is a good approximation for most cases encountered.

The calculated Nusselt number for each subassembly type is catalogued within the computer program. With the subassembly type and heat generation known, the temperature-dependent properties of the argon coolant gas can be used to calculate the local heat-transfer coefficient.

The effect of the spacer wire around the fuel pin is to mix the coolant gas, acting to enhance the overall heat-transfer coefficient. Conduction in the cladding will limit the temperatures beneath the wire, where convective cooling is negligible. It was found that heat-transfer coefficients obtained from heat transfer-tests⁶ conducted for EBR-II Mark-I driver subassemblies showed agreement within 10% of those calculated by this method.

B. Maximum Fuel Temperature

Axial conduction of heat was shown to be negligible and was not considered. Any axial conduction would tend to reduce the maximum temperatures encountered. Also, the temperature drop from the fuel-pin center to the cladding surface is negligible compared to the temperature drop from the cladding surface to the gas stream. The temperature drop from the pin center to the cladding surface expressed as a percentage of the temperature drop from the cladding to the coolant gas ranges from 0.38% for Mark-IA subassemblies to 2.1% for an A-19 subassembly fueled with UO_2 . The cladding surface temperature therefore represents closely the maximum fuel temperature.

C. Argon Flowrates in FTP and FUM

The argon flowrates during the "blowing" cycle in the FTP can be determined from data taken as the subassembly is being transferred into the primary tank. There is significant leakage past the subassembly when in this position because of the clearance between the FUM gripper and the guide tube of the FTP. Figure 6 shows the curve of leakage flow past the subassembly as a function of pressure drop across it. These data were obtained by taking flow-vs-pressure-drop measurements with a blanked-off subassembly (no flow through the subassembly). Figure 7 shows the pressure drop in the argon line from the point of pressure measurement to the top of the subassembly when in the "blowing" position in the FTP. As a subassembly is transferred into the primary tank, measurements are made of "pressure to fuel" and total flowrate. To determine the pressure drop across the subassembly, enter Fig. 7 with the total flowrate and determine the line-pressure drop. By subtracting the line-pressure drop from the "pressure-to-fuel" measurement, the pressure drop across the subassembly is obtained, and the leakage flow past the subassembly can then be determined from Fig. 6.

Water- and air-flow tests are conducted in an independent test loop for experimental subassemblies to verify their calculated flow characteristics. The air-flow data can be used to predict argon flow for the subassembly when in the FTP and FUM, providing a second source of information for this important parameter.

When a subassembly is being removed from the primary tank, the flow-rate through the subassembly is less than when the subassembly was transferred in, because of heating effects on gas flow, with the major effect associated with acceleration of the gas. The pressure drop associated with the effect of heating a gas in a channel of constant cross section can be written as

$$\Delta P_{\text{HEAT}} = \frac{\rho_1 U_1 R Q}{g_c \Delta P_2 C_p}$$

Fig. 6. Leakage Flow Past Subassembly When in FTP

Fig. 7. Line-pressure Drop from Pressure Gauge to Top of Subassembly in "Blowing" Position in FTP

where

ρ_1	=	density of gas at inlet
U_1	=	velocity of gas at inlet
R	=	gas constant
Q	=	heat added to gas
A	=	flow area of channel
P_2	=	pressure of outlet
C_p	=	specific heat of gas
g_c	=	gravitational constant.

This expression represents only the effect of heating on gas acceleration. Thus, for gas flowing through a channel from pressure P_1 to P_2 and being heated, the fraction $\Delta P_{HEAT}/(P_1 - P_2)$ of the total pressure drop is required for acceleration of the gas by addition of heat. The effect is to reduce the flow through a subassembly for a given pressure drop across it. Figure 8 shows the behavior of flow at a pressure drop of 3.0 psi for a Mark-IA subassembly.

As can be seen, the effect of increasing the heat generation is to reduce the flow through the subassembly. Fortunately, this effect is significant only for heat-generation rates greatly in excess of what is encountered in normal operation of the FUM. For future design of fuel-transfer systems, it is recommended that positive-displacement blowers be used and that leakage flow be eliminated to allow large pressure drops when needed across subassemblies with significant heat generation.

The measured flow through a cold subassembly is used as input to the program that calculates the effect of heat generation on flow. This measured flow is further reduced by 10% to allow for possible reduction in flow because of changing conditions in the FUM, to obtain a conservative estimate in all cases. The calculated flow through the subassembly may be only a small fraction of the total flow through the FUM.

D. Argon Flowrates in IBC

The flowrates in the IBC are more easily obtained, since leakage past the subassembly is only about 10%. The internal cooling is provided by a positive-displacement lobe-type blower, resulting in a nearly constant

Fig. 8. Effect of Subassembly Heat Generation on Coolant Flow Through a Mark-IA Subassembly with a Pressure Differential of 3.0 psi

flow of 30 scfm. This drops to about 20 scfm after 4 hr of operation with the batteries. During the drying cycle, plant argon or air is forced through the subassembly at 30 scfm. The instrumentation external to the IBC in the drying cycle is sufficient to provide flowrate-vs-pressure-drop curves.

E. Radial Distribution of Flowrates

Another factor in flowrate determination is the radial distribution of flowrates within the subassembly. Heat-transfer experiments conducted on Mark-I subassemblies showed a significant radial distribution of temperatures across the subassembly.⁹ The radial maximum-to-average gas-temperature rise was found in these experiments to be 1.2. The radial flow distribution can be calculated for various subassemblies based on relative areas available for flow as a function of pin location. This effect was incorporated into the heat-transfer calculation, resulting in a calculation based on the lowest coolant flowrate within the subassembly during the "blowing" cycle. The inlet gas temperature in the FTI was taken as 650°F, 40°F higher than the nominal temperature.

F. Heat-generation Rates

Heat-generation rates were based on decay-heat correlations compiled by Burris and Dillon.¹⁰ These give fission-product energy dissipation as a function of irradiation history and cooling time for ²³⁵U and ²³⁹Pu. In determining the decay heat absorbed in a subassembly, it was assumed that all of the beta energy was absorbed. Calculations based on data presented in Ref. 11 resulted in a value of 58.6% of the gamma energy being absorbed by a Mark-IA subassembly. Subsequent comparison with values given in Ref. 9 supported this result. A conservative value of 70% for gamma-energy absorption was used for all subassemblies.

The radial flux distribution across a subassembly results in a non-uniform fission rate. Cladding surface temperatures for individual subassemblies are calculated on the basis of the decay-heat generation of the pin suffering the maximum fission rate and, as mentioned earlier, the lowest coolant flowrate. This ensures a conservative estimate of surface temperatures in all cases.

The axial fission-rate distribution used in the heat-generation calculation is based on an average distribution obtained from flux-wire measurements. This distribution of decay-heat generation in the fuel pins is used to obtain axial temperature profiles for each subassembly.

G. Irradiation History

The irradiation history is obtained from the burnup code currently in use at EBR-II. This information includes fission rates, flux distribution, fuel composition, and total irradiation time in megawatt-days for each subassembly. By inclusion of a catalogue of the duration and termination date of each reactor run, the complete irradiation history of each subassembly can be obtained. For the purposes of decay-heat calculation, it is assumed that each reactor run was made continuously at the rated power level to attain the specified megawatt-days and that the run was ended at the termination date specified. This ensures that the calculated decay-heat generation will always be greater than or equal to the actual heat generation. Comparison of these results with those obtained from tables developed at the Fuels and Examination Facility show favorable agreement.

VII. VERIFICATION OF RESULTS

For verification of the results calculated by the DECAY program, several sources of information are available. Heat-transfer tests have been conducted in the IBC's using electrically heated pins to simulate a Mark-I subassembly.⁶ Comparison of calculated temperatures with those obtained from experiment show good agreement, with calculated cladding surface temperatures about 10% higher than those measured.

Temperature measurements were made of several irradiated subassemblies while in the IBC's. For IBC-I, the temperatures recorded were the subassembly-inlet and -outlet coolant temperatures. For IBC-II, the temperatures available were the subassembly-inlet temperature and the IBC-heat-exchanger outlet temperature. Measurements were made not only for cooling by recirculating argon but for the air-dry and argon-purge cycles. The measurements allowed a determination of the effect of the IBC heat exchanger and blower on the subassembly-inlet coolant temperatures; they also gave the total heat generated by the subassembly as a check against

calculated heat-generation rates. The IBC's thus served as effective calorimeters.

These measurements showed that the subassembly-inlet temperature is nearly independent of subassembly power. This condition is due to the efficient heat exchanger in the IBC and the major contribution of the blower (1000 Btu/hr), which masks the effect of subassembly heat generation. As a result of these measurements, the recirculating-argon inlet temperature was taken to be a constant 120°F.

During the purge and drying cycles, the flow direction is reversed and the blower turned off. The gas travels first through the heat exchanger, then through the subassembly, and finally to the exhaust. The temperature of the gas as it enters the subassembly reflects the heat added as it travels through the heat exchanger. For the drying cycle, this subassembly-inlet temperature was taken to be 90°F for all cases, as a result of measurements taken on the IBC.

Comparison of calculated gas-outlet temperatures with measured values showed good agreement, as can be seen in Table II. This indicates the accuracy of the calculations of decay-heat generation for these subassemblies.

VIII. DEVELOPED NOMOGRAMS AND TABLES

A. Fueled Subassemblies

The nomograms given in Appendix A were developed for determining the cooling-time requirements of experimental subassemblies before their transfer from the primary tank. These results are based on DECAY calculations of the maximum cladding-surface temperatures experienced during the "blowing" cycle in the FTP. The nomograms were drawn with the assumptions that the last continuous run length was 1800 MWd and that the subassemblies had had a previous irradiation of 30,000 MWd at a reactor power of 62.5 MW. The previous run history was based on an EBR-II plant factor of 80%. For a given subassembly type with a known coolant flowrate, the nomograms can be used to determine the required holding time.

Table II. Comparison of Calculated and Measured Coolant-outlet Temperatures in IBC

<u>Subassembly No.</u>	<u>Date Transferred</u>	<u>Days Cooled</u>	<u>Cycle</u>	<u>Temperature of Exit Gas, °F</u>	
				<u>Measured</u>	<u>Calculated</u>
X036	9/8/70	16	Recirc. argon	128	135
C2229S	9/9/70	17	Air dry	125	135
C2192	9/9/70	17	Recirc. argon	178	180
C2207	9/10/70	18	Recirc. argon	170	170
			Air dry	124	130

Table III shows the holding time required to ensure a maximum cladding temperature of less than 900°F , assuming the irradiation history given above and a minimum flowrate of 20 scfm for each of the fueled subassemblies.

B. Structural Subassemblies

Structural subassemblies commonly contain materials with widely varying activation-product half-lives and decay-heat generation. In addition, most are highly orificed, and many have insulating gaps to maintain high temperatures in the core. Most materials, however, produce little decay heat and may be identified as causing no cooling problems during transfer. It should be emphasized that with the widely varying activation-product half-lives, an arbitrary 15-day cooling period is not applicable to most. Table IV lists the most commonly used materials with values of saturation decay heat, rate of temperature rise with no cooling, and half-life of the principal activation product. The last two nomograms in Appendix A give the maximum surface temperatures attained in commonly used types of structural subassemblies.

The saturation activity for each material was calculated at core center for a reactor power of 62.5 MW (total flux = 3.2×10^{15} n/sec-cm²), assuming continuous irradiation. Values of heat generation were obtained with the assumption that all of the disintegration energy from decay was degraded to thermal energy in the material. No credit was taken for only partial absorption of gamma-ray energy. The specific heats used in determining the maximum rates of temperature rise were those for the metals as indicated, with no additional alloying agents included.¹²

With the exception of tantalum and tungsten, values of activation cross sections were those measured in the EBR-II core. For tantalum and tungsten, the energy-dependent capture cross sections taken from BNL-325 were averaged over the EBR-II neutron spectrum at the reactor center.

As can be seen from Table IV, tantalum represents a fairly serious heating problem because of significant heat generation coupled with low specific heat. In the event of loss of cooling, the temperature rise is very fast. On the other hand, materials such as iron and titanium have such a low rate of temperature rise with no cooling that immediate

TABLE III

^aCooling Time Required to Ensure a Maximum
Cladding-surface Temperature of Less Than 900°F

Max. Fuel-pin Power Generation While In Core, kW	Subassembly Type			
	91 Pin	61 Pin	37 Pin	19 Pin
	Delay Before Transfer, days			
2	2	1	1	1
4	5	3	1	1
6	8	5	3	1
8	15	7	4	2
10	20	11	6	3
12		15	8	4
14		19	11	5
16			14	6
18			17	7
20			19	9
22				11
24				12
26				14
28				15
^b Decay Heat Generated per Fuel Pin, W				
	8.6	12.7	17.6	27.8
^b Max. Rate of Temperature Rise on Loss of Cooling, °F/min				
60.5	50 (L61)	44.3 (B37)	41.3 (B19, A19)	
	52.8 (B61)	58.8 (F37, H37, J37)	92.8 (E19)	
	87.8 (E61)	69.4 (E37)		

^aFor previous irradiation less than 30,000 MWd at a reactor power of 62.5 MW and a plant factor of 80%. Minimum argon flowrate through cold subassembly greater than 20 scfm when in FUM.

^bValues at end of required cooling time; subassembly designations in parentheses.

TABLE IV
Decay-heat Characteristics of Materials Irradiated
to Saturation Activity at the Core Center

<u>Material</u>	<u>Decay Heat, W/g</u>	<u>Rate of Temp. Rise, No Cooling, °F/min</u>	<u>Half-lives of Principal Acti- vation Products</u>
Ta	0.750	537.0	115 days
W	0.106	80.0	1.0 day, 75 days
Ni	0.211	38.5	71.5 days
Au	0.043	34.8	2.7 days
Cu	0.100	20.6	0.54 day
SS 316	0.0368	8.69	71.5 days
SS 304	0.0252	5.95	71.5 days
Fe	0.00823	1.35	313 days
Ti	0.005	1.15	83.0 days, 3.3 days, 1.82 days
Al	0.0076	0.709	63 days
V	--	--	3.75 min.
Nb	--	--	2.0×10^4 years
B	--	--	20.4 msec

transfer can be made without regard for the amount of forced cooling available in the FUM.

IX. SPECIAL CONSIDERATIONS

A. Loss of Coolant Flow

In the event of loss of coolant flow in either the FUM or IBC, cooling will be by natural convection only. Figure 9 shows the maximum temperature of the hottest pin in the bundle when the subassembly is cooled by natural convection in air or argon. The results for the Mark-I subassembly in air are from Ref. 9. The results for other subassemblies are derived from the measurement of the Mark-I subassembly. The temperature rise occurring with natural convective cooling in argon is approximately twice that occurring in air.

These curves should be considered as giving only approximate temperatures, because of the wide variety of orificing, of configuration of experimental subassemblies, and of condition of the FUM or IBC at the time of flow failure. It does indicate, however, that the temperature reached will be intolerably high for the values of decay heat generation normally encountered, resulting in most cases in fuel melting. It is therefore important to consider the rate of temperature rise on loss of cooling, as listed in Table III, to ensure that adequate time exists for taking emergency steps to protect the subassembly from overheating. If cooling is lost in the FUM, the subassembly must be moved into either the primary bulk sodium or the IBC for safe storage. Loss of coolant gas within the IBC requires that the subassembly be moved into the FUM, or else the IBC flooded with mercury, to prevent fuel melting.

B. Transient Behavior

The calculations presented have been for equilibrium conditions at each location of interest. The transient behavior remains to be considered. During the "blowing" cycle, 410°F argon is blown over the subassembly for 7 min, followed by 610°F argon for 8 min. Because the entire subassembly is at 700°F initially, the subassembly temperature will undergo complicated

Fig. 9. Maximum Cladding-surface Temperature with Natural-convection Cooling, Subassembly Intact

transient behavior that is influenced by the amount of decay-heat generation. For most subassemblies, the limited time in the blowing cycle will prevent cladding temperatures from rising to the calculated equilibrium temperatures upon which the transfer schedule is based. This is particularly true for subassemblies having low heat-generation rates and low flow, adding another margin of safety in establishing the minimum holding time.

The subassembly when transferred to the IBC is at the temperature resulting from cooling by 410° argon while in the FUM. The subassembly will then be cooled in the IBC from this initial temperature while being transported. Measurements taken on the IBC indicate that the temperature has essentially dropped to an equilibrium value by the time it has been transferred from the reactor building to the FEF.

C. Temperature Profile

When a subassembly is in the FUM, argon enters through the top and exits at the bottom of the subassembly, reversing the temperature profile encountered in the core. When the subassembly is being cooled with 610°F argon in the FTP, the temperature near the bottom of the fuel pins is normally much greater than when in the core. Temperature-sensitive devices or experiments may be adversely affected unless this fact is considered in designing the experiment.

The maximum equilibrium cladding temperatures for a Type-H37 subassembly through the transfer cycle are shown in Fig. 10. This figure shows the normal transfer route, with estimates of the time taken for each process. By far the highest temperatures are encountered in the "blowing" cycle, when 610°F argon is blown through the subassembly.

X. SUMMARY

The primary objective of this study has been to develop a means of evaluating the temperature characteristics of each subassembly before it is scheduled to be transferred. The purposes of this evaluation are two-fold: first, to allow greater flexibility in scheduling transfers; and second, to provide a subassembly's temperature history when of interest to the experimenter.

Fig. 10. Typical Transfer Schedule and Associated Temperatures for an H37 Subassembly Producing 1.0 kW

The DECAY program for temperature calculations has been written so as to involve a minimum of effort in its use. The necessary input has been kept to a minimum, and as much information as possible has been catalogued within the program. Only two punched cards are required for each subassembly, and all of the information except subassembly type and argon flowrate is available from the burnup code used at EBR-II. Detailed temperature profiles can be derived for subassemblies with this program.

Appendix B shows the input format for the DECAY program. Also shown are computer-produced temperature-vs-cooling-time curves for a typical subassembly.

APPENDIX A

Nomograms for Determining Required Holding Times and Cladding Temperatures of Subassemblies During Transfer Through the FUM

This appendix includes nomograms that have been developed to allow conservative results to be obtained without a detailed calculation for a particular subassembly. In the development of the nomograms, a subassembly irradiation of 30,000 MWd at a reactor power of 62.5 MW was assumed with a maximum run length of 1800 MW and a plant factor of 80%. These results are quite conservative for most subassemblies, but if more exact calculations are desired, the computer program DECAY may easily be used.

The argon cooling flow to be used with the nomograms is the net flow through the subassembly. This can be obtained from total-flow-measurements (which are taken for each subassembly transferred into the primary tank) by using Figs. 6 and 7 of this report.

Nomogram for 7-pin Subassemblies

Delay before transfer required to ensure a maximum fuel-cladding-surface temperature less than 900°F . Subassembly irradiated for 30,000 MWd at a reactor power of 62.5 MW, with a maximum run length of 1800 MWd and a plant factor of 80%.

Nomogram for 19-pin Subassemblies of Types J19 and J19A

Delay before transfer required to ensure a maximum fuel-cladding-surface temperature less than 900°F. Subassembly irradiated for 30,000 MWd at a reactor power of 62.5 MW, with a maximum run length of 1800 MWd and a plant factor of 60%.

Nomogram for 19-pin Subassemblies
Other Than Types J19 and J19A

Delay before transfer required to ensure a maximum fuel-cladding-surface temperature less than 900°F. Subassembly irradiated for 30,000 MWd at a reactor power of 62.5 MW, with a maximum run length of 1800 MWd and a plant factor of 80%.

Nomogram for 37-pin Subassemblies

Delay before transfer required to ensure a maximum fuel-cladding-surface temperature less than 900°F. Subassembly irradiated for 30,000 MWd at a reactor power of 62.5 MW, with a maximum run length of 1800 MWd and a plant factor of 80%.

Nomogram for 61-pin Subassemblies

Delay before transfer required to ensure a maximum fuel-cladding-surface temperature less than 960°F . Subassembly irradiated for 30,000 Mwd at a reactor power of 62.5 MW, with a maximum run length of 1800 Mwd and a plant factor of 80%.

Nomogram for 91-pin Subassemblies

Delay before transfer required to ensure a maximum fuel-cladding-surface temperature less than 900°F. Subassembly irradiated for 30,000 MWd at a reactor power of 62.5 MW, with a maximum run length of 1800 MWd and a plant factor of 80%.

Nomogram for 7-pin Subassemblies

Nomogram for determining the maximum material-surface temperature as a function of decay heat and argon flow during transfer. Total sub-assembly heat generation is based on a radial maximum-to-average burnup of 1.2.

Nomogram for 19-pin Subassemblies
Other Than Types J19 and J19A

Nomogram for determining the maximum material-surface temperature as a function of decay heat and argon flow during transfer. Total subassembly heat generation is based on a radial maximum-to-average burnup of 1.2.

APPENDIX B

Use of the Computer Program DECAY

Subassembly information needed as input to the program DECAY, used to calculate decay-heat generation and resultant cladding-surface temperatures, is shown below:

Card 1

Format

14	6X	A4	6X	E10.5	E10.5	A4	6X1	I1

Variable

NMBR	-	FIND	-	FLOW	DPTOT	RUN	-	IHST

where:

- NMBR = Subassembly number
- FIND = Subassembly type
- FLOW = Total measured argon flow in FTP when subassembly was transferred into the primary tank
- DPTOT = Measured pressure to fuel when subassembly was transferred into the primary tank
- RUN = Last run number during which subassembly was irradiated
- IHST = Designation for type of irradiation history. When IHST=0, irradiation occurred without the subassembly being transferred out of the core between intermediate runs. When IHST=1, a listing of run numbers during which the subassembly was irradiated must be included on cards 3 and 4.

Card 2

Format 8F 10.0

Variable

DD POWER BV BX FT5 FT8 FT9 FFP

where:

- DD = Total irradiation time of subassembly in megawatt-days
- POWER = Total subassembly power production in core, in kilowatts
- BV = Average fuel burnup, %
- BX = Maximum fuel burnup, %

FT5   =   Loading in grams of ^{235}U at end of irradiation
FT8   =   Loading in grams of ^{238}U at end of irradiation
FT9   =   Loading in grams of ^{239}Pu at end of irradiation
FFP   =   Fraction of pins in subassembly that contain fuel.

Card 3 (needed only if IHST=1)

Format

I4

NRAD

where:

NRAD   =   Number of runs during which subassembly was irradiated.

Card 4 (needed only if IHST=1)

Format 16 A4

Variable

PRUN (J)

where:

PRUN (J)   =   Previous run number during which subassembly was
                 irradiated.

Following are examples of the graphic output of the program. Cladding-surface temperatures are plotted for five axial positions along the length of the fuel pin. The plots are made for the "blowing" cycle in the FTP, the recirculating-argon flow in the IBC, and the air-dry cycle in the IBC. This information is also printed as numerical computer output.

1-5 = EQUALLY SPACED AXIAL POSITIONS.
 1 = CLAD TEMP. AT FUEL BOTTOM
 5 = CLAD TEMP. AT FUEL TOP
 LINE 5 = TEMP. OF EXIT GAS

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