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GCFR RESIDUAL HEAT REMOVAL CAPABILITY

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GCFR RESIDUAL HEAT REMOVAL CAPABILITY*

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ABSTRACT

The residual heat removal (RHR) capability for providing lines of protection (LOPS) 1 and 2 of the gas-cooled fast breeder reactor (GCFR) demonstration plant is described. Included are design criteria and system descriptions for the RHR cooling systems and the portion of the plant protection system that is related to initiation of the RHR system operation. The design features of these systems provide inherently redundant and diverse means of core cooling for the GCFR. The hierarchy in the selection of the RHR systems and the application of the systems to key transient events are discussed. Methods of RHR system operation, dynamic responses of the GCFR plant, and margins of safety in RHR operations are also presented.

INTRODUCTION

The GCFR demonstration plant being developed by General Atomic Company (GA) employs helium pressurized to about 10.5 MPa as the reactor primary coolant. The reactor core, the steam generators and helium circulators in each of the three main cooling loops, and the auxiliary circulator and heat exchangers in each of the three core auxiliary cooling system (CACS) loops are contained within a massive prestressed concrete reactor vessel (PCRV) (Fig. 1). Reactor cooling during power operation is provided by the main cooling loops, and shutdown cooling is performed by any one of several RHR systems.

Earlier analyses of the GCFR core cooling capabilities are described in Ref. 1, which was submitted to the Nuclear Regulatory Commission (NRC) as a

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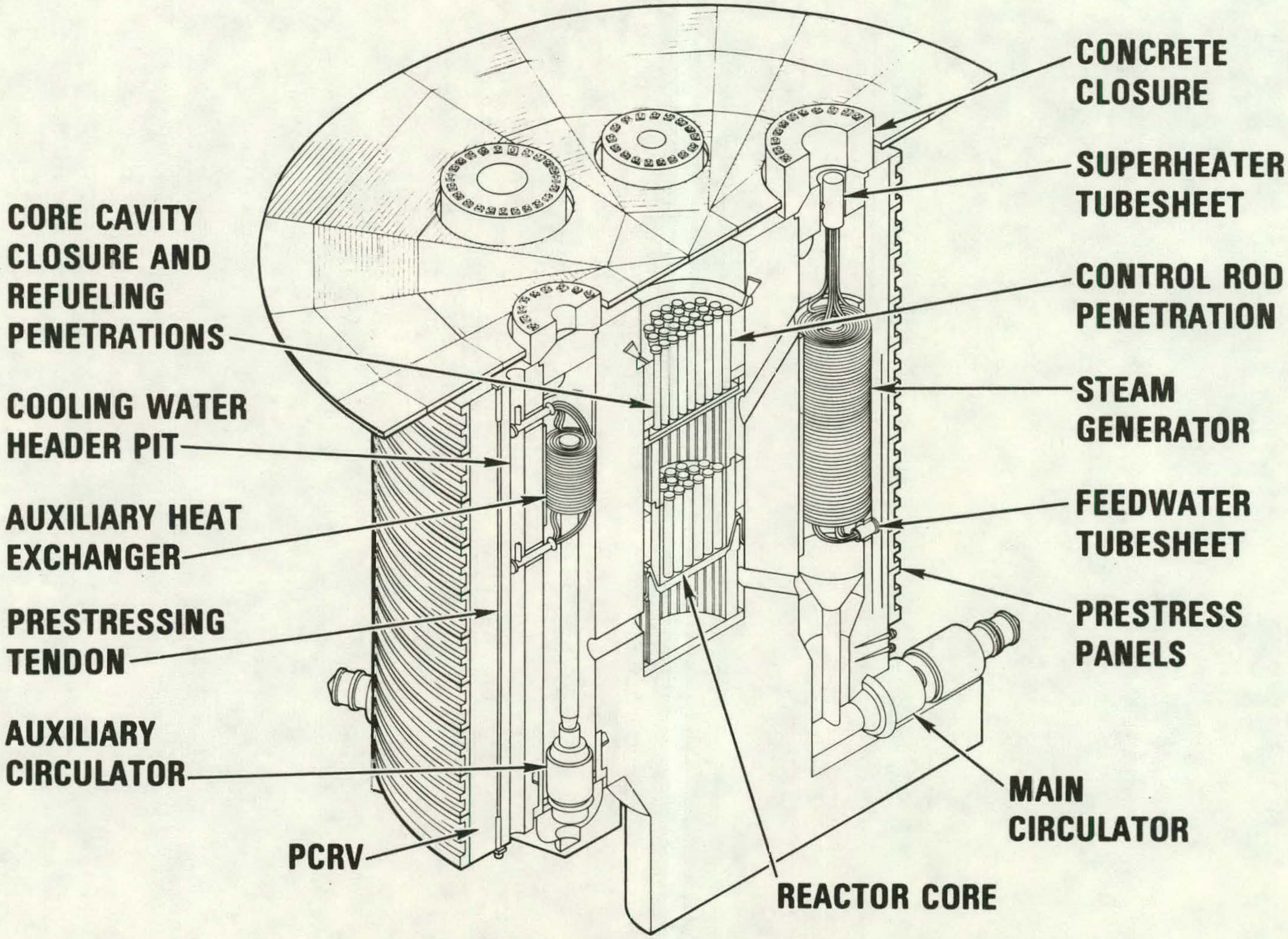

Fig. 1. GCFR nuclear steam supply system

basis for evaluation of the GCFR concept. After the initial phase of its review, the NRC issued a preapplication safety evaluation of the GCFR (Ref. 2).

The safety design bases for GCFR RHR are derived to attain the fundamental objective of providing adequate assurance that acceptable fuel cladding and pressure boundary temperatures are maintained for all credible events which lead to reactor shutdown. The key elements of the GCFR safety design bases are

1. Two redundant safety systems shall be provided for long-term RHR: the CACS and the shutdown cooling system (SCS).

2. The CACS and the SCS shall be Seismic Category I.

3. The SCS and the CACS shall be independent from each other.

4. The CACS shall be diverse from the SCS.

5. The reliability goal for the RHR function shall be such that the probability of loss of design core cooling geometry shall be beyond the design basis.

6. The nonsafety class main loop cooling system (MLCS) shall be available during nonseismic events if power is available.

In addition to the safety design basis for the LOP-1 and LOP-2 RHR systems, LOP-3 will provide additional protection for the public if both LOP-1 and LOP-2 fail. The requirement of two safety RHR systems enhances safety and reliability in excess of the Atomic Energy Commission (USAEC) General Design Criteria (GDC) 34 and 35 for light water reactors. These criteria require one safety system for RHR.

This paper describes these diverse and redundant RHR systems and their performance during key transient events. The RHR systems are designed in accordance with the GCFR safety program plan (Ref. 3) LOP philosophy:

LOP-1 = nonsafety-grade MLCS,
safety grade SCS.
LOP-2 = safety-grade CACS.
LOP-3 = CACS in natural circulation mode.

The forced cooling capability fully meets or exceeds all design requirements, and the natural circulation RHR capability provides an added margin of safety. The natural circulation capability is discussed in Ref. 4. Table 1 shows the design requirements for the various RHR systems.

LOP-1 MAIN LOOP COOLING SYSTEM

Design Basis Events

The MLCS must be capable of providing sufficient core cooling during the RHR phase of the following events with either an on-site (main turbine generator) or an off-site power source:

1. Pressurized cooldown, including single failure, following all events except those arising from failure of the MLCS.

2. Depressurization events up to and including the design basis depressurization accident (DBDA), provided that off-site power is available and there is no concurrent seismic event.

3. Refueling operation with two MLCS loops.

System Description

The MLCS consists of three independent and separate helium loops arranged around the reactor cavity. They are connected to the cavity by

TABLE 1
DESIGN REQUIREMENTS FOR RHR SYSTEMS

	LOP-1		LOP-2
	MLCS	SCS	CACS
Number of loops	3	3	3
Seismic class	Not applicable	I	I
Power source	On site	On site	On site
	Off site	Off site	Off site
		IE	IE
Safety grade/ seismic class	No/no	Yes/1	Yes/1
System capability			
Pressurized	1 out of 3	1 out of 3	2 out of 3
Depressurized	2 out of 3	--	2 out of 3
Refueling	2 out of 3	2 out of 3	2 out of 3
Natural convection	Not applicable	Secondary side only	2 out of 3

upper and lower cross ducts within the PCRV. They are also connected to independent water/steam loops. Each helium loop contains a steam generator, a main helium circulator, and a loop isolation valve. The components for each loop are contained in a separate cavity in the PCRV and are accessible through top and bottom penetrations of the PCRV. The closure for each steam generator cavity is a composite steel and reinforced concrete structure.

The steam generator is a once-through unit with a helically wound tube bundle with upflow boiling. Hot helium from the core flows via the cross ducts from the upper part of the reactor cavity into the steam generator modules. The helium then passes downward through the steam generator. Helium leaving the steam generator flows into the main circulator inlet plenum and is then compressed by the circulator to a pressure of 0.241 MPa above the coolant inlet pressure. Leaving the diffuser, the helium then passes through the main loop isolation valve and enters the reactor inlet plenum via the lower cross ducts.

The three water/steam loops and associated equipment outside the PCRV are part of the balance of plant (BOP). The normal power conversion water/steam loop receives superheated steam from the steam generators and transports it to a single main steam turbine. After expansion, the wet steam flows into the main condenser. Condensate pumps then deliver the water through the low-pressure feedwater heaters to a deaerator. From there, steam-turbine-driven main boiler feedwater pumps return the water through a high-pressure feedwater heater to the steam generator.

During start-up and shutdown, a conventional main turbine bypass steam system is used, which contains desuperheaters, flash tanks, and steam bypass lines to the main condenser. Steam is supplied to the bypass system from the steam generators or the auxiliary boiler. This system can provide steam for driving the boiler feedwater pump steam turbine to 25% capacity and heating steam lines and feedwater heaters. The flow diagram for the MLCS during normal plant operation and during shutdown cooling is shown in Fig. 2.

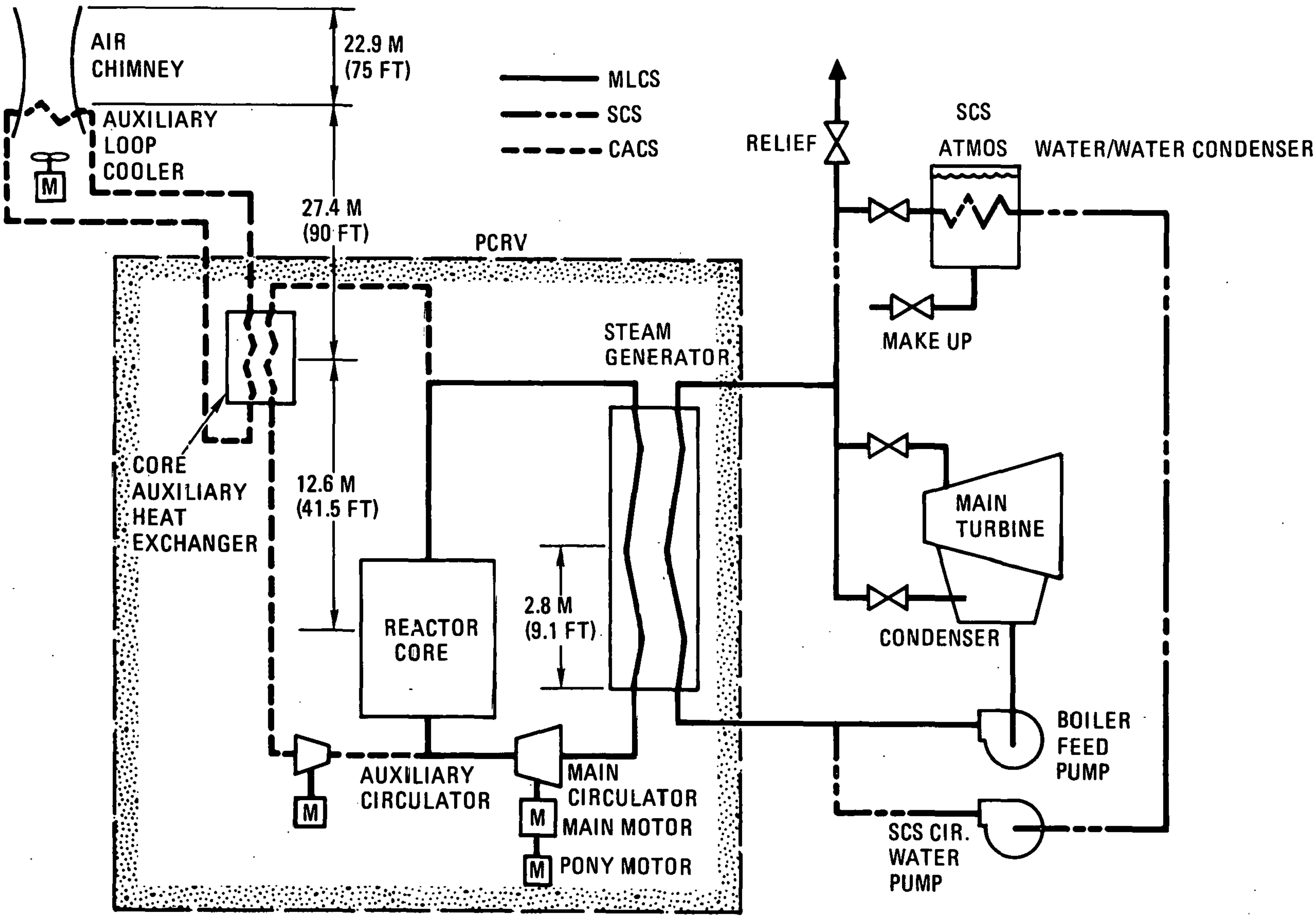

Fig. 2. GCFR heat removal systems

System Initiation

The MLCS RHR operation is initiated by reactor trip, which in turn is initiated by either the plant protection system (PPS) or operator action.

Operation and Control

The MLCS automatic transition sequence from the normal station power production configuration to the RHR configuration is initiated by a reactor trip. The transition occurs in two stages. In the first stage, the main steam generators supply the auxiliary steam headers through the desuperheaters and flash tanks. The second stage begins when the auxiliary boilers start to supply steam to these headers. By this time, the steam generators are flooded out and are being used as helium-to-water heat exchangers.

The sequencing steps can be thought of as open-loop control. Closed-loop (automatic feedback) control is also needed to maintain the desired process conditions and to provide acceptable process transient conditions. The three automatic control loops used during MLCS RHR operation are main steam pressure regulation, feedwater flow regulation, and helium flow regulation.

A bypass valve is used to regulate the steam generator exit pressure. This provides adequate boiling in the steam generators during flood-out and minimizes the transient conditions imposed on the steam generator.

Regulation of steam generator feedwater flow is accomplished by the flow control loop from the on-load plant control system. The purpose of this control loop is to provide an appropriate feedwater flow rate to the steam generator. Upon confirmation of reactor trip, the feedwater set point is ramped to 25% of full flow. The flow is held there unless the operator changes the set point.

Helium flow regulation uses the circulator speed control subsystem from the normal on-load control system. The purpose of this loop is to provide adequate helium flow for maintaining core internal temperatures within acceptable limits. The speed set point is an inverse function of PCRV static pressure, with the fully pressurized value set at 30% of the full reactor power speed level. The motor speed rapidly increases in response to a PCRV depressurization event to compensate for the decreasing density of the coolant.

Transient Performance

Pressurized Cooldown. This postulated event is a two-loop trip which results in a reactor trip due to high core power-to-flow ratio. This event will require RHR operation using one MLCS loop. The sequence of events for this transient is given in Table 2. Figure 3 shows that the fuel and blanket cladding hot spot temperatures are within acceptable limits and there is ample margin in the cooling capability of one MLCS loop during pressurized cooldown.

Depressurized Cooldown. A large leak of 194 cm^2, the same as the DBDA, is postulated to occur in the primary coolant boundary, resulting in rapid depressurization of the primary coolant. The reactor is tripped by the PPS owing to low primary coolant pressure, and RHR continues for two MLCS loops, assuming that a single failure causes the loss of one MLCS loop. The sequence of events for this accident is given in Table 3. Figure 4 shows the plant response to this event, and Fig. 5 indicates that the fuel and blanket cladding hot spot temperatures are well within the faulted limit.

TABLE 2
SEQUENCE OF EVENTS FOR TWO-LOOP TRIP PRESSURIZED COOLDOWN

Time(s)	Event
0	Simultaneous loss of two MLCS loops during 100% power operation
0	Reactor trip due to high power-to-flow ratio
45	Main circulator speed steady at 30%
>600	Steam generator flood-out complete

TABLE 3
SEQUENCE OF EVENTS FOR LARGE PRIMARY SYSTEM LEAK
WITHOUT LOSS OF OFF-SITE POWER

Time(s)	Event
0	194-cm^2 leak occurs
13	Reactor trip due to high power-to-flow ratio
30	Main circulator speed reaches minimum
180	Main circulator speed at maximum speed
650	Peak fuel cladding hot spot temperature reached
~1500	Peak blanket cladding hot spot temperature reached

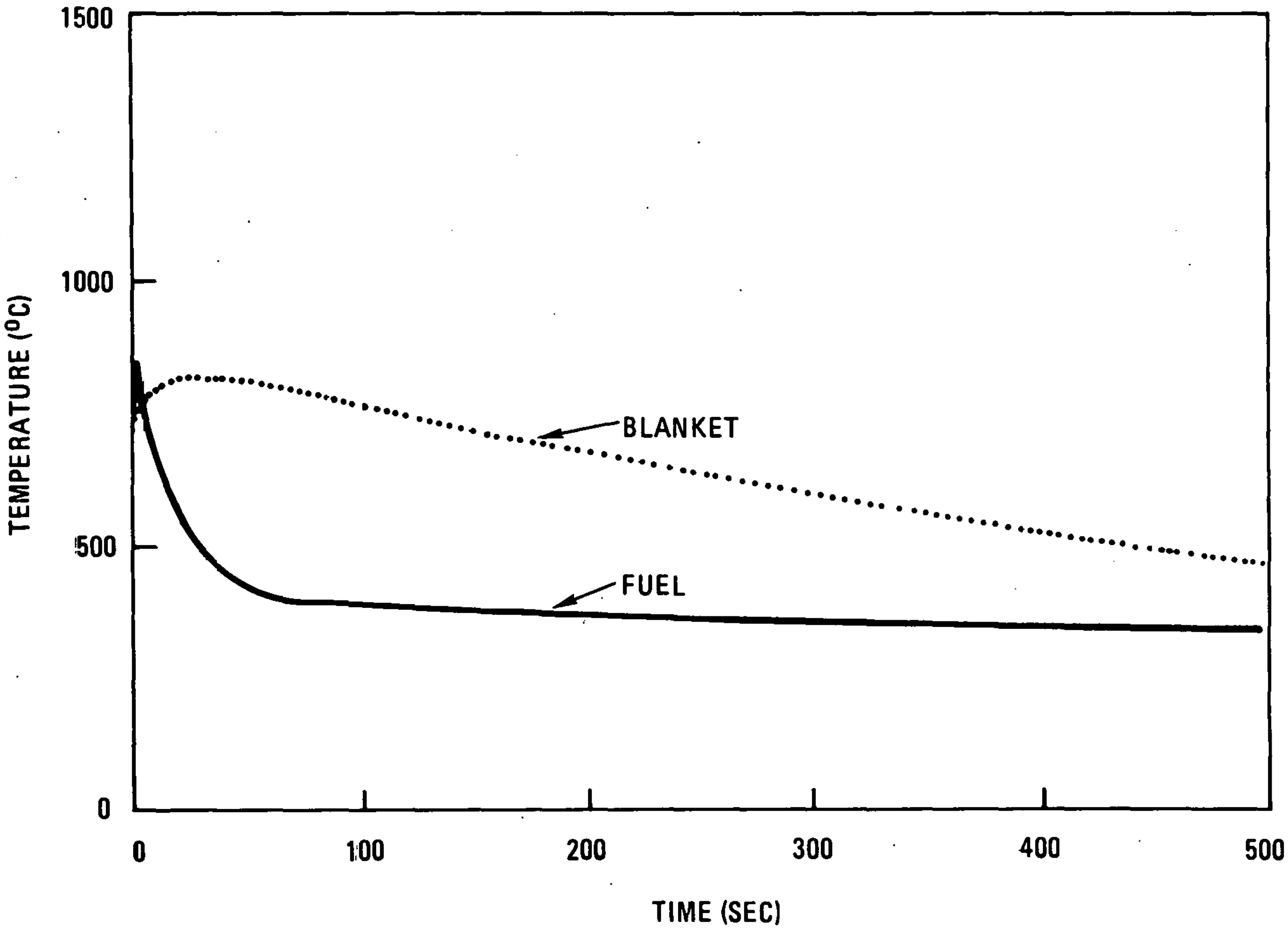

Fig. 3. Two-loop trip; RHR on 1 MLCS

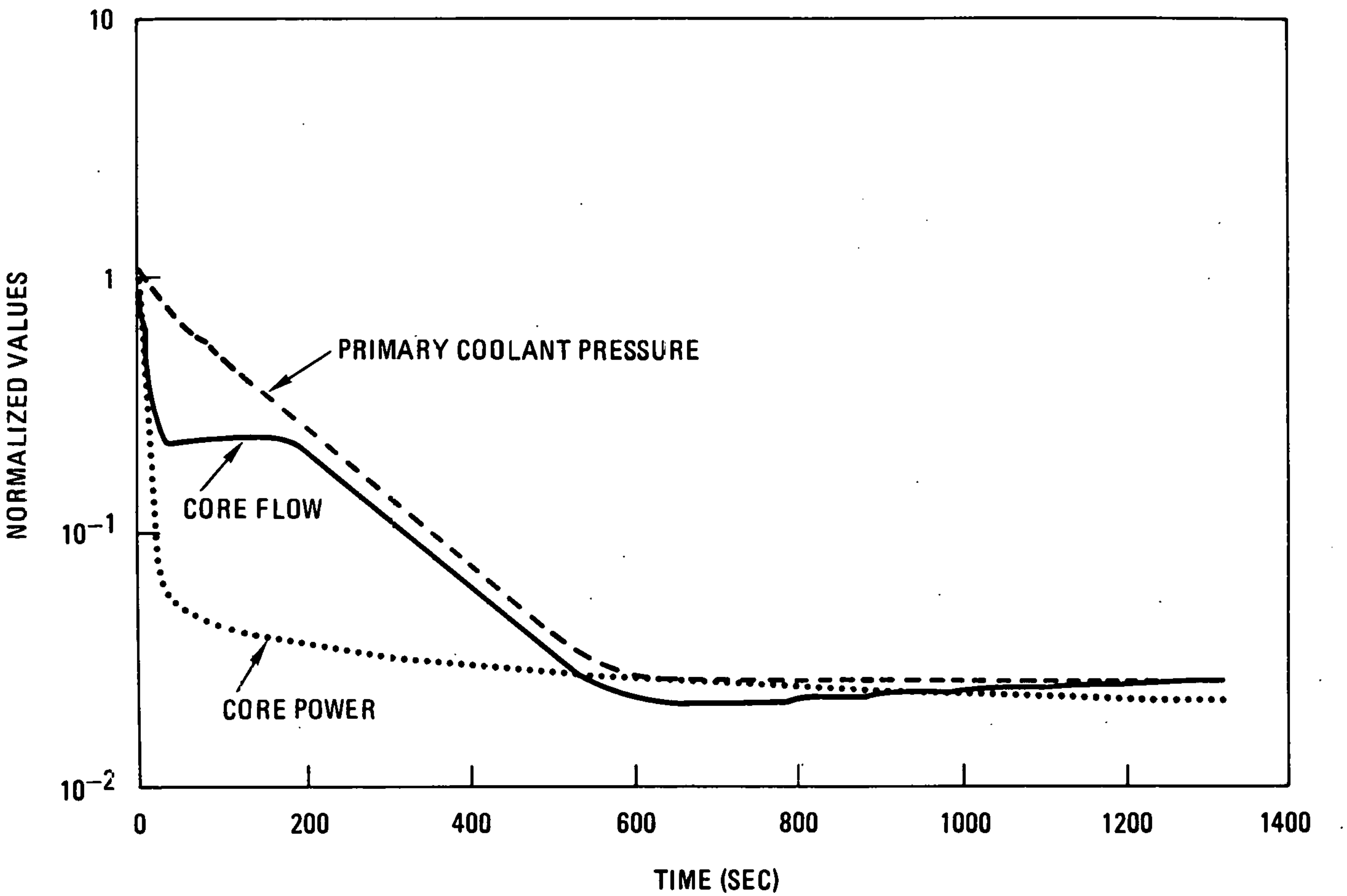

Fig. 4. Large primary coolant leak (194 cm^2); RHR on 2 MLCS, system response

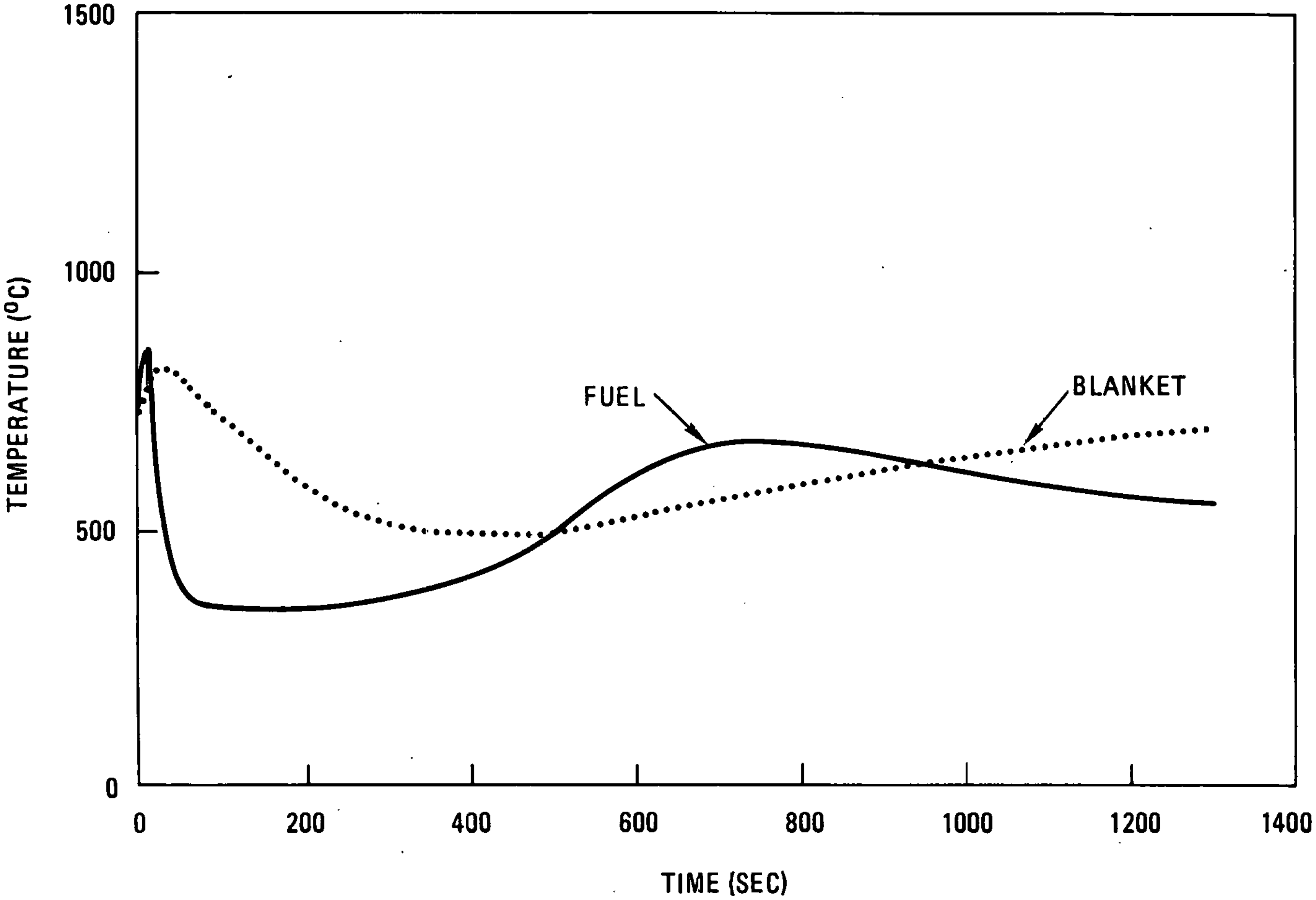

Fig. 5. Large primary coolant leak (194 cm^2); RHR on 2 MLCS, cladding response

LOP-1 SHUTDOWN COOLING SYSTEM

Design Basis Events

The SCS must be capable of providing safety-grade core cooling during the RHR phase of the following events:

1. All pressurized cooldown events except those due to common mode failure of the SCS.

2. Loss of on-site (main turbine generator) and off-site power.

3. Seismic events.

4. Refueling.

5. Loss of forced feedwater systems.

System Description

The SCS is an engineered safety system which provides a backup to the MLCS for cooling the shut-down reactor and removing decay heat produced by the core. The SCS is one of two independent and diverse safety class systems for providing RHR; the other is the CACS.

The SCS consists of three independent and separate loops. Each loop has two heat transfer circuits, the primary coolant circuit and secondary water circuit, with heat ultimately rejected to the atmosphere. The SCS shares the main circulator, its drive shaft, and the steam generator with the MLCS. The SCS includes a pony motor drive and a protected power source to drive the main circulator.

Helium circulated by the pony-motor-driven main helium circulators removes heat from the core and transfers it to the steam generators. The water is circulated in the closed loops between the steam generators and water-water condenser either by using the circulating pump or by natural convection. The heat is rejected to the atmosphere by boiling from the condenser, to which makeup water is added (Fig. 1).

System Initiation

The initiation system is designed to automatically initiate start-up of the SCS loops and shutdown of the MLCS any time the MLCS loops are not operating in a mode which adequately cools the reactor core. The conditions that cause the SCS loops to start up are as follows:

1. Low normal feedwater flow to all main loop steam generators.

2. Tripping of main circulator motors in all loops.

3. Speed of all three main circulators less than 28% with the reactor pressurized.

Operation and Control

The transition sequence from MLCS operation to SCS cooling is fully automatic and is initiated by the PPS or the plant operator. Following the initiation sequence, the SCS loop is closed around the steam generator and RHR conditions are established. For long-term heat removal, makeup water is required for the water-to-water condenser.

Helium flow regulation is accomplished in essentially the same manner as that for the MLCS RHR function. The pony motor is provided with a speed controller which synchronizes motor rotation to the coasting circulator shaft, phases in the circulator load, and regulates the motor speed about a set point. The control system also responds to a PCRV depressurization event in the same way as the MLCS controller. However, the SCS pony motor is limited because of a maximum of 50% speed and is therefore not capable of handling depressurization accident events. For refueling, the operator may manually select the SCS to provide cooling if no other system is available.

Transient Performance

For SCS performance evaluation, a two-loop trip combined with loss of off-site power (LOSP) is postulated, resulting in RHR operation for one SCS loop. Table 4 shows the sequence of events, and Fig. 6 indicates that the fuel and blanket cladding hot spot temperatures are well within the limits.

LOP-2 CORE AUXILIARY COOLING SYSTEM

Design Basis Events

The CACS must be capable of providing safety-grade core cooling for the following events:

1. All pressurized RHR events.
2. All depressurized RHR events up to and including DBDA.
3. Refueling.

System Description

The CACS is an engineered safeguard and is designed as a Class 1 system. It consists of three separate and independent cooling loops. A typical loop is shown in Fig. 2. Each loop contains an auxiliary heat exchanger, an auxiliary circulator, and a loop isolation valve located in a cavity in the PCRV and a pressurized cooling water loop primarily located external to the PCRV. The CACS is capable of cooling the core with the reactor coolant system under either pressurized or depressurized conditions.

TABLE 4
SEQUENCE OF EVENTS FOR TWO-LOOP TRIP WITH LOSS OF OFF-SITE POWER

Time(s)	Event
0	Loss of 2 MLCS loops
0	Reactor trip due to high power-to-flow ratio
18.5	Main circulator speed at 30%; LOSP
29	SCS resumes core cooling
>600	Steam generator flood-out

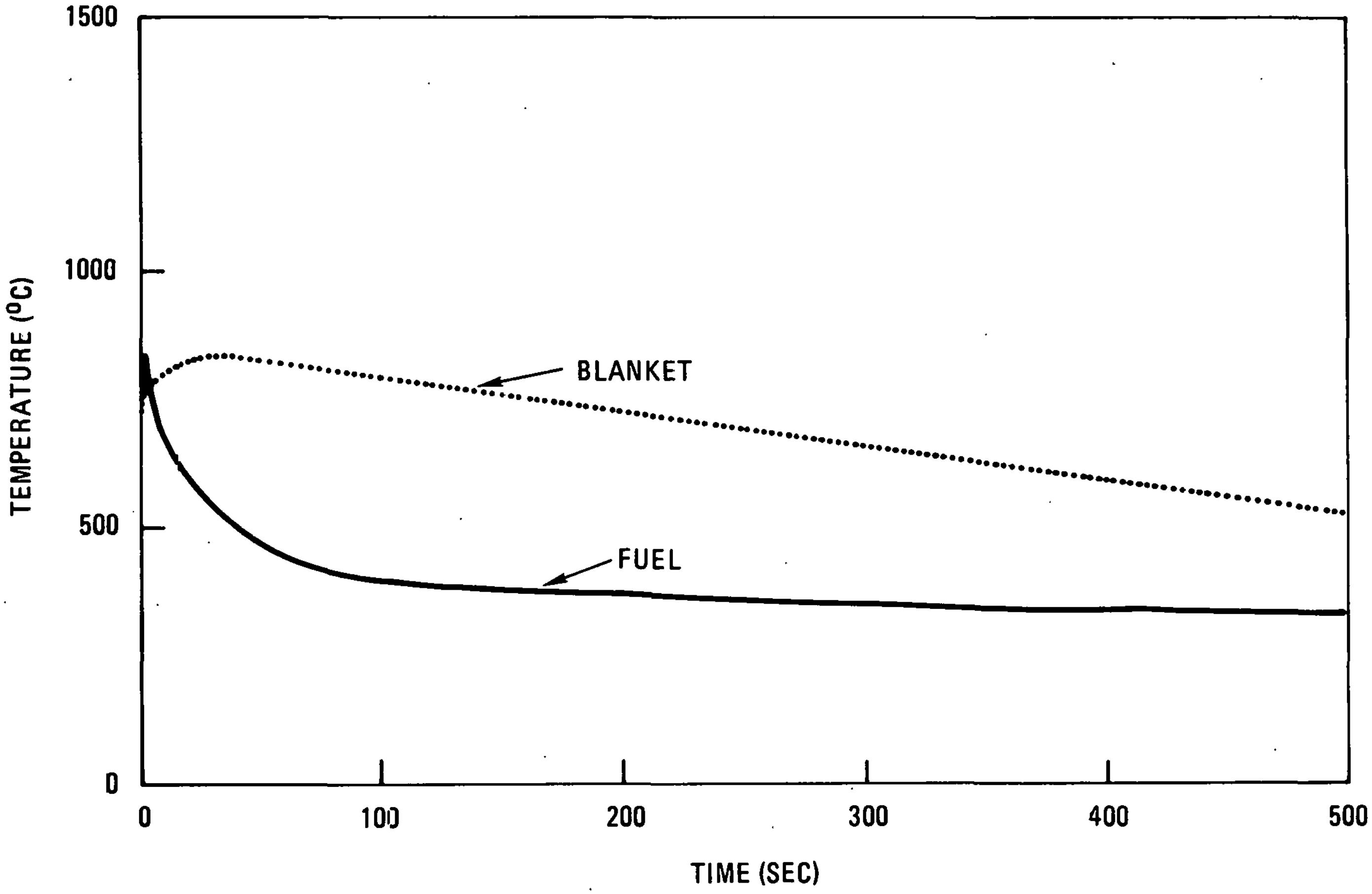

Fig. 6. Two-loop trip with loss of off-site power; RHR on 1 SCS

Each auxiliary circulator is electrically driven by a motor supplied by an independent power supply. The auxiliary loop isolation valve is mounted in the inlet duct of the auxiliary circulator and is actuated to open by gravity and/or the differential pressure produced by gas flow. When there is no forced circulation, the valve is designed to open by gravity to allow natural circulation flow in the forward direction. The auxiliary heat exchangers employ helically coiled tubes with a single-pass helium cross-counterflow passing over the tubes.

The core auxiliary cooling water system (CACWS) is a pressurized water loop which thermally couples the CACS with its ultimate heat sink via the auxiliary loop cooler (ALC). The CACWS is designed to operate with either forced or natural circulation.

The ALC is a finned, multipass, water/air heat exchanger. Three ALCs are located in the upper corners of the confinement building. Natural draft for each of these heat exchangers is provided by a 23-m chimney.

The system failure tolerance is obtained by virtue of its single-failure-proof design and independence from other plant RHR systems. The system can adequately cool the core under all design basis conditions with complete loss of one of three loops. In addition, within 2 h after reactor trip from full power, one loop is sufficient to provide adequate cooling. The CACS is overdesigned to the extent that no system adjustments are required to continue adequate cooling following a loop failure.

System Initiation

The initiation system is designed to automatically start up the CACS loops and shut down the SCS and MLCS loops any time the MLCS and SCS loops are not operating in a mode which adequately cools the reactor core, or certain other events occur that require CACS operation. The conditions that initiate CACS are as follows:

1. High primary coolant pressure (from moisture ingress).

2. Low primary coolant pressure and main helium circulator speed of less than 80% in two out of three loops.

3. Low feedwater flow to two out of three main steam generators (can be bypassed if core helium outlet temperature is below 427°C). (Flow must be delayed to allow SCS to act if it is not on line.)

4. Two out of three main circulator speeds less than 20%.

Operation and Control

The safety class CACS is completely independent from the other two RHR systems. When the system is not performing its core cooling function, it is maintained in a standby mode. Natural convection provides sufficient flow to maintain the water chemistry and the desired water temperature. The activation sequence is fully automatic and is initiated by the PPS or the plant operator.

Transition from MLCS or SCS core cooling to CACS cooling occurs without any specific control action when the pressure rise generated by the CACS circulators exceeds the decreasing pressure rise from the coasting-down main circulators. The auxiliary and main helium shutoff valves open and close, respectively, and the helium flow is channeled through the auxiliary loops by either the auxiliary circulators or natural circulation.

Helium flow control is required to compensate for changing helium conditions during PCRV depressurization. Helium flow control as a function of PCRV pressure is accomplished in essentially the same manner as that for the MLCS RHR function. A motor speed set point equivalent to 10% of CACS motor design speed is used when the PCRV is fully pressurized. The motor speed is rapidly increased in response to a depressurization event.

Transient Performance

Pressurized Cooldown. If there is a two-loop trip combined with LOSP and single failure of the remaining SCS loop, RHR is carried out by three CACS loops. To demonstrate additional margin, RHR with two CACS loops was analyzed. Table 5 shows the sequence of events for pressurized cooldown for two CACS loops, and Fig. 7 shows the transient response of the fuel and blanket cladding hot spot temperatures.

Design Basis Depressurization Accident. When a design basis leak area of 194 cm^2 is postulated, the primary coolant starts to flow into the containment building, which has a volume about 20 times that of the PCRV . A signal of high power-to-flow ratio, high containment pressure, or high containment radioactivity actuates reactor trip and containment isolation. The assumed safety-related event sequence includes simultaneous LOSP, which disables the MLCS. LOSP results in coastdown of main circulators and start-up of emergency diesel generators. The primary coolant pressure decreases exponentially, and the leak flow is choked during most of the blowdown period.

After LOSP, the PPS initially selects the SCS, one of the two safety RHR systems. The SCS pony motors are powered to prevent the main circulator speed from coasting down and to maintain a prescribed value for SCS operation. As pressure decays, the pony motor accelerates with a motor speed which is inversely proportional to pressure, providing a roughly constant mass flow rate, until the maximum pony motor speed is reached. When the pressure reaches less than the set point value (2.07 MPa), the cooling mode is automatically transferred to the CACS owing to insufficient circulator speed (<80%).

TABLE 5
SEQUENCE OF EVENTS FOR TWO-LOOP TRIP FOLLOWED BY LOSS OF SCS FUNCTION

Time(s)	Event
0	Loss of 2 MLCS loops
0	Reactor trip due to high power-to-flow ratio
18.5	Main circulator at 30% speed; failure of SCS to resume cooling
28	CACS operation initiated
30.5	Cooling resumed by CACS

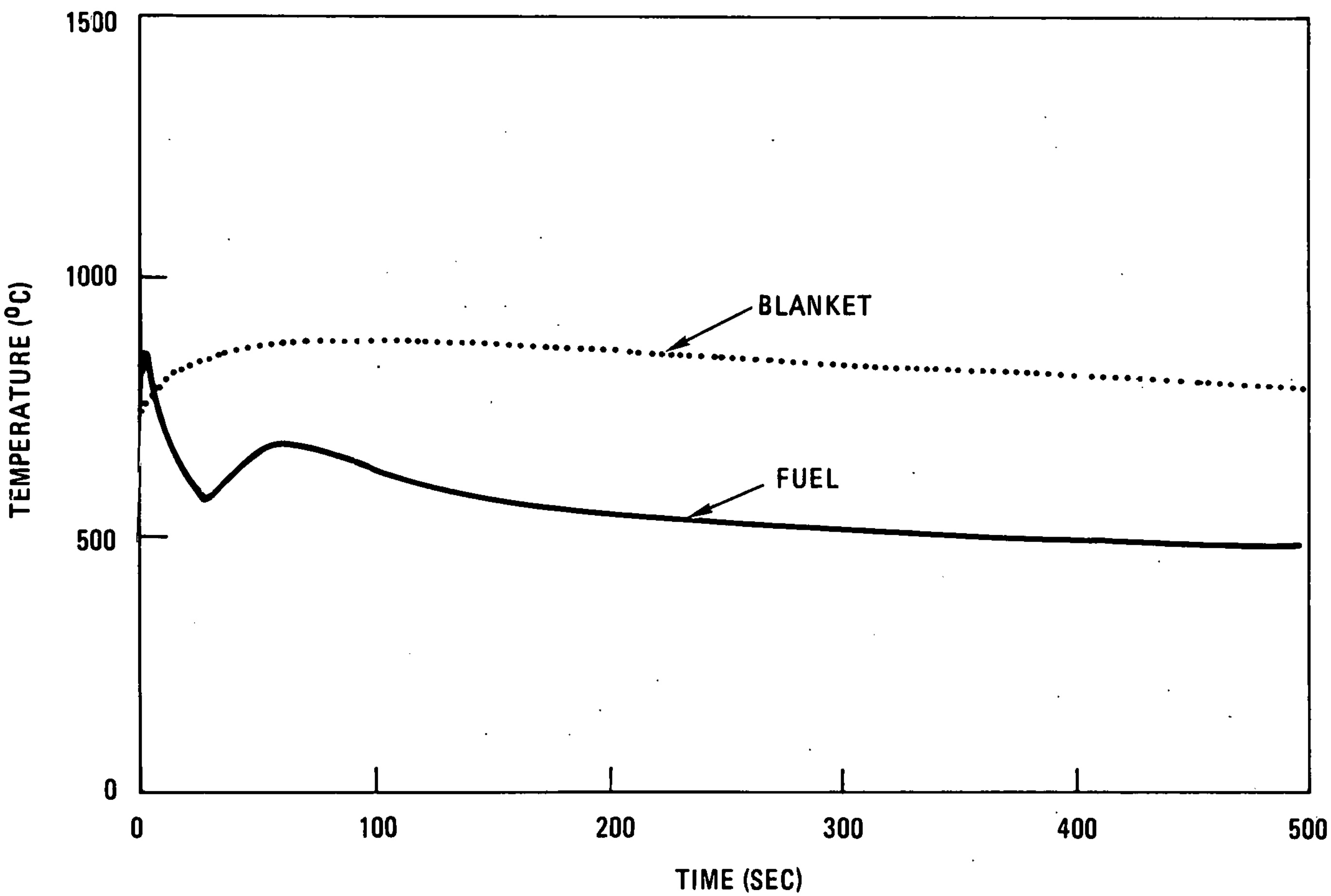

Fig. 7. Two-loop trip with loss of off-site power, SCS unavailable; RHR on 2 CACS

When the CACS is called upon, the full design torque is applied to the auxiliary circulators. The auxiliary circulator pressure head forces the auxiliary loop isolation valve open and the main loop isolation valve closed. Thus, the helium circulation loop switch is accomplished. In addition, the water pumps are started for the pressurized water loop between the CAHE and the ALC. Thus, the core decay heat, carried by helium to the CAHE and transported by water to the ALC, is ultimately dissipated into the atmosphere by a fan or natural draft of air through the ALC.

The typical core flow rate, core thermal power, and pressure transients following the DBDA are shown in Fig. 8. Figure 9 shows the main and auxiliary circulator speed variations before and after the loop transfer in the same transient. FIgure 10 shows the maximum hot spot temperatures for the fuel and blanket rods following this transient.

CONCLUSIONS

The studies described in this paper lead to the following conclusions:

1. Safety design bases for the GCFR RHR systems provide a margin of safety in excess of the minimum requirements for the general design criteria for the LWR.

2. The RHR systems of the GCFR demonstration plant provide adequate protection against design basis events. The GCFR core is protected by two independent and redundant safety RHR systems (SCS and CACS) in addition to the nonsafety class MLCS for pressurized RHR events.

3. The CACS and the nonsafety class MLCS provide protection for the DBDA, which is an extremely low probability event.

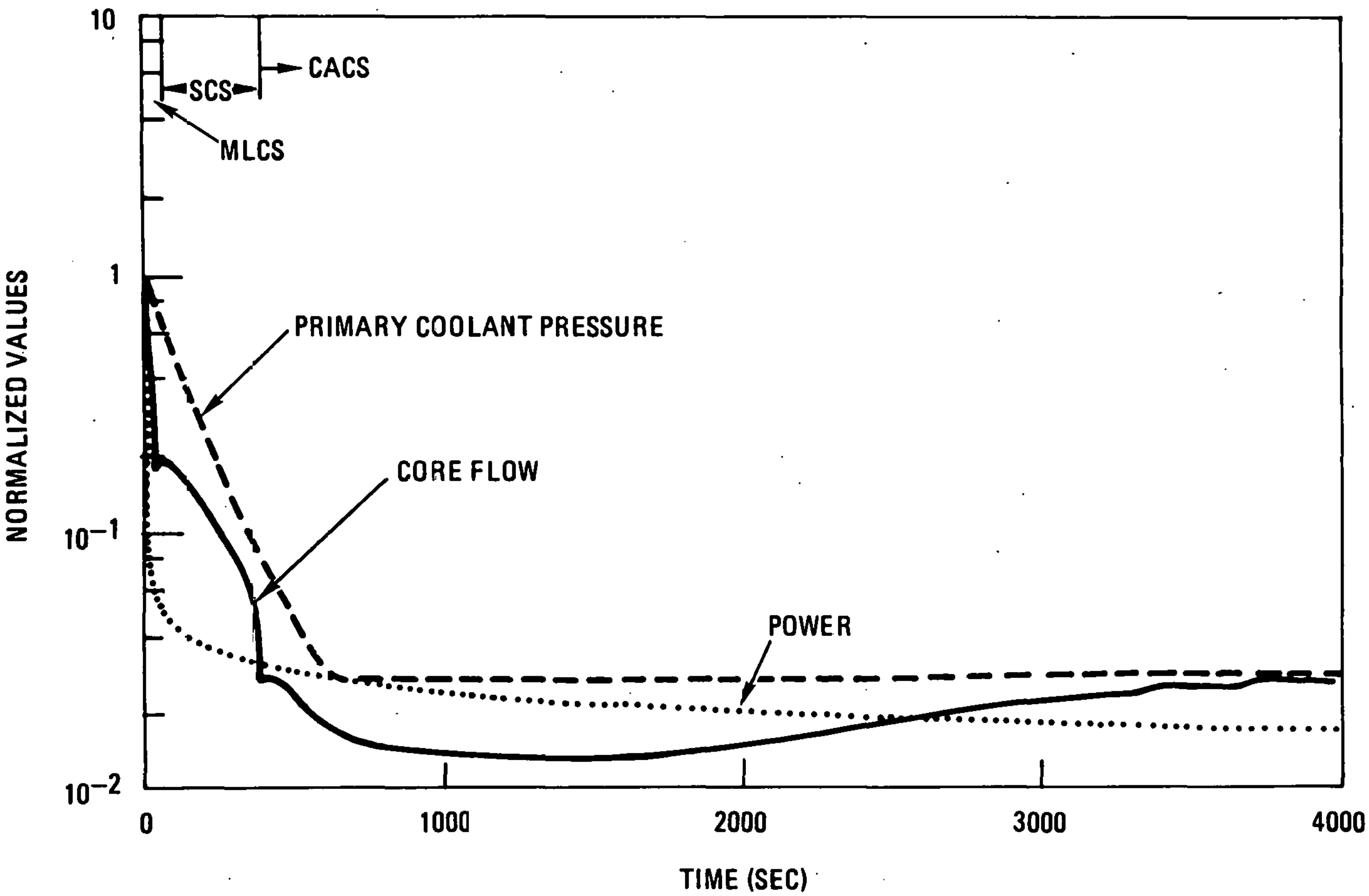

Fig. 8. DBDA (194 cm^2); RHR on 2 CACS, system response

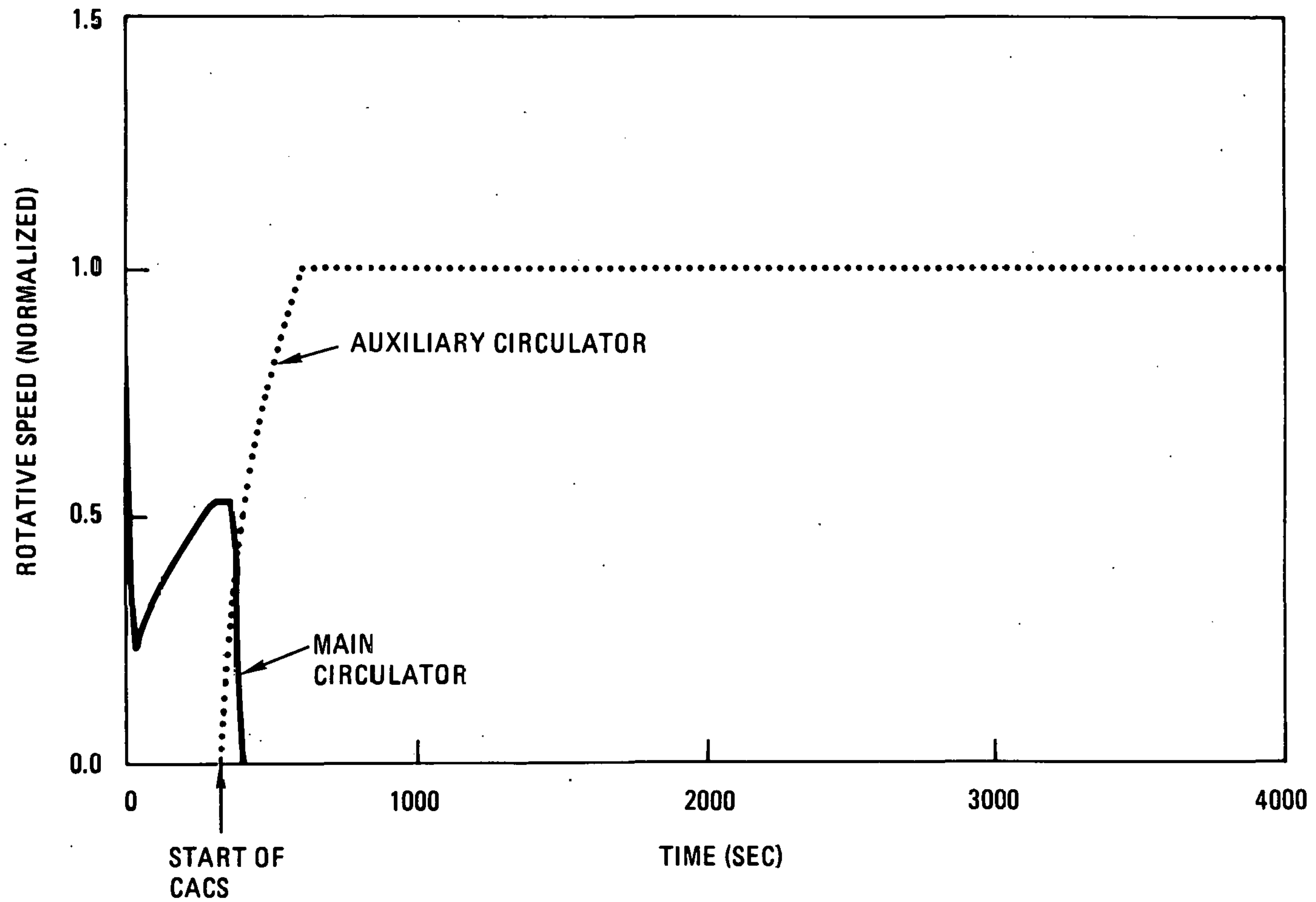

Fig. 9. DBDA (194 cm^2); RHR on 2 CACS, circulator response

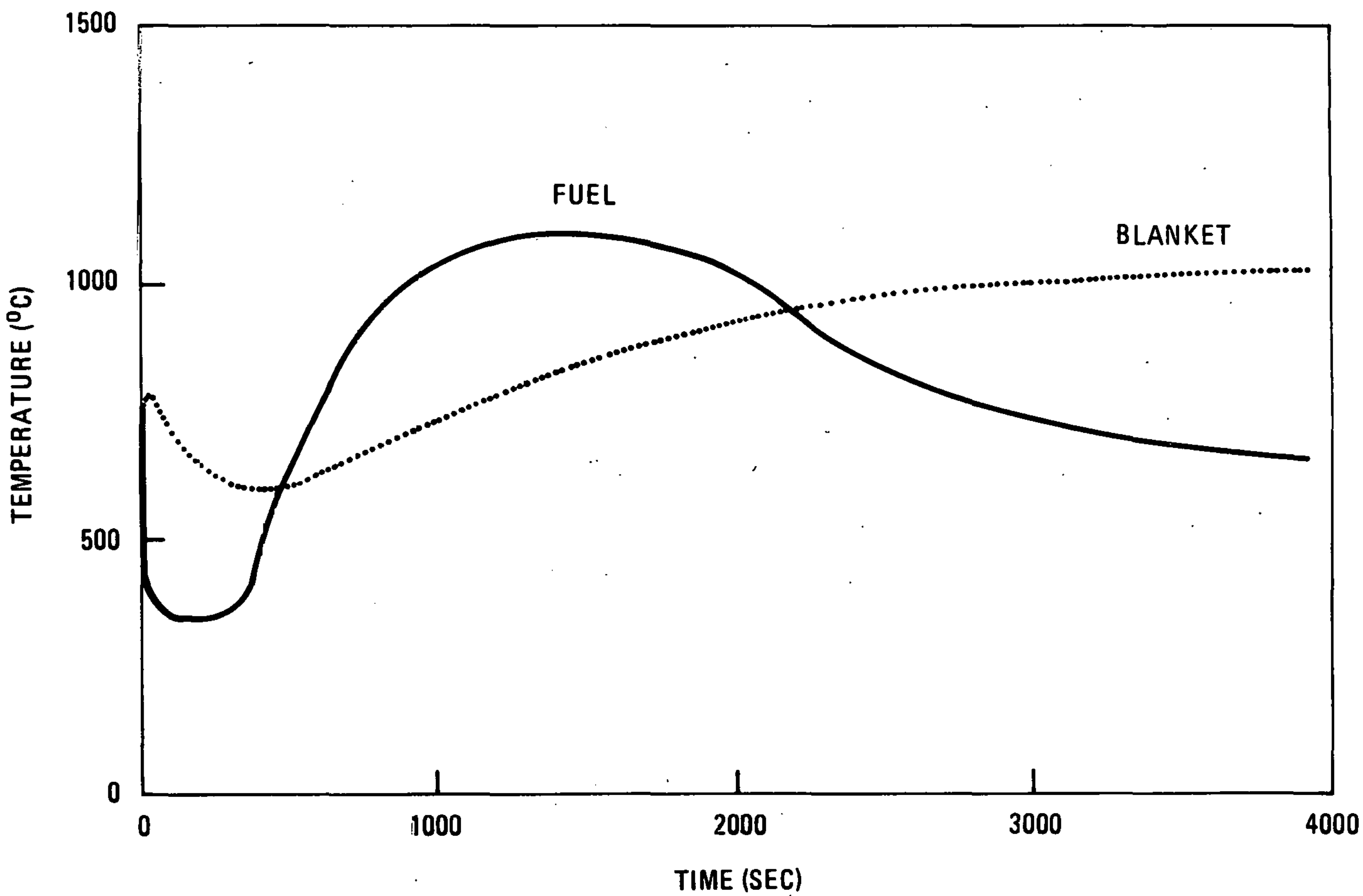

Fig. 10. DBDA (194 cm^2); RHR on 2 CACS, cladding response

REFERENCES

1. "Gas-Cooled Fast Breeder Reactor Safety Information Document," General Atomic Report GA-10298 (Amendment 7), February 23, 1976.
2. "Preapplication Safety Evaluation of the Gas-Cooled Fast Breeder Reactor, General Atomic Company, Project 466," USAEC Directorate of Licensing, August 1, 1974.
3. Kelley, A. et al., "Revised GCFR Safety Program Plan," in Proceedings of The Second Annual GCFR Program Technical Review Meeting, June 4-6, 1980, Rancho Bernardo, California, Helium Breeder Associates, 1980.
4. Medwid, W., et al., "Inherent Design Features of the GCFR," in Proceedings of the Second Annual GCFR Program Technical Review Meeting, June 4-6, 1980, Rancho Bernardo, California, Helium Breeder Associates, 1980.