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GCFR CORE AUXILIARY COOLING SYSTEM DESIGN STUDY

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ABSTRACT

This report presents results from a General Atomic Company alternate design study for the core auxiliary cooling system (CACS) of the 300-MW(e) Gas-Cooled Fast Reactor (GCFR) Demonstration Plant. The purpose of this study was to evaluate CACS design concepts similar to that used in the large High-Temperature Gas-Cooled Reactor (HTGR), which has a non-boiling core auxiliary heat exchanger (CAHE) and CACS startup from rest.

The study considers current 1977 safety criteria and requirements and includes design, transient analysis, drive and control trade-off studies, and analysis methods development. Transient analysis of the revised CACS design indicates satisfactory core cooling for all required operating conditions, according to current criteria.

Some of the work presented was performed by subcontractors. This includes a study on "Alternate Auxiliary Circulator Drive and Control System Conceptual Design Concepts" performed by Aerojet Manufacturing Company and a study on "CACS Dynamic Simulation" performed by Jaycor.

Open issues for the GCFR CACS are also presented. Additional work is required to resolve these issues.

CONTENTS

FIGURES

FIGURES (Continued)

FIGURES (Continued)

TABLES

TABLES (Continued)

1. INTRODUCTION AND SUMMARY

The GCFR auxiliary cooling system comprises the core auxiliary cooling system (CACS) and the core auxiliary cooling water system (CACWS). The components of the CACS include the auxiliary circulator, its drive and control, and the core auxiliary heat exchanger (CAHE). The CACS in conjunction with the main loop cooling system (MLCS) and reactor core assembly is known as the GCFR nuclear steam supply system (NSSS). The NSSS for the 300-MW(e) GCFR is shown in Fig. 1-1. The CACWS components include the air loop cooler (ALC) as a final heat sink, and the pipes to transport the cooling water between the CAHE and ALC, forming a closed loop, are generally referred to as balance of plant (BOP) equipment. The objective of the study described herein is restricted to an evaluation of the CACS conceptual designs for the GCFR 300-MW(e) Demonstration Plant.

The GCFR CACS and the MLCS are required to perform the reactor shutdown cooling or residual heat removal function. The primary function of the CACS, however, is to provide adequate cooling for the reactor core and other prestressed concrete reactor vessel (PCRV) internal structures in the event that the main loop cooling is not available. Therefore, the CACS is designed to be an independent and diverse backup to the main loop cooling.

This report presents all the major work on the GCFR CACS that was performed during 1977 by General Atomic Company (GA). It also includes subcontractor studies performed by Aerojet Manufacturing Company on "Alternate Auxiliary Circulator Drive and Control System Design Concepts" and by Jaycor on "CACS Dynamic Simulation."

The work described in this report was performed as part of the alternate design study for the GCFR 300-MW(e) Demonstration Plant. One requirement of this design study was to revise the CACS component design data, especially for the CAHE and the auxiliary circulator. In order to generate the design

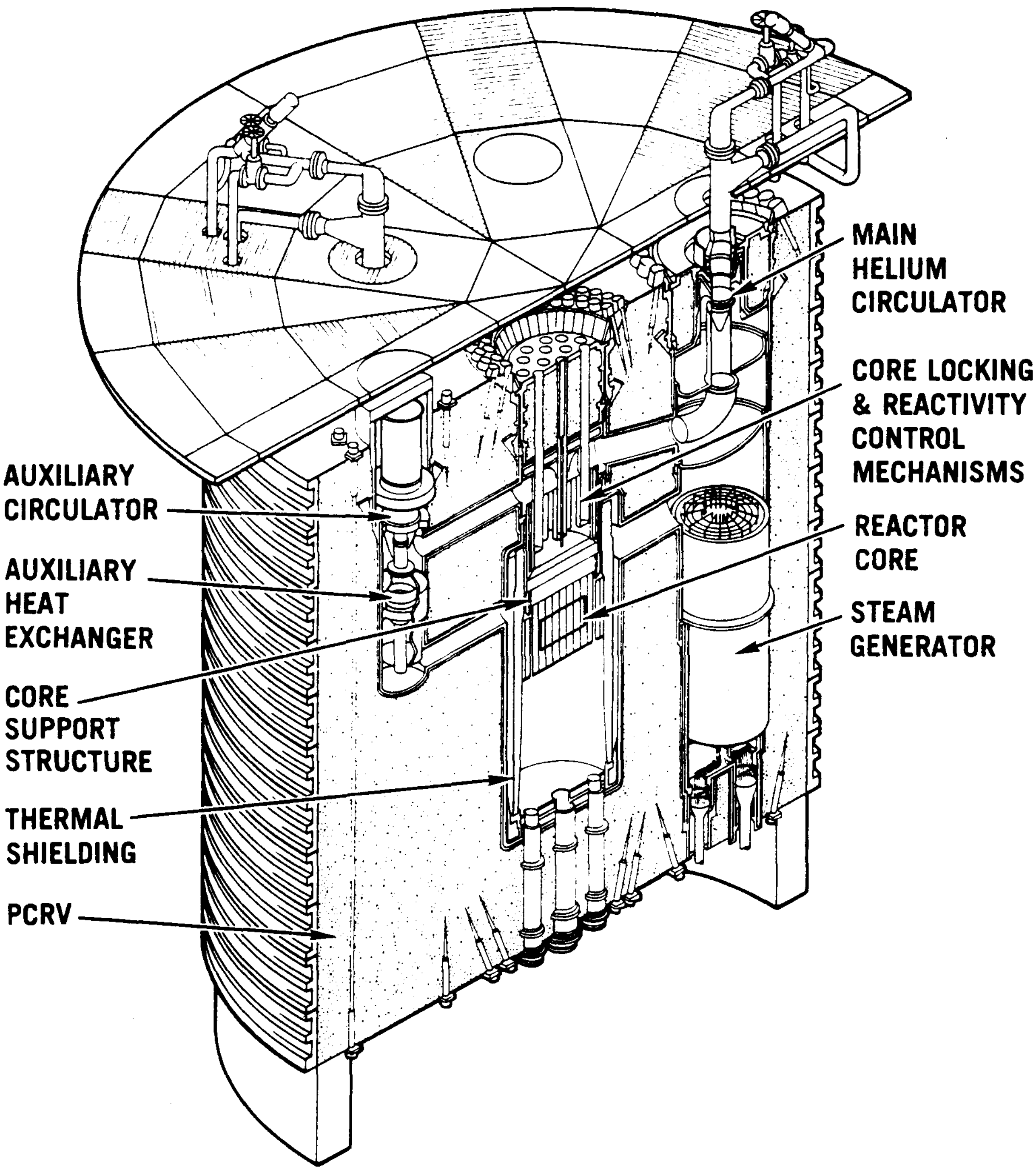

Fig. 1-1. 300-MW(e) GCFR nuclear steam supply system

parameters for the CACS components, it was necessary to examine first the system safety criteria identifying all design events under which the system is required to accomplish its safety function. Then the system design requirements for CACS performance were defined. The principal performance and design considerations for the CACS are those concerned with its function as an engineered safety system for reactor core cooling. The design basis of the CACS comprises the capability to maintain adequate reactor cooling and acceptable reactor core and PCRV internal temperatures under all plant conditions leading to reactor shutdown with a single independent failure of safety-grade equipment.

Once the system safety and design requirements were established, the next task was analysis of the CACS design parameters. Preliminary transient analyses were conducted by means of the GAFTRAN code for pressurized and design basis depressurization accident (DBDA) conditions. Final design parameters for the CAHE, auxiliary circulator, and CACWS were selected based on the results of this transient analysis. Although the design parameters selected were not cost or performance optimized, they are consistent with the design considerations of (1) providing acceptable pressurized and depressurized accident core cooling, (2) reducing CACWS pressure, (3) maintaining a high auxiliary cooler log-mean temperature difference (LMTD), (4) providing circulator motor power of less than 1000 hp, and (5) preventing CAHE boiling.

A DBDA trade-off study for core cooling between main loops and CACS loops was carried out based on data from Amendment 7 of the Preliminary Safety Information Document (PSID). The study investigated the relationships between main loop cooling and main circulator overspeed and the CACS transfer time, assuming different single failure scenarios. The results indicate that for conservative and versatile requirements, a CACS with a 1000-hp auxiliary circulator and a capability of startup within 1 min will be adequate. A CACS transient analysis for a revised reference design is presented in Section 13 of this report. It is concluded that the CACS components of the revised reference design are capable of performing core cooling under all operating conditions.

The conceptual design evaluation of the alternate auxiliary circulator motor drive and control system for the GCFR CACS was carried out by Aerojet Manufacturing Company (AMCO). Twelve alternate auxiliary circulator drive system configurations were evaluated: five types of electric motor drive systems, one gas turbine drive system, two hydraulic turbine drive systems, and four steam turbine drive systems. These configurations were selected based on GA and AMCO experience with similar systems and on information obtained from vendors and other sources. The 12 system configurations were evaluated in a systematic manner. Each was evaluated qualitatively to establish its advantages and disadvantages. In addition, each system was evaluated numerically with respect to a list of 11 evaluators. A matrix of numerical rating results was thus produced. The results were combined by using weighting factors to produce a quantitative evaluation for each system. The results and recommendations from this study are presented in Sections 9, 10, and 11. Based on these results the system recommended for the GCFR is a frequency controlled a.c. induction motor drive similar to that employed by the large HTGR.

The CACS dynamic simulation was carried out by Jaycor. The objective of this task was to develop a system design code which is more adaptable for CACS control and trade-off studies, since the existing GA code GAFTRAN is primarily a safety-oriented code developed to examine safety questions and is not built for system design purposes. The code developed by Jaycor is called CASY. A summary of this study is presented in Section 12 of this report.

Open issues for the GCFR CACS which will affect performance and design are presented in Section 14. Additional work is required to resolve open issues. Future design changes are anticipated based on more complete definition of design requirements.

2. GENERAL CORE COOLING SYSTEM SAFETY CRITERIA

2.1. INTRODUCTION

The CACS and the associated CACWS comprise a portion of the GCFR shutdown core cooling or residual heat removal (RHR) system. Certain RHR functions are assigned to the MLCS, so that the combination of main and auxiliary systems provides all core cooling functions for the GCFR plant. The fundamental RHR system objective is to provide adequate assurance that acceptable fuel cladding temperatures and primary system pressure boundary temperatures are maintained for all events within the design basis which lead to reactor shutdown.

2.2. EVENT CLASSIFICATION

2.2.1. Credible Plant Conditions

The spectra of credible plant conditions have been identified in accordance with their anticipated frequency of occurrence and divided into four categories as follows (Ref. 2-1):

Plant Condition	Event Frequency (F) per Reactor Year
Normal	Planned operations
Upset	$1 > F \geq 10^{-2}$
Emergency	$10^{-2} > F \geq 10^{-4}$
Faulted	$10^{-4} > F \geq 10^{-6}$

These four categories are described below.

Normal Plant Condition

"Normal plant condition" defines the plant safety status during events which are planned to occur regularly in the course of plant operation.

Upset Plant Condition

"Upset plant condition" defines the plant safety status following events which are expected to occur occasionally or with moderate frequency during the plant life. Upset plant conditions, i.e., plant conditions that result from events whose expected frequency of occurrence is between 1 and 10^{-2} per reactor year, are assumed to be synonymous with the 10CFR50, Appendix A, definition of Anticipated Operational Occurrences.

Emergency Plant Condition

"Emergency plant condition" defines the plant safety status following events which may occur infrequently during the plant life ($10^{-2} > F \geq 10^{-4}$).

Faulted Plant Condition

"Faulted plant condition" defines the plant safety status following events which are limiting faults and are not expected to occur ($10^{-4} > F \geq 10^{-6}$), but are postulated because their consequences would include the potential for the release of significant amounts of radioactive material and because they represent upper bounds on failures or accidents with a probability of occurrence sufficiently high to require consideration in design.

Plant conditions characterized by a frequency of occurrence approximately less than 10^{-6} per reactor year are not included within the design basis envelope.

With a postulated event categorized using the above correlation, the plant design shall meet the safety criteria for the given plant conditions. The safety criteria have been established on the premise that (1) those situations in the plant which are assessed as occurring normally or frequently shall yield little or no consequence to the public, and (2) those extreme situations having the potential for the greatest consequence to the public shall be those having a very low probability of occurrence. In applying this principle, the plant conditions having the highest probability of occurrence are designed to have the largest design margins.

2.2.2. Probabilistic Approach

A probabilistic assessment will be performed to determine the likelihood of the combination of the initiating event plus single failure. This combined event may then be categorized as a plant condition in accordance with the probability ranges defined above and the corresponding safety criteria may be applied. In no case shall this probabilistic approach be used as a justification that the combination of any credible initiating event and single failure need not be considered for design. In cases where the combination of any credible initiating event and a single failure has an occurrence rate less than 10^{-6} per reactor year, faulted limits must be applied.

2.3. RHR SYSTEM SAFETY CRITERIA

Within the framework of event classification described in Section 2.2, regulatory requirements have been applied to establish the RHR system safety criteria described below.

2.3.1. General RHR System Criteria

1. Two independent, diverse, and functionally redundant decay heat removal systems shall be provided to ensure that a loss of coolable core geometry resulting from decay heat removal failure shall not have a frequency greater than 10^{-6} per reactor year.

2. The General Design Criteria of Amendment 8 to the PSID (Ref. 2-2) are to be met, particularly Criterion 34 and Criterion 35, which are reproduced below.

Criterion 34: Residual Heat Removal

A system to remove residual heat shall be provided. The system safety function shall be to transfer fission product decay heat and other residual heat from the reactor core at a rate such that specified acceptable fuel design limits and the design conditions of the primary coolant system boundary are not exceeded.

Suitable redundancy in components and features and suitable interconnections, leak detection, and isolation capabilities shall be provided to assure that for onsite electric power system operation (assuming offsite power is not available) and for offsite electric power system operation (assuming onsite power is not available), the system safety function can be accomplished, assuming a single failure.

Criterion 35: Emergency Core Cooling

A system to provide abundant emergency core cooling shall be provided. The system safety function shall be to transfer heat from the reactor core following any depressurization accident at a rate such that fuel and clad damage that could interfere with continued effective core cooling is prevented.

Suitable redundancy in components and features and suitable interconnections, leak detection, isolation, and containment capabilities shall be provided to assure that for onsite electric power system operation (assuming offsite power is not available) and for offsite electric power system operation (assuming onsite power is not available), the system safety function can be accomplished, assuming a single failure.

2.3.2. MLCS Safety Criteria

Employing the above general criteria, apportionments may be made to the CACS and MLCS. The safety-related performance criteria apportioned to the MLCS are as follows:

1. The MLCS shall have the capability to provide residual and decay heat removal following all anticipated operational occurrences* (basis: General Criterion 1).

2. The MLCS shall have the capability to provide continuous core cooling for a period sufficient to bridge the startup of the CACS following all design events* that result in reactor trip. Capability must be provided assuming a single independent failure, operating from either onsite or offsite power sources, and relying upon seismic category equipment only (basis: General Criterion 2).

Criterion 1 follows directly from General Criterion 1. To meet the 10^{-6} per reactor year goal and allow for common mode failures within systems, two independent cooling systems (MLCS and CACS) need to have the capability of handling the more likely initiating events. Criterion 1, in essence, requires that the failure probability of the MLCS to provide residual and decay heat removal be less than approximately 10^{-2} per reactor year, leaving the remainder of the 10^{-6} per year goal to be met by the CACS.

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*A listing of pertinent design events is given in Section 2.3.4.

Criterion 2 follows directly from General Criterion 2. In making the RHR system duty apportionment, it has been recognized that the CACS startup time will be finite, and that a CACS standby mode is a preferred alternate to a continuously operating CACS.

2.3.3. CACS Criteria

Based upon the general criteria in Section 2.3.1 and the apportionment of these criteria to the MLCS in Section 2.3.2, the remainder of the general criteria must be met by the CACS:

1. The CACS shall supply a source of cooling that is completely independent of and diverse from that supplied by the main loops (basis: General Criterion 1).

2. The CACS shall have the capability to provide residual and decay heat removal following all design events.* Capability must be provided assuming a single independent failure, operating from either onsite or offsite power sources, and relying upon seismic category equipment only (basis: General Criterion 2).

2.3.4. Cooling System Design Events

Table 2-1 lists the design events to be considered in establishing the adequacy of the cooling systems in accomplishing their safety function. These events are generally consistent with HTGR precedent, except for event 10, which has been established by Light Water Reactor (LWR) and Liquid Metal Fast Breeder Reactor (LMFBR) precedent. Event 15 is considered desirable because it establishes a CACS startup margin which considers the mechanical inertia coastdown capability of the main circulators only.

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*A listing of pertinent design events is given in Section 2.3.4.

TABLE 2-1
COOLING SYSTEM DESIGN EVENTS

Anticipated Operational Occurrences

1. Loss of main feedwater.

2. Loss of condenser vacuum.

3. Loss of offsite power and turbine trip.

4. Loss of one redundant d.c. system.

5. Operating basis earthquake (OBE).

6. Reactor trip.

Design Basis Accidents

7. Design basis depressurization accident (DBDA).

8. Safe shutdown earthquake (SSE).

9. SSE and DBDA.

10. Loss of offsite and onsite (emergency diesels) a.c. power for 2 hr.

11. Rupture of a single high-energy water/steam pipe.

12. Structural failure or bearing seizure of a single circulator.

13. Failure of speed control (circulator accelerates to maximum possible speed) on a single circulator.

14. Leaks of a single steam generator/CAHE.

15. Loss of all driving power to the main circulators following a reactor trip.

2.4. FAILURE CRITERIA FOR DESIGN EVENTS

2.4.1. Single Failure

An established requirement in nuclear plant design is that safe shutdown be achievable for design basis events, allowing for a single independent failure and with reliance only on safety-grade equipment. The GCFR Plant Safety Criteria (Ref. 2-1) include this requirement. The single failure must be taken as an active failure within 24 hr, or either an active or passive failure beyond 24 hr. The first 24-hr period is of primary concern for the GCFR, since this period is expected to govern cooling system design.

As stated previously, an objective of Criteria 35 from PSID Amendment 8 (Ref. 2-2) is to ensure effective core cooling during the DBDA with a single independent failure of safety-grade equipment. For the GCFR, where RHR-related portions of the main loops are safety class, the single failure is taken either as a main loop, a CACS loop, or a main loop isolation valve. (Consequential failures must also be considered.) Appropriate credit is taken for all remaining cooling loops. The single failure criterion is similarly applied to design events other than the DBDA.

2.4.2 Common-Mode Failure

Common-mode failures require consideration for RHR system design and reliability evaluation. The primary concern is active failure, during the initial 24 hr after an event. However, within the broad common-mode failure category, distinction should be made between two types of common-mode failures.

The first type can be described as causal, consequential, dependent, or mechanistic. Failures of this type must be designed for, or preferably designed around, since this is simply a matter of effectively dealing with the predicted plant response to a particular event. Design approaches which avoid mechanistic multiple circulator failures must be implemented to ensure adequate core cooling.

The second type is an independent common-cause failure, with no mechanistic coupling to the event, such as improper modulation of turbine control valves for three main circulators. Such failures can be appropriately dealt with on a probabilistic basis. Simply stated, if adequate probability of successful core cooling can be demonstrated, with consideration of relevant common-mode failures, then no design change is necessary; if not, then additional redundancy and/or diversity must be provided.

2.4.3. Number of Available Cooling Loops

With the position on failure criteria established, a DBDA event spectrum will now be examined in further detail and will be shown to comply with the established single failure criteria. The relevant spectrum of DBDA events is presented in Table 2-2.

A depressurization through the core cavity closure should not be permitted, by design, to disable a cooling loop as a consequential failure. Thus, a postulated loss of one main circulator or one auxiliary circulator satisfies the single failure requirement. If the single failure is postulated as a main loop isolation valve, then all cooling loops can be considered available for this type of depressurization. Other single failures can be postulated, but they do not cause special concern for core cooling.

Turning next to a depressurization through a steam generator/circulator cavity closure, loss of a main circulator as a consequential failure can be expected, although it may be possible to demonstrate otherwise. In addition to any consequential failures, a single independent failure must be considered as for previous cases. This leads to events 4 through 7 in Table 2-2.

TABLE 2-2
DBDA EVENTS - PARTIAL SPECTRUM

Case	Closure Failed	Depressurization Type [a]	Single Failure	Main Loops Available	Aux. Loops Available
1	Core cavity	Inlet	Main cir.	2	3
2	Core cavity	Inlet	Aux. cir.	3	2
3	Core cavity	Inlet	Main loop valve	3	3
4	SG cavity	Inlet	Main loop valve	2[b]	3
5	SG cavity	Outlet	Main circ.	1[b]	3
6	SG cavity	Outlet	Aux. circ.	2[b]	2
7	SG cavity	Outlet	Main loop valve	2[b]	3

[a] The terms "Inlet" and "Outlet" refer to the location of the break relative to the core.

[b] One main circulator assumed disabled as consequential failure due to steam generator cavity closure failure.

DBDA events can also be categorized as inlet or outlet depressurizations, depending on the location of flow discharge relative to the core. This distinction is made to emphasize that full credit can be taken for the core cooling effects of outlet depressurization flow. Approximately 2268 kg (5000 lb) of helium is released from the primary system, which on a mass basis is equivalent to 2.5-min flow from three CACS loops or 3.8-min flow from two CACS loops. During the period from 8 to 20 s into the DBDA, the depressurization flow [0.048 m^2 (75 $in.^2$)] is two to three times the total flow for two main loops.

To establish system and component requirements for post-DBDA core cooling, analyses are required consistent with the failure basis in Table 2-2 and accounting for depressurization flow effects. Requirements for pressurized cooling should be developed considering a single failure and the various accident modes, such as a 2-hr a.c. blackout or loss of drive power to the main circulators.

2.4.4. Isolation Valves

In the preceding discussion of cooling loop availability and single failures, the main loop isolation valves were recognized as safety class components, so that a postulated malfunction of a single valve satisfies the single failure requirement. However, auxiliary loop valves were not singled out in this manner, and the effect of failure is implicitly grouped with auxiliary circulator failure. The reason is that failure in the normal position has been considered as the only credible failure for these self-actuated valves. That is, main loop valves were considered to fail only in an open position, while auxiliary loop valves were considered to fail only in a closed position, thus producing an effect similar to an auxiliary circulator failure. The "failure to change state" is taken as a single active failure. Other valve failures would be structural or passive in nature. This treatment has precedence in HTGR licensing and reliability studies. For accident analysis, the flow bypass effect of a failed main loop isolation valve must be considered.

2.4.5. Summary of Failure Criteria and Accident Analysis

1. A single independent failure of safety equipment must be considered for design events.

2. Consequential or event-dependent failures must be considered.

3. Independent or non-mechanistic common-mode failures should be considered only as required from reliability/probability evaluations.

4. Analysis of plant response to the DBDA should be based on the event spectrum in Table 2-2.

5. Credit can be taken for depressurization flow core cooling for the core outlet DBDA.

6. Main loop isolation valves require independent consideration as a single component failure.

REFERENCES

2-1. "Design Criteria: Plant Safety," General Atomic Company, unpublished data.

2-2. "Gas-Cooled Fast Breeder Reactor Preliminary Safety Information Document," General Atomic Report GA-A10298, Amendment 8, Appendix A, December 1976.

3. CORE AUXILIARY COOLING SYSTEM DESIGN REQUIREMENTS

3.1. FUNCTIONAL REQUIREMENTS

3.1.1. Engineered Safety Function

The primary CACS functional requirement is to provide residual heat removal for the core and other PCRV internal components and structures in the event that the main cooling loops cannot adequately perform this function when the reactor is shut down. Cooling shall be sufficient to maintain core and PCRV internal temperatures within safe shutdown limits in accordance with plant safety requirements specified in Ref. 3-1. The CACS shall be an independent and, to the greatest practical extent, a diverse backup to the main cooling loops. It shall provide "abundant" (per 10CFR50, Criterion 35) core cooling for all design basis events which render the main loop cooling inadequate for this purpose.

3.1.2. Decay Heat Removal

The CACS shall be capable of removing low-level decay heat during periods of extended reactor shutdown and during refueling. For this function the CACS is used as an alternate to main loop cooling during normal plant conditions.

3.1.3. Safety Requirements

The principal performance and design considerations for the CACS are those concerned with its function as an engineered safety system for core cooling. Therefore, it must comply with all of the applicable requirements, conditions, and criteria specified in Ref. 3-1.

3.2. PERFORMANCE REQUIREMENTS

3.2.1. General

To accomplish its cooling function, the CACS shall provide for the forced circulation of gaseous coolant within the PCRV, the transfer of heat from the gas to a secondary coolant, and the transfer of heat from the secondary coolant to the ultimate heat sink.

The CACS shall have three modes of operation:

1. Accident Cooling - The system performs its primary design function as an engineered safety system.

2. Normal Decay Heat Removal - The system performs as an optional alternate to main loop cooling to provide core cooling during extended plant shutdown and during refueling.

3. Standby - In this mode the system parameter states required at the initiation of the other two operational modes are established and maintained.

3.2.2. Performance Criteria

The CACS must meet the following criteria to ensure its capability to perform its safety functions:

1. For normal and upset plant conditions, the CACS shall remove residual and decay heat at a rate such that the core and PCRV internals shall be maintained below the design limits.

2. For emergency and faulted plant conditions, the CACS shall remove residual and decay heat at a rate such that the core and PCRV internals shall be maintained below the damage limits.

3. The CACS shall supply a source of cooling that is completely independent of that supplied by the main loops.

4. The CACS shall be capable of automatic initiation by signals from the plant protection system and by manual initiation and control.

5. The CACS shall be capable of operating from either onsite or offsite power sources.

6. The CACS shall be capable of resuming proper operation and supplying adequate cooling following an interruption of preferred power at any time during any accident sequence.

7. The CACS shall be capable of being operated and monitored from either the main control room or the safe shutdown room.

8. CACS equipment shall be designed to limit the maximum accidental depressurization flow area to the value used for accident calculations.

9. CACS equipment shall be designed to limit the maximum water ingress into the PCRV to the value used for accident calculations.

10. The CACS shall be designed to provide adequate residual and decay heat removal within the minimum time used for accident calculations.

3.3. ACCIDENT COOLING REQUIREMENTS

Accident cooling requirements arise from postulated emergency and faulted plant conditions. In this mode of operation the system must be capable of taking over the core cooling function from the main cooling loops while a plant transient is in progress.

3.3.1. Capability

The CACS cooling capability shall be adequate to maintain temperatures of the core and other PCRV internal components and structures within the limits specified in Section 3.2.2.

3.3.2. Design Basis

The CACS shall be designed to have the capability described above for all design basis events specified in Table 2-1. In general, all occurrences which establish CACS operating conditions shall be applied at the worst times and in the worst sense from the standpoint of overall demand on the CACS. For example, all degrading effects of the safe shutdown earthquake shall be imposed at the worst time during the cooldown.

3.3.3. Startup Time

Starting from the accident cooling mode initiation signal, the elapsed time before the system will be required to provide the core cooling function depends on the particular design basis condition. The maximum elapsed time for a pressurized core shall be determined by event 15 and for a DBDA it shall be determined by event 9 of Table 2-1.

3.3.4. Restart Capability

The CACS shall be automatically returned to its full operational status (required cooling) following a loss of preferred power. The power loss and subsequent switchover to another power source shall not in any way impair the system's ability to satisfy its performance requirements.

3.3.5. Plant Conditions and Uncertainties

The CACS shall provide the capability specified in Section 3.3.1 when uncertainties are included for each of the design basis conditions. Table

3-1 is a summary of the expected values and uncertainties related to these design basis conditions.

3.3.6. Performance Margin

Sufficient margin shall be incorporated into the system performance capability so that an "abundance" of CACS core cooling capability can be demonstrated.

3.3.7. Credit for Non-Safety Systems

The CACS shall be capable of meeting the performance requirements for all design basis events assuming no credit for non-safety-related systems. Credit will be taken for the safety class portion of the main loop cooling system during the CACS startup.

3.4. NORMAL DECAY HEAT REMOVAL REQUIREMENTS

3.4.1. Capability

The CACS cooling capability shall be adequate to maintain temperatures of the core and other PCRV internal components and structures within their appropriate normal design ranges (Section 3.2.2). Generally, temperature limits during long-term plant shutdown shall be identical to the limits for normal plant operation unless a specified refueling or maintenance procedure requires lower temperatures.

3.4.2. Design Basis

The CACS shall be designed to have the capability described in Section 3.4.1 for all plant conditions applicable to normal decay heat removal (times greater than 48 hr following reactor shutdown) and to normal refueling operations.

TABLE 3-1
SYSTEM UNCERTAINTY FACTORS TO BE USED FOR
BEST ESTIMATE AND CONSERVATIVE MODELS

Parameter	Best Estimate Model	Conservative Model
Decay heat	1.0	1.2
Local power uncertainty	1.0	1.05

3.4.3. Startup Time

There is no startup time requirement for this mode of operation.

3.4.4. Restart Capability

The CACS shall be automatically returned to its full operational status (required cooling) following a loss of preferred power. The power loss and subsequent switchover to another power source shall not in any way damage the system equipment or impair its ability to satisfy its performance requirements.

3.4.5. Plant Conditions and Uncertainties

The CACS shall have the capability specified in Section 3.4.1 when all of the applicable conditions and uncertainties are included. Table 3-1 summarizes the expected values and uncertainties related to the normal long-term decay heat removal function and the normal refueling function.

3.4.6. Performance Margin

There are no performance margins applicable to this mode of operation.

3.4.7. Accident Cooling Interface

Utilizing the CACS in these normal plant operations shall in no way impair its performance and operation as an engineered safety system. If there are differences or conflicts, the performance requirements for accident cooling and any associated operating procedures shall take precedence over the requirements for normal decay heat removal.

3.5. STANDBY REQUIREMENTS

The only performance requirement applicable to the standby mode is that a condition of readiness shall be established and maintained such that the requirements in Sections 3.3 and 3.4 can be satisfied. The CACS conditions established in this mode form the initial conditions for both the normal decay heat removal and accident cooling modes of operation. These initial conditions will have a major impact on the accident cooling mode startup time and on the transient design considerations applicable to CACS equipment.

3.6. DESIGN REQUIREMENTS

3.6.1. Single Failure

The CACS design shall conform with the single failure criterion as identified in Section 2.4.1. When one CACS loop is unavailable (for scheduled and unscheduled maintenance or testing purposes), the plant shall be operating within appropriate Technical Specification Limiting Conditions of Operation.

3.6.2. Independence

The CACS and main cooling loops shall be functionally and mechanically independent of each other. A failure in the main cooling loop system shall not prevent the CACS from satisfying its performance requirements. Similarly, a failure in the CACS shall not prevent the main cooling loops from satisfying their performance requirements. This same degree of independence shall also be provided between individual CACS loops. No initiating event shall cause the loss of more than one CACS loop, nor the loss of all main loop cooling and one or more CACS loops.

3.6.3. Diversity

To the greatest practical extent, the CACS design shall be diverse from that of the main cooling loops. This requirement pertains particularly to the helium circulators, circulator motive power source, secondary coolant heat transport systems, and bearing lubrication.

3.6.4. Separation

Physical separation, barriers, or restraints shall be provided such that no design basis event shall result in the inability of the CACS to satisfy its performance requirements.

The CACS shall be protected against the loss of its safety function from missiles generated by accidents, equipment failures, or natural occurrences and from other dynamic effects resulting from equipment failures. Consequential damage to portions of the CACS is acceptable only if the system can meet performance requirements with consideration of an independent single failure. Physical separation or protection of redundant components is required. CACS circulators and heat exchangers shall be located and/or protected such that failure of a circulator or its drive motor will not cause further consequential damage such as heat exchanger rupture or damage to circulators or other components in other loops.

No design basis containment environment or natural occurrence shall preclude adequate CACS performance. Affected components shall be designed to withstand transient conditions caused by postulated penetration ruptures and steam leaks.

3.6.5. Common-Mode Failures

Special consideration shall be given to identifying and eliminating potential common-mode failures within the CACS and between the CACS and other plant systems. As part of this effort, the following categories of common-mode failure causes shall be considered:

1. Design deficiencies.

2. Errors in maintenance procedures and practices.

3. Manufacturing errors.

4. Functional deficiencies.

5. Environmental conditions and natural events (e.g., fire, earthquake, missiles).

3.6.6. Equipment Classification

The safety classification of CACS equipment is given in Table 3-2.

3.6.7. Industry Codes

The codes applicable to the design of CACS equipment are listed in Table 3-3.

In addition, the following standard provides guidance: ANS-53.12 - "Nuclear Safety Criteria for the Design of Stationary Gas Cooled Reactor Plant Core Auxiliary Cooling System."

3.6.8. Government Requirements

The CACS shall comply with the following General Design Criteria (Ref. 3-2):

1. Criterion 1-5, "Overall Requirements."

2. Criterion 19, "Control Room."

3. Criterion 30, "Quality of Reactor Coolant Pressure Boundary."

4. Criterion 31, "Fracture Prevention of Reactor Coolant Pressure Boundary."

5. Criterion 32, "Inspection of Reactor Coolant Pressure Boundary."

TABLE 3-2
CACS EQUIPMENT CLASSIFICATION

Principal Component	Safety Class	Principal Design and Construction Code or Standard	Seismic Category[a]	10CFR50 Appendix B	Quality Assurance Level
Core Auxiliary Cooling System (CACS) (22)					
Auxiliary circulators	1[b] & 2	ASME Section III-Div. 1,[b] Class 1 and Class 2	I	Applies	QAL I
Auxiliary circulator shutoff valves	2		I	Applies	QAL I
Core auxiliary heat exchangers	1[b] & 2	ASME Section III-Div. 1,[b] Class 1 and Class 2	I	Applies	QAL I
Instrumentation	(d)		I & Non-Cat. I	Applies	QAL I & II
Auxiliary Circulator Service System (22)					
Motor cooling water modules with associated piping and valves	2[c] & 3	ASME Section III-Div. 1,[c] Class 2 and Class 3	I	Applies	QAL I
Bearing oil replacement modules	NN	ASME Section VIII	Non-Cat. I	Applies	QAL II
Buffer helium system piping and valves up to and including second isolation valve	2	ASME Section III-Div. 1, Class 2	I	Applies	QAL I
Instrumentation	(d)		I & Non-Cat. I	Applies	QAL I & II

[a] All seismic Category I piping and equipment shall have Category I supports. Non-seismic Category I piping and equipment shall have Category I supports where failure could lead to damage to other seismic Category I piping and equipment.

[b] Primary coolant system boundary components only.

[c] To containment isolation valves only.

[d] Essential portions are covered by plant protection system; other portions are non-nuclear.

TABLE 3-3
DESIGN REQUIREMENTS FOR GCFR SYSTEMS, STRUCTURES, AND COMPONENTS

Item	Safety Class 1	Safety Class 2	Safety Class 3
PCRV and supports (including liner, penetrations, and closures)	ASME Boiler and Pressure Vessel Code, Section III (ASME III), Division 2	ASME III, Div. 2	ASME III, Div. 2
Steel vessels	ASME III, Div. 1, Section NB 3300	ASME III, Div. 1, Sections NC 3300 and 3310	ASME III, Div. 1, Sections ND 3300 and 3310
Circulators and compressors	No particular codes available. Guidance on pumps is available in ASME III, Div. 1, under Sections: ASME NB 3400	NC 3400	ND 3400
Valves	ASME III, Div. 1, Section NB 3500	ASME III, Div. 1, Section NC 3500	ASME III, Div. 1, Section ND 3500
Piping	ASME III, Div. 1, Section NB 3650	ASME III, Div. 1, Sections NC 3600 and 3611.1	ASME III, Div. 1, Sections ND 3600 and 3640
Instrument piping and tubing	Under Development		
Supports for equipment, valves, and piping			
Concrete	ASME III, Div. 2	ASME III, Div. 2	ASME III, Div. 2
Steel	ASME III, Div. 1, Section NF	ASME III, Div. 1, Section NF	ASME III, Div. 1, Section NF
Structural foundations (bldg. and equip. foundations)	No particular codes available. Design requirements shall be developed for the specific component.		
Pumps	(There are no Class 1 pumps.)	ASME III, Div. 1, Section NC 3400	ASME III, Div. 1, Section ND 3400
Atmospheric tanks	(There are no Class 1 atmos. tanks.)	ASME III, Div. 1, Sections NC 3800 and 3871.2	ASME III, Div. 1, Sections ND 3870 and 3871.2
Heat exchangers (including CAHEs and steam generators)	Primary coolant system boundary portions only - ASME III, Div. 1, Section NB 3000	ASME III, Div. 1, Section NC 3300	ASME III, Div. 1, Section ND 3300

TABLE 3-3 (Continued)

Item	Safety Class 1	Safety Class 2	Safety Class 3
Ductwork and ductwork valves	No particular codes are available. Design requirements shall be developed for the specific component.		
Thermal barrier	No particular codes are available. Design requirements shall be developed for the specific component.		
Fuel assemblies, support structures, seals, and orifice assemblies	No particular codes are available. Design requirements shall be developed for the specific component.		
Electrical systems and components	There are no Class 1 electrical systems or components.		
Class IE systems (overall)		IEEE 308, IEEE 323, IEEE 336, IEEE 338, IEEE 344, IEEE 383, IEEE 384, IEEE 494	Same as Class 2
Class IE connectors, switchgear, and transformers		IEEE 420	Same as Class 2
Plant protection system (overall)		IEEE 279, ANS 4.1, IEEE 352, IEEE 379	Same as Class 2
Plant protection system components, cables, modules, and sensors		ANS 4.1	Same as Class 2
Motors			Same as Class 2
Valve actuators			Same as Class 2
Penetrations	There are no Class 1 electrical penetrations.	IEEE 334, IEEE 323, IEEE 344, IEEE 382	There are no Class 3 electrical penetrations.
Containment		BOP	
PCRV		IEEE 344, ASME III, Div. 2	
Liner and primary closure		ASME III, Div. 2	

6. Criterion 34, "Residual Heat Removal."

7. Criterion 35, "Emergency Core Cooling."

8. Criterion 36, "Inspection of Core Auxiliary Cooling System."

9. Criterion 37, "Testing of Core Auxiliary Cooling System."

10. Criterion 44, "Cooling Water System."

11. Criterion 45, "Inspection of Cooling Water System."

12. Criterion 46, "Testing of Cooling Water System."

The following regulator documents are to be used for guidance in the design of the CACS. General Atomic licensing position statements on regulatory guides are given in Ref. 3-1.

1. RG 1.20, "Comprehensive Vibration Assessment Program for Reactor Internals During Preoperational and Initial Startup Testing."

2. RG 1.48, "Design Limits and Loading Combinations for Seismic Category 1 Fluid System Components."

3. RG 1.84, "Code Case Acceptability, ASME Section 3 Design and Fabrication."

4. RG 1.85, "Code Case Acceptability, ASME Section 3 Materials."

5. RG 1.87, "Guidance for Construction of Class 1 Components in Elevated-Temperature Reactors."

3.6.9. Design Life and Operating Cycles

All CACS components and equipment shall be designed to be compatible with a plant design life of 30 yr. The system and component design shall also be compatible with the number, type, and duration of system operating cycles (including margins) presented in Table 3-4. The system operating cycle information in Table 3-4 is based on the following four types of system operation:

1. Design Basis Cooling - The events for upset, emergency, and faulted conditions are presented in Section 2.3.4. The corresponding number of cycles is representative of the highest probability of occurrence of each type of event.

2. Decay Heat Removal - Allowance has been made for this operating mode, which is not a planned operation.

3. Standby - For each reactor trip, the CACS is brought to a standby condition in readiness for operation.

4. Planned Testing - This category includes periodic testing to verify CACS performance and integrity.

3.6.10. Seismic Design

The components of the CACS shall be designed in accordance with Seismic Category 1 requirements. Loading combinations shall conform with the intent of USNRC Regulatory Guide 1.48.

Electrical components in the CACS shall be designed and qualified in accordance with IEEE 323 and IEEE 344.

TABLE 3-4
CACS DUTY CYCLE

Category	Number of Events	Operating Time per Event (days)	Justification
1. Design basis cooling[a]			
Emergency events[b]	3	21	Number of events Three events is a conservative allowance for emergency events which are individually not expected to occur during a plant lifetime. Operating time Balance of plant estimates of time to repair worst failure, assumed here to be rupture of common feedwater piping. Additional review of assumptions and the spectrum of emergency events should be conducted.
Faulted events[b]	1	78	Number of events Single occurrence is a conservative allowance for this event category. Operating time 30 days decontamination of containment following DBDA plus 3 times the 16 days to remove and reload 1/3 of the core.

[a] The main loop cooling system is to be designed with sufficient reliability (probability of failure to provide residual and decay heat removal $<10^{-2}$ per reactor year) that the design basis for the CACS includes only emergency and faulted events.

[b] The spectrum of emergency and faulted events must be analyzed to determine which form the design basis for specific components of the CACS (see Ref. 3-1 for a listing of emergency and faulted duty cycle events). Single failure or common-mode failures in safety class equipment responding to mitigate event consequences must also be considered.

TABLE 3-4 (Continued)

Category	Number of Events	Operating Time per Event (days)	Justification
2. Decay heat removal	6	35	Number of events Arbitrary. Currently there are no plans to routinely use the CACS to provide decay heat removal. Here it is assumed that at 5-yr intervals the CACS loops are used during the annual refueling and maintenance period (e.g., steam generator tube plugging, turbine-generator repair). Operating time Estimated time to overhaul turbine-generator set - currently scheduled every fifth year.
3. Standby	127	5	Number of events CACS brought to standby following each reactor trip. Operating time Assumed to apply on average to all events.
4. Planned Testing[c]	30	1	Number of events Annually during refueling per footnote (c).

[c] PSID Amendment 8 (Ref. 3-2) provides GCFR adaptations of the General Design Criteria for Nuclear Power Plants. Criterion 37 covers testing of the CACS and states "the generation of the core auxiliary cooling loops as a system can be tested during shutdown by using them for decay heat removal while holding the primary loops in reserve."

TABLE 3-4 (Continued)

Category	Number of Events	Operating Time per Event (days)	Justification
4. Planned Testing (cont)			<u>Operating time</u> This is judged to represent an adequate length of time to test CACS.
	780	0.042	Start up 1 hr and run circulator at 500 rpm for 1 hr every 2 weeks.

3.6.11. Design for Testing and Inspection of Components

CACS components shall be designed to permit testing to assure the structural and leaktight integrity and the operability of the system. These components shall also be designed to permit in-service inspection of components external to the PCRV.

3.6.12. Circulator Design

CACS circulators shall be designed to operate against a closed valve for a time and at a speed sufficient to permit testing of the circulators and their associated control and protective provisions, and to accommodate transient startup considering possible flow and pressure mismatch between the independent loops in both the CACS and main cooling systems.

REFERENCES

3-1. "Design Criteria: Plant Safety," General Atomic Company, unpublished data.

3-2. "Gas-Cooled Fast Breeder Reactor Preliminary Safety Information Document," General Atomic Report GA-A10298, Amendment 8, Appendix A, December 1976.

4. REFERENCE DESIGN PARAMETERS FOR CACS

4.1. BASIS

The preliminary design parameters for the CACS are based on the results of a transient analysis using the GAFTRAN code for pressurized and depressurized (DBDA) residual heat removal. The input data to the code are summarized in Table 4-1. Additional input data are taken from the PSID, Amendment 7 (Ref. 4-1) and Ref. 4-2. All analyses were based on steam-driven main circulators.

Five basic cases were investigated in this analysis, as shown in Table 4-1:

1. Three main loops, two CACS loops, under DBDA conditions (Case 1A).

2. Same conditions as in Case 1A, but with 8165 kg (18,000 lb) of water added to the CACWS (Case 1B).

3. Two main loops, three CACS loops, under DBDA conditions (Case 2A).

4. Three main loops, two CACS loops, reference design CACS under pressurized core operation (Case 4F).

5. Same conditions as Case 4F, but with 5443 kg (12,000 lb) of water added to the cold leg of the CACWS (Case 4G).

The analysis used the conservative analysis model which was defined in PSID Amendment 7 to account for uncertainty margins (Section 6) associated with the system parameters, such as coolant loop pressure drop, decay heat, containment backpressure, etc. For all cases the CACWS pumps and auxiliary

TABLE 4-1
SUMMARY OF INPUT DATA FOR TRANSIENT ANALYSIS OF CACS DESIGN PARAMETERS

Case	Steam Generator Loop	CACS Loop	CACS Transfer Time (s)	CAHE (CACSW) Initial Temp. [°C (°F)]	CACWS Cold Leg Water Inventory	Remarks
1A	3	2	300	316 (600)	PSID Amendment 7	Depressurization
1B	3	2	300	93 (200)	Amendment 7 + 8165 kg (18,000 lb)	Depressurization
2A	2	3	300	316 (600)	Amendment 7	Depressurization
4F[(a)]	3	2	30	316 (600)	Amendment 7	Pressurized core main circulator coastdown
4G[(a)]	3	2	30	93 (200)	Amendment 7 + 5443 kg (12,000 lb)	Pressurized core main circulator coastdown

[(a)] In Cases 4F and 4G, a torque limit for the auxiliary circulator of 67.8 Nm (50 lb-ft) was used, which was adequate for core cooling and was necessary for code stability. Also in Cases 4F and 4G, the main circulator coastdown under a loss-of-power condition was assumed. In other cases, the main circulators were assumed to be driven by steam in accordance with the shutdown control system.

loop cooler (ALC) fans were assumed to start simultaneously with reactor trip at the beginning of the transient, but actual loop transfer from the main loops to the CACS was assumed to occur at a later time (CACS transfer time in Table 4-1). At the CACS transfer time, the auxiliary circulators are started and the loop isolation valves are actuated to accomplish the loop switch. Some main circulator overspeed was used for the three main loop, DBDA cases because it was shown in another study (Section 5) that without an overspeed circulator, stalling occurred. It was necessary to further increase main circulator overspeed in the two main loop, DBDA case to provide for adequate core cooling.

4.2. RESULTS OF ANALYSIS

A typical output of the preliminary design parameter analysis for Case 2A is shown in Figs. 4-1 through 4-8. A complete summary of the results for all cases investigated is given in Table 4-2. The results are discussed below.

Under the three main loop, two CACS loop, DBDA conditions analyzed, there was little difference in results using the PSID Amendment 7 CACS (Ref. 4-1) and the CACS with increased CACWS water inventory (as shown by the results given in Table 4-2 for Cases 1A and 1B). However, with essentially the same design parameters but with a pressurized core, the results showed significant differences in CACWS water temperatures (see Table 4-2). In the Amendment 7 CACS (Case 4F), CACWS water temperatures exceed boiling temperatures to 440°C (820°F). With the increased CACWS water inventory (Case 4G), water temperatures are acceptable but high [330°C (630°F)], leaving little margin before the design pressure of 2100 psia (Ref. 4-1) is reached.

Results for Case 2A (two main loop, three CACS loop, DBDA conditions with the Amendment 7 CACS) show that the Amendment 7 CACS design is acceptable for cooling the core. However, it was necessary to impose a 35% overspeed requirement on the main circulators to maintain acceptable core

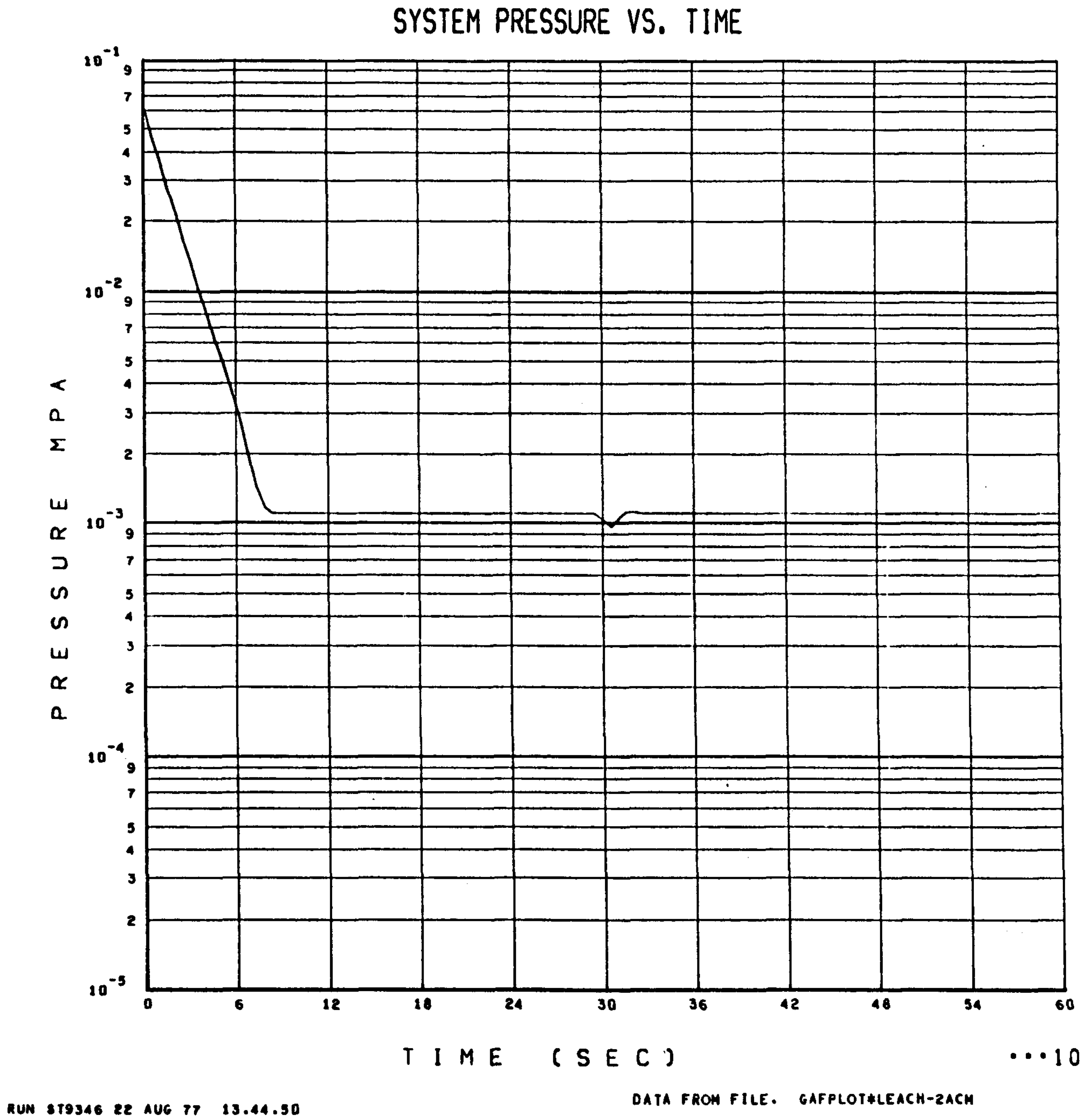

Fig. 4-1. Results of Case 2A analysis: system pressure versus time

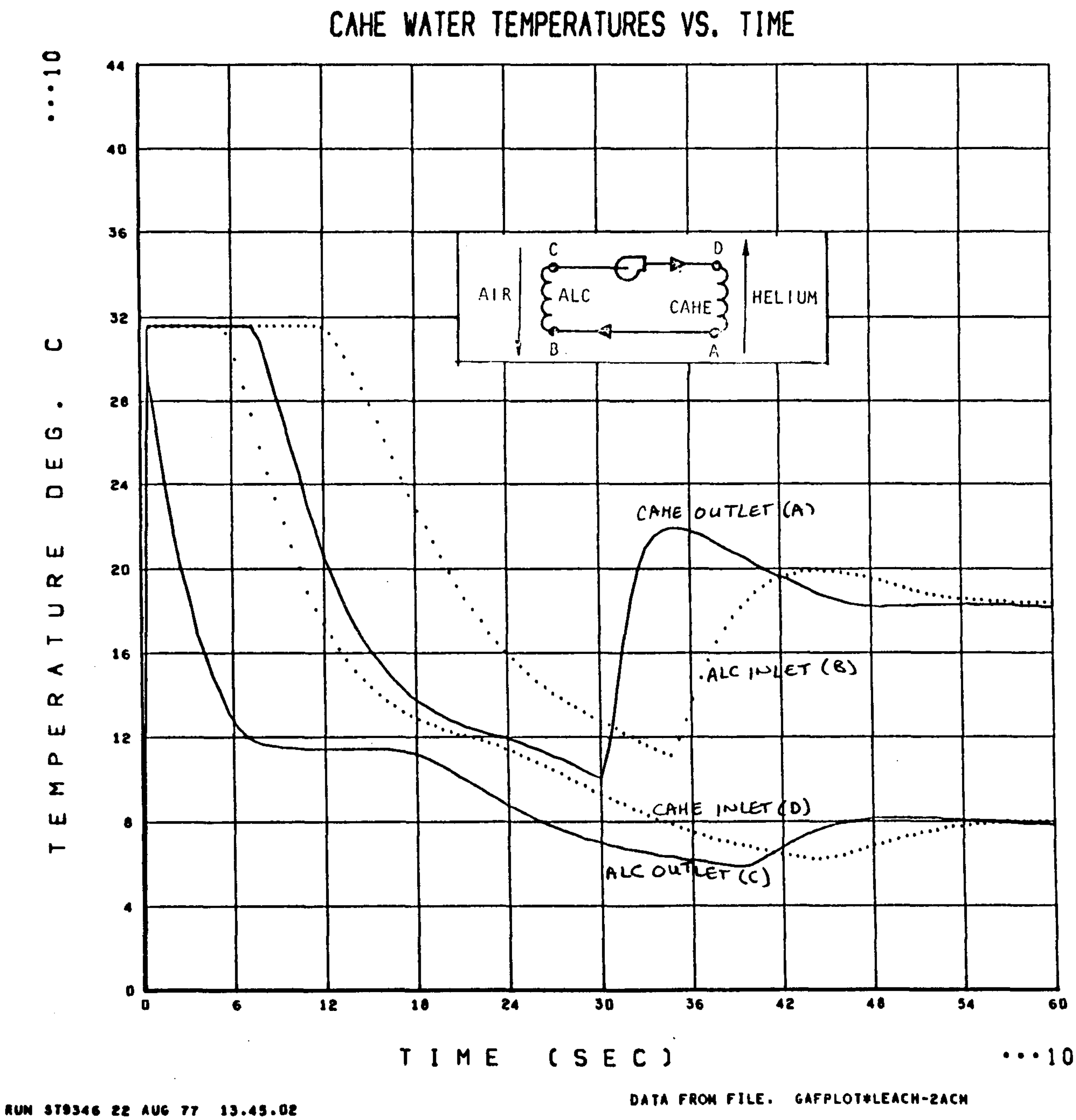

Fig. 4-2. Results of Case 2A analysis: CAHE water temperature versus time

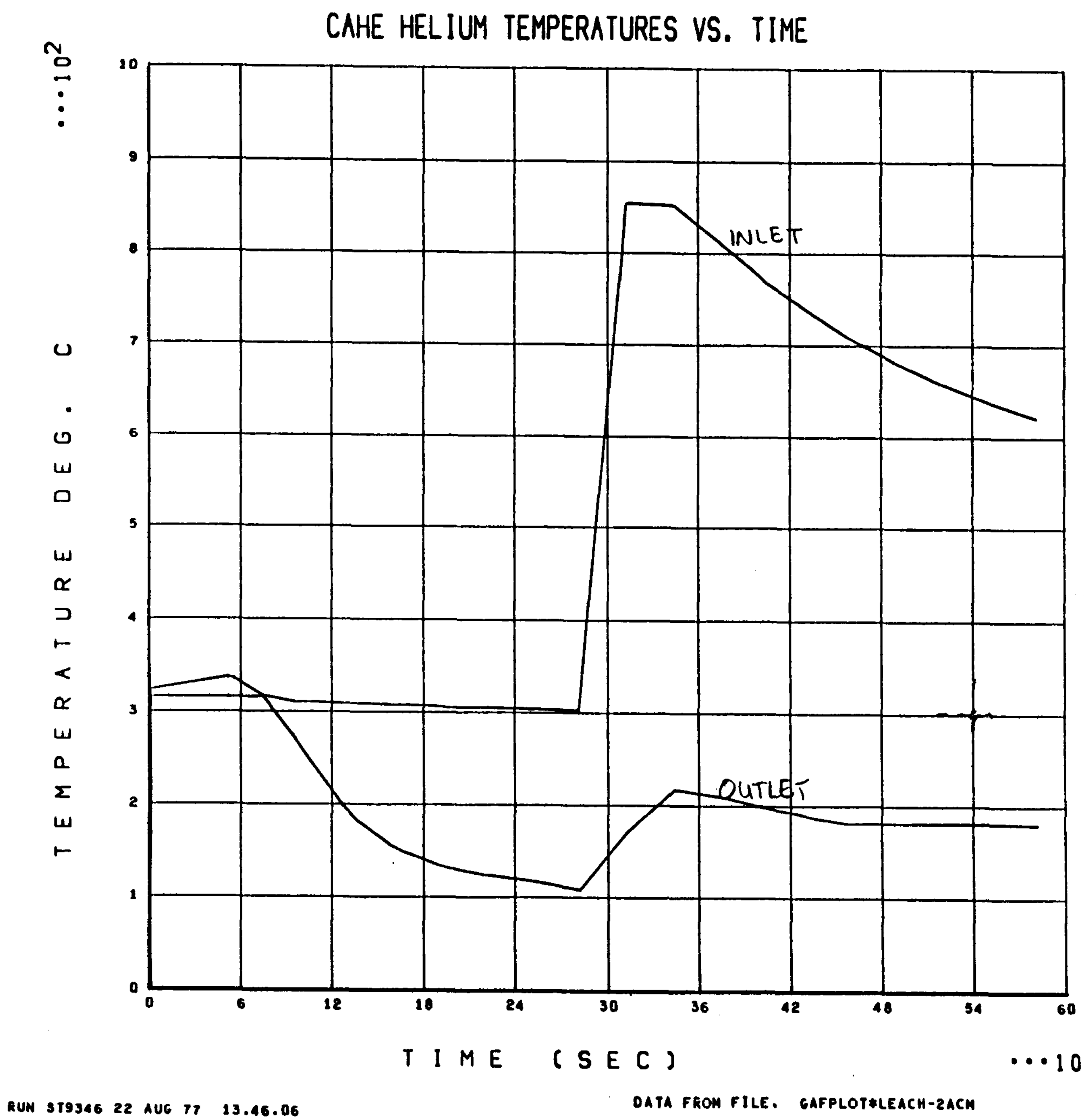

Fig. 4-3. Results of Case 2A analysis: CAHE helium temperature versus time

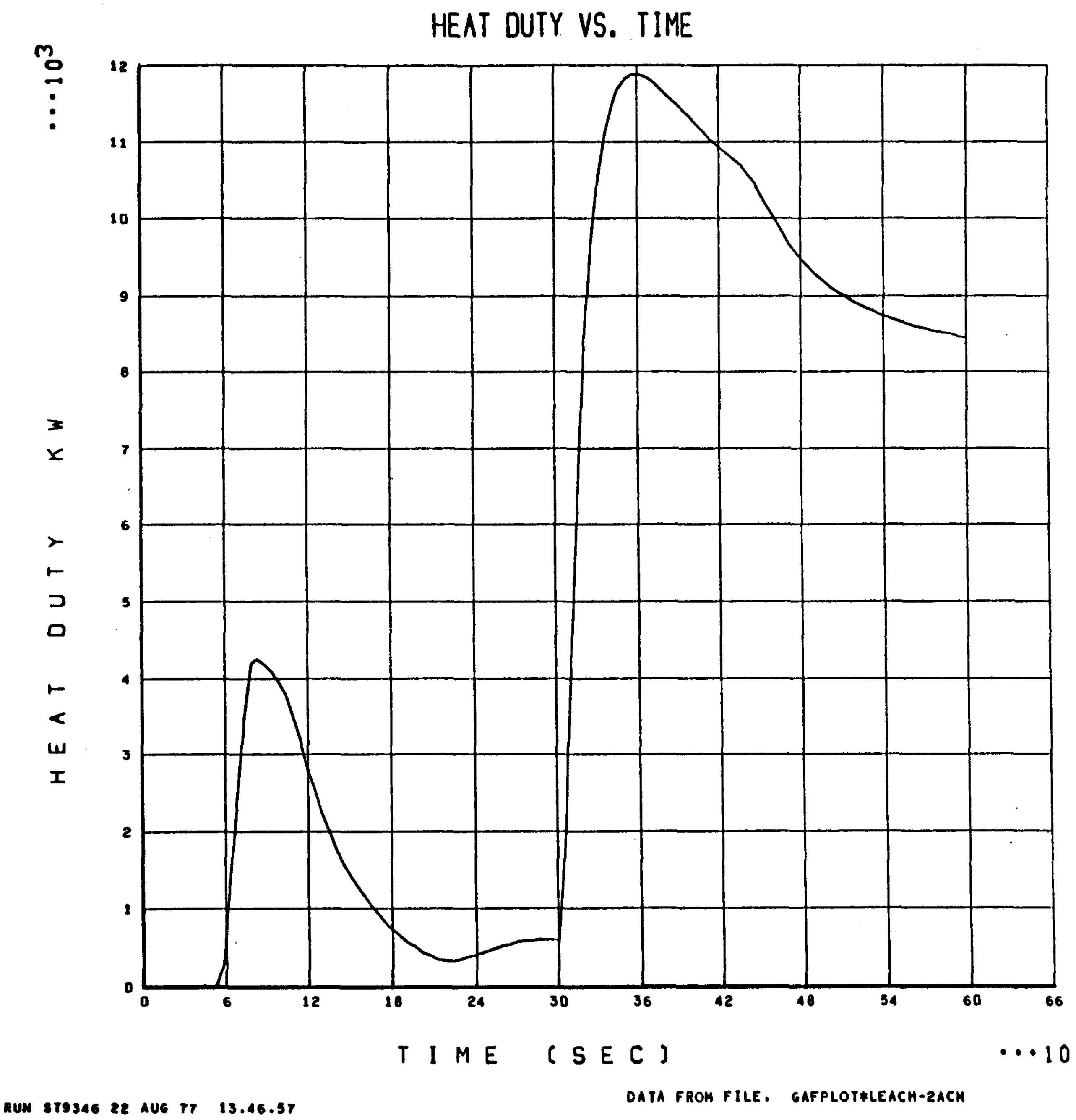

Fig. 4-4. Results of Case 2A analysis: heat duty versus time

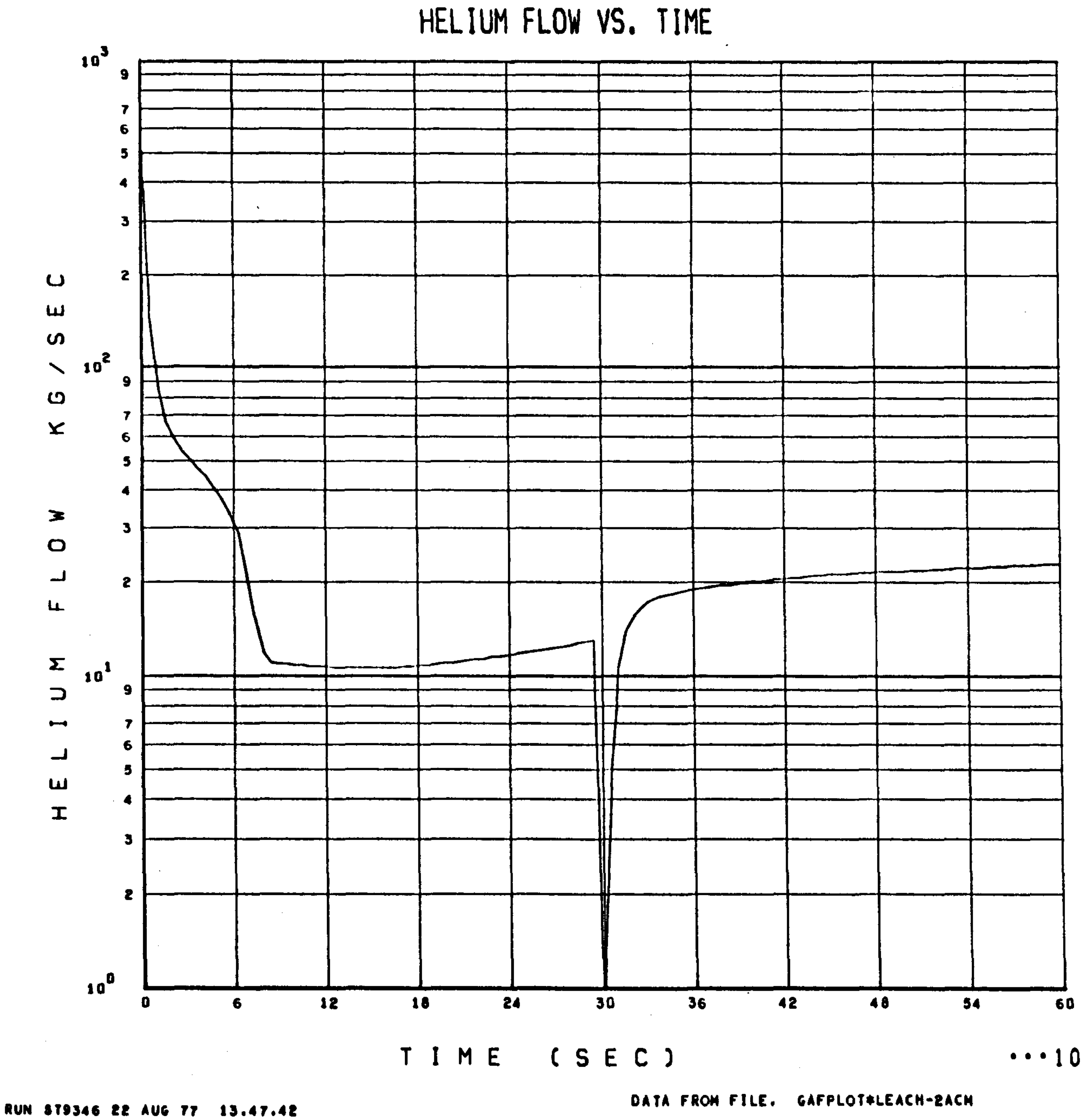

Fig. 4-5. Results of Case 2A analysis: helium flow versus time

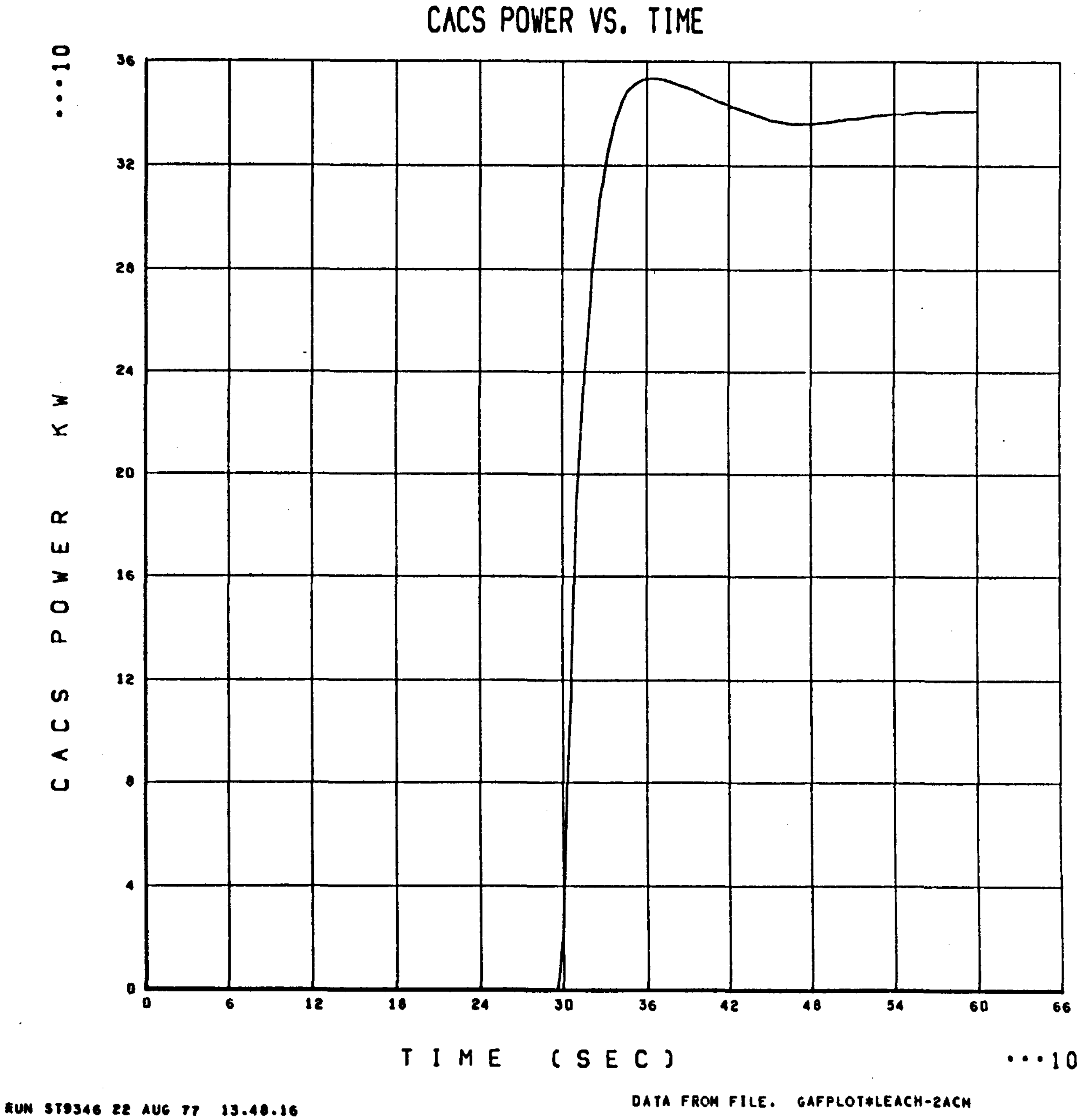

Fig. 4-6. Results of Case 2A analysis: CACS power versus time

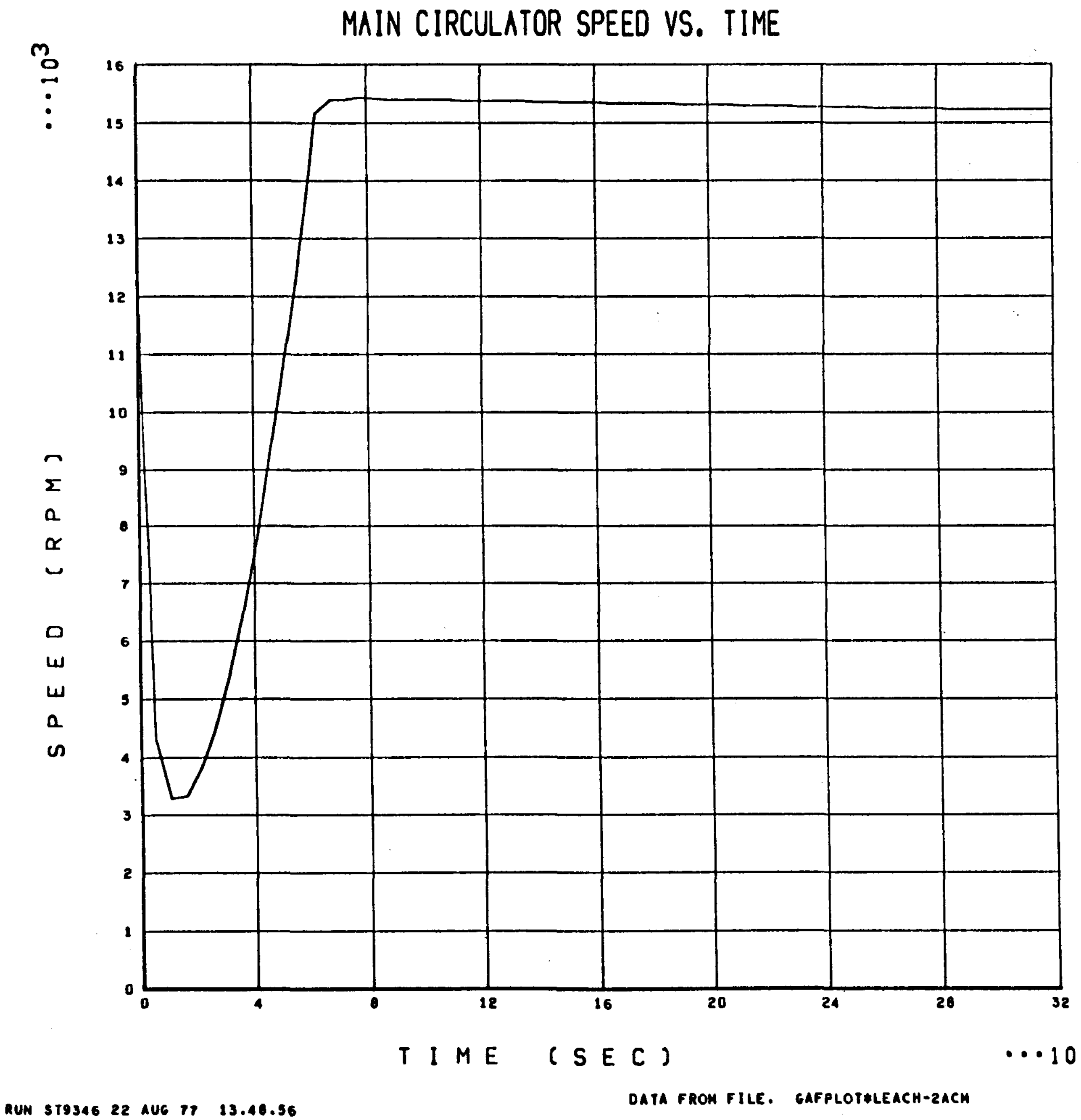

Fig. 4-7. Results of Case 2A analysis: main circulator speed versus time

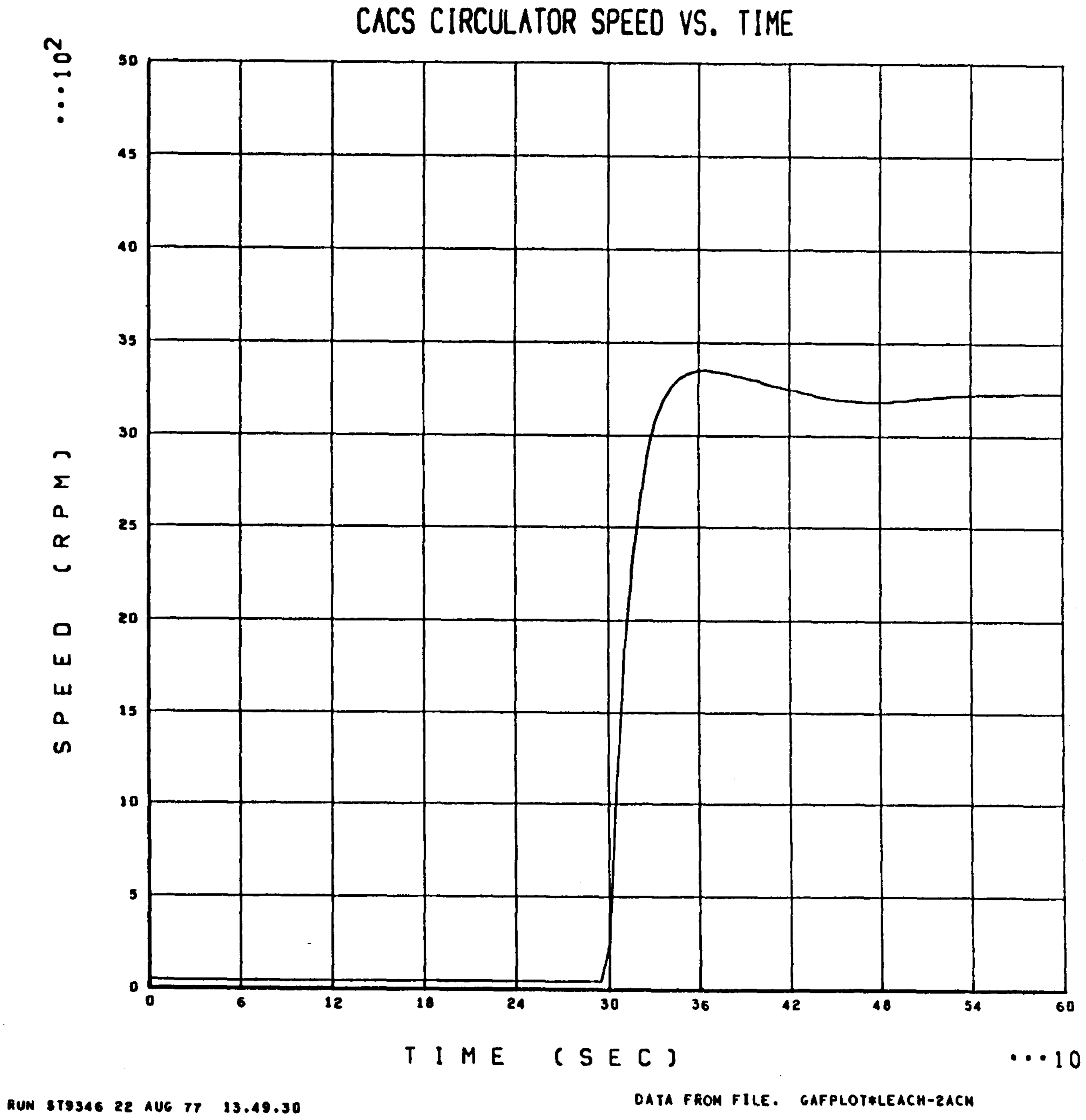

Fig. 4-8. Results of Case 2A analysis: CACS circulator speed versus time

TABLE 4-2

SUMMARY OF RESULTS FROM PRELIMINARY CACS DESIGN PARAMETER ANALYSIS

Parameter	Case 1A	1B	2A	4F	4G
1. Auxiliary circulator power (max), kw (hp)	515 (691)	513 (687)	353 (474)	3.21 (4.3)	2.98 (4.0)
2. Auxiliary circulator flow, kg/hr (lb/hr)	34,029 (75,020)	32,618 (71,910)	27,406 (60,420)	53,632 (118,238)	56,007 (123,474)
3. Auxiliary circulator speed (max), rpm	4796	4900	3347	363	335
4. Main circulator speed (max), rpm	13,666	13,834	15,423	11,671	11,671
5. CAHE helium pressure, MPa (psia)	0.152 (22.0)	0.152 (22.0)	0.152 (22.0)	8.83 (1280)	8.83 (1280)
6. ΔP across auxiliary circulator, MPa (psi)	0.013 (1.9)	0.013 (1.9)	0.013 (1.9)	0.0011 (0.16)	0.0011 (0.16)
7. CAHE helium inlet temperature (max), °C (°F)	853 (1567)	856 (1573)	854 (1569)	676 (1249)	601 (1114)
8. CAHE helium outlet temperature, (max after transfer, °C (°F)	250 (482)	264 (507)	217 (422)	443 (829)	344 (651)

TABLE 4-2 (Continued)

Parameter	Case				
	1A	1B	2A	4F	4G
9. CACWS temperature (max after transfer), °C (°F)	250 (482)	264 (507)	218 (425)	438 (820)	333 (631)
10. Maximum cladding temperature (core), °C (°F)	1147 (2097)	1146 (2095)	1165 (2129)	928 (1703)	890 (1634)

temperatures prior to transfer to the CACS (see Fig. 4-7). For this case a maximum cladding temperature of 1165°C (2130°F) was reached 100 s prior to loop transfer at 300 s. (Some margin was given in the maximum acceptable cladding temperatures to allow for the high temperatures at the edge channels.) It was found that the overspeed requirement could be reduced to less than 20% by initiating loop transfer prior to 90 s.

4.3. REFERENCE DESIGN PARAMETERS

Based on the results of the transient analysis discussed in Section 4.2, design parameters for the CAHE, auxiliary circulator, and CACWS were selected as shown in Tables 4-3, 4-4 and 4-5, respectively. These parameters are not cost or performance optimized, but are consistent with the design considerations discussed below.

4.3.1. Acceptable Pressurized and DBDA Core Cooling

The design parameters envelop a range of pressurized and DBDA two CACS loop cooling modes, with start times as low as 30 s and including air ingress effects. Steady-state calculations indicate the CAHE and circulator designs are only slightly affected by variation in post-DBDA start times in the 30-s to 100-s period. However, electrical aspects of the system, which are not addressed here, are significantly affected by start time. Owing to the "loss of main circulator drive power" design event, the system heat duty has increased ~37% compared with the Amendment 7 design (Ref. 4-1).

4.3.2. Reduced CACWS Pressure

Pressures exceeding 2000 psi impose heavy-walled tubing in the ALC and complicate the design; the selected 1300-psi pressure eases these difficulties. Also, the 1300-psi pressure essentially balances the primary system pressure, so that long-term CAHE stresses and consequences of leakage are minimal. This forms a probable basis for reduced in-service inspection frequency.

TABLE 4-3
CAHE REFERENCE DESIGN PARAMETERS

Parameters (One Loop)	Pressurized Primary System	Depressurized Primary System
Thermal duty, MW (Btu/hr)	20.2 (68.9×10^6)	16.1 (55.0×10^6)
Primary system flow, kg/s (lb/hr)	14.7 (117,000)	9.07 (72,000)
Primary gas molecular weight, g/g-mole (lb/lb-mole)	4.0 (4.0)	7.54[a] (7.54)
Primary gas specific heat, J/kg-K (Btu/lb-°F)	5200 (1.242)	2910[a] (0.695)[a]
Primary gas inlet temperature, °C (°F)	604 (1120)	832 (1530)
Primary gas outlet temperature, °C (°F)	341 (645)	221 (430)
Primary system pressure, MPa (psia)	8.8256 (1280)	0.1793 (26.0)
Maximum primary side ΔP, kPa (psi)	-	1.724 (0.25)
Cooling water flow, kg/s (lb/hr)	75.9 (602,300)	75.9 (602,300)
Cooling water inlet temperature, °C (°F)	234 (453)	132 (270)
Cooling water outlet temperature, °C (°F)	288 (550)	182 (359)
Cooling water average pressure, MPa (psia)	8.964 (1300)	8.964 (1300)
Maximum water-side ΔP, MPa (psi)	0.241 (35)	0.241 (35)

[a] Helium-air mixture at 5 min following DBDA.

TABLE 4-4
AUXILIARY CIRCULATOR REFERENCE DESIGN PARAMETERS

Parameters (One Loop)	Pressurized Primary System	Depressurized Primary System
Mass flow, kg/s (lb/hr)	14.7 (117,000)	9.12 (72,370)
Molecular weight, g/g-mole, (lb/lb-mole)	4 (4)	5.9[a] (5.9)
Inlet temperature, °C (°F)	341 (645)	221 (430)
Inlet pressure, MPa (psia)	8.8256 (1280)	0.1744 (25.3)
Outlet pressure, MPa (psia)	8.8267 (1280.16)	0.1896 (27.5)

[a] Helium-air mixture at 5 min following DBDA.

TABLE 4-5
CACWS REFERENCE DESIGN PARAMETERS

Parameters (One Loop)	Depressurized Primary System[a]
Water flow, kg/s (lb/hr)	75.89 (602,300)
Cooling water inlet temperature, °C (°F)	182 (359)
Cooling water outlet temperature, °C (°F)	132 (270)
Air flow, m^3/s at 38°C and 89.6 kPa (CFM at 100°F and 13 psia)	331.3 (702,000)
Air flow, kg/s (lb/hr)	332.64 (2.64×10^6)
Air inlet temperature, °C (°F)	38 (100)
Coolant UA,[b] MW/°C (Btu/hr-°F)	0.17 (321,600)
Thermal duty, MW (Btu/hr)	16.1 (55.0×10^6)

[a]Parameters for pressurized cooling were not computed. However, it has been established that the DBDA case determines the CACWS design.

[b]U = overall heat transfer coefficient,
A = heat transfer area.

4.3.3. High Auxiliary Loop Cooler (ALC) LMTD

To keep ALC surface area requirements within reason, parameters were selected such that the ALC logarithmic mean temperature difference (LMTD) exceeds 56°C (100°F) for all operating modes.

4.3.4. Circulator Motor Power Less Than 7.46 MW (1000 HP)

This goal was adopted to keep the HTGR-derived circulator motor option open.

4.3.5. Prevention of CAHE Boiling

A boiling CAHE was considered to raise system and component concerns which could not be adequately investigated in the allotted time frame and was therefore ruled out. Suppression of boiling also means that the CACWS must maintain standby conditions appropriate to the 8.96 MPa (1300 psia) pressure.

4.3.6. ALC Sizing

The ALC was recognized as a major cost item, and the reference parameters result in an ALC/CAHE area ratio $\approx$ 10, as compared with 20 for the Amendment 7 design. It was further recognized that water flow can be varied considerably with small cost effects. For example, the selected 78.89 kg/s (602,300 lb/hr) water flow is within the capability of an average single-stage pump, although it represents nearly a fourfold increase from Amendment 7 design (Ref. 4-2). Nor does the associated increase in heat exchanger water-side frontal area present special difficulties.

4.3.7. Air Ingress Versus Time

Air ingress effects were found to be a major factor in determining CAHE surface area requirements. Steady-state calculations were performed for various times following the DBDA and indicate that the crucial period is 5 to 6 min after initiation of the DBDA.

REFERENCES

4-1. "Gas-Cooled Fast Breeder Reactor Preliminary Safety Information Document," General Atomic Report GA-A10298, Amendment 7, Appendix B, February 1976.

4-2. "Development Plans for Gas-Cooled Fast Breeder Reactor (GCFR) Nuclear Steam Supply (NSS) Components - 300-MW(e) Demonstration Plant Management Summary," General Atomic Report GA-A14462, September 1977.

5. DBDA TRADE-OFF STUDY FOR CORE COOLING WITH MAIN LOOPS AND CACS LOOPS

5.1. INTRODUCTION

In the original GCFR PSID (Ref. 5-1), the depressurization leak area was 0.016 m^2 (25 $in.^2$) and application of the CACS following a DBDA was not studied in detail. In the original safety analysis, the shutdown core cooling following the depressurization accident was shown to be achieved by the main coolant loops without the main circulator overspeed (Ref. 5-1).

To answer NRC concerns regarding DBDA core cooling identified in the GCFR Safety Evaluation Report (SER) (Ref. 5-2), PSID Amendment 7 analyses (Ref. 5-3) were performed using a 0.048-m^2 (75-$in.^2$) leak area and conservative uncertainty margins for safety parameters. The Amendment 7 analyses are based on the following fixed DBDA scenario:

1. Two main loops transferred to two CACS loops at 85 s.

2. Three main loops transferred to three CACS loops at 85 s.

3. Maximum main circulator overspeed of 30%.

4. Maximum auxiliary circulator power of 0.51 MW (690 hp).

The present study indicates that several requirements for adequate core cooling are interrelated. This section summarizes the results of a trade-off study to evaluate specific effects of the following variables:

Variable	Impact
Main circulator overspeed	Circulator design options
CACS transfer time	Emergency power availability
Auxiliary circulator power	Development cost
Various single failure scenarios	Licensing implication

Results of the study identify two base cases of adequate main loop cooling in which transfer time to the CACS is not limiting or transfer is not required:

1. Three main loops with no main circulator overspeed.

2. Two main loops with 35% main circulator overspeed.

In case of the steam generator cavity break DBDA, one single failure and one consequential failure are allowed, which leaves one main loop to cool the core until three CACS loops are started up. CACS transfer time is most limiting in this case.

Summarizing various cases, the conservative and versatile requirement for the CACS is a 7.46-MW (1000-hp) auxiliary circulator capable of starting within 1 min after the accident.

5.2. ANALYSIS

The objective of the DBDA analysis was to evaluate the auxiliary circulator power that is required to maintain the maximum cladding temperature below the DBDA design limit [1260°C (2300°F)]* for various combinations of

*The design fuel cladding temperature for a faulted condition is being defined; 1260°C (2300°F) is the value consistent with PSID Amendment 7, Appendix B (Ref. 5-3).

the main circulator overspeed, CACS transfer time, and single failure scenarios. Since the maximum cladding temperature developed during the DBDA transient is an output, the auxiliary circulator power is perturbed by changing the maximum torque and the design flow rate in the region of expected values around the temperature limit. From two cases which bracket the desired point, the required auxiliary circulator power was linearly interpolated.

The analytical model used in this study is based on the GCFR core and the component designs in accordance with PSID Amendment 7 except for parameters varied in this study. The GAFTRAN program was used throughout instead of DEPTRN, which was used in the Amendment 7 analyses for the blowdown period. Use of GAFTRAN for the blowdown period is convenient, and its results are in approximate agreement with those obtained by DEPTRN for the blowdown period in conjunction with GAFTRAN for the period of CACS operation (the latter method was used in the Amendment 7 analyses). The system parameter uncertainty margins allowed in Amendment 7 (Ref. 5-3) were also assumed in this study. In addition, the edge channel undercooling effect (Ref. 5-4) was accounted for by allowing a cladding temperature difference of 83°C (150°F) between the assembly edge rod and the typical interior rod. The edge channel temperature defect of 83°C (150°F) was approximately estimated using a new edge channel laminar friction factor (Ref. 5-5) and a new edge rod-to-duct spacing (52% of the rod-to-rod spacing). Accurate calculation of the edge channel effects has been deferred until the revised design parameters of the core and the system are implemented. Since GAFTRAN calculates the thermal response of the maximum cladding temperature of the assembly interior rods, the design limit of 1177°C (2150°F) is imposed on these interior rods to allow for the edge rod temperature defect as described above.

The DBDA core cooling cases in which the main loop cooling is used to bridge CACS startup are shown in the following table. It is noted that the single active failure criterion is applied to the combined system of the main loop cooling system and CACS rather than to each system as was done in PSID Amendment 7.

Central Cavity Break DBDA Cases	Steam Generator Cavity Break DBDA Cases
3 main loops, 0 CACS	2 main loops, 0 CACS
3 main loops, 2 CACS	2 main loops, 2 CACS
2 main loops, 3 CACS	1 main loop, 3 CACS
3 main loops, 3 CACS, isolation valve failure	2 main loops, 3 CACS, isolation valve failure

The cases of steam generator cavity break are more limiting due to a consequential failure allowed in the number of main loops operating. The cases with one isolation valve failure have not been studied since GAFTRAN has not been developed for these cases.

5.3. RESULTS

The GCFR shutdown control system requires that the main circulator-turbine control valve (CTCV) be closed in 3 s and a parallel small CTCV be controlled so as to give steam flow proportional to the decay heat. The steam flow reduction to suit RHR needs results in initial reduction of the circulator speed. As depressurization progresses, the circulator speed increases again owing to a low gas density as shown in Fig. 5-1.

Figures 5-1 and 5-2 illustrate the relationships between the main circulator speed, CACS transfer, and the core temperature response for three example cases. Two main loops are assumed to operate for all the cases. Case A allows 35% circulator overspeed under depressurized conditions, resulting in an adequate core cooling with main loops only, as indicated by Curve A in Fig. 5-2. If an equally adequate CACS replaces the core cooling function at any time in Case A, the cladding temperature will follow Curve

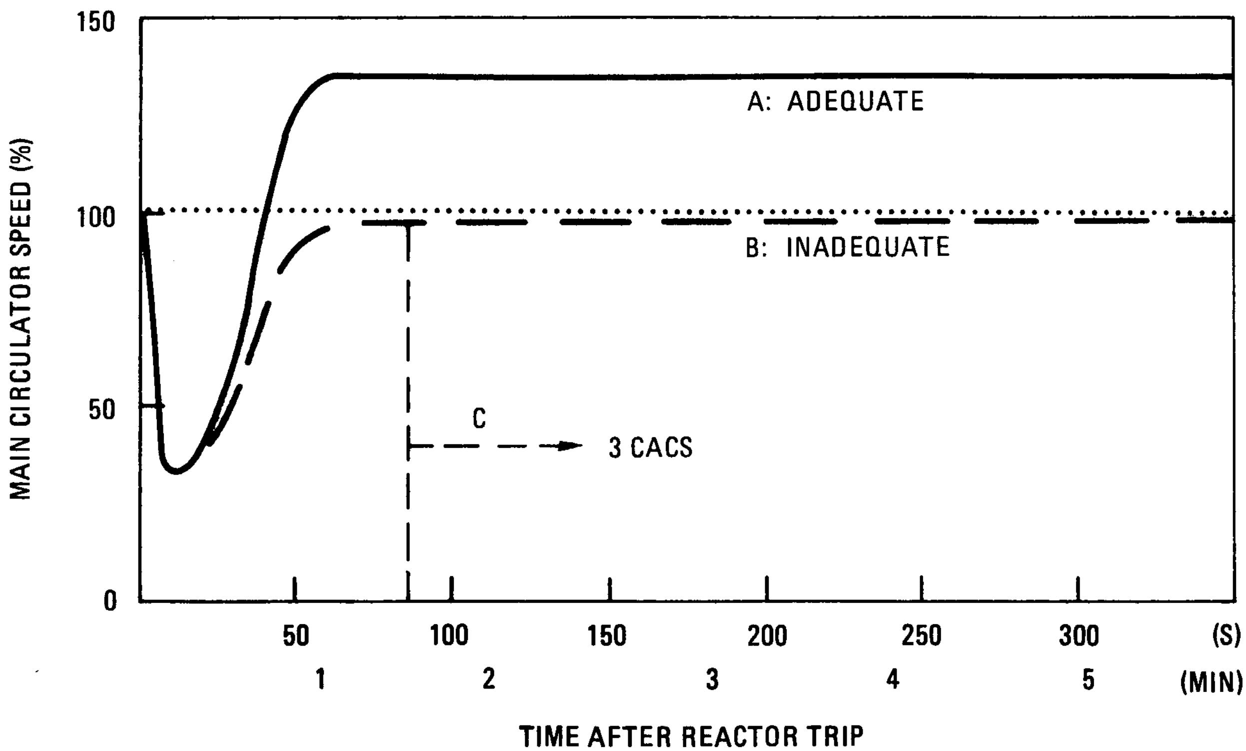

Fig. 5-1. Example cases of DBDA main circulator speeds (two main loops in all cases)

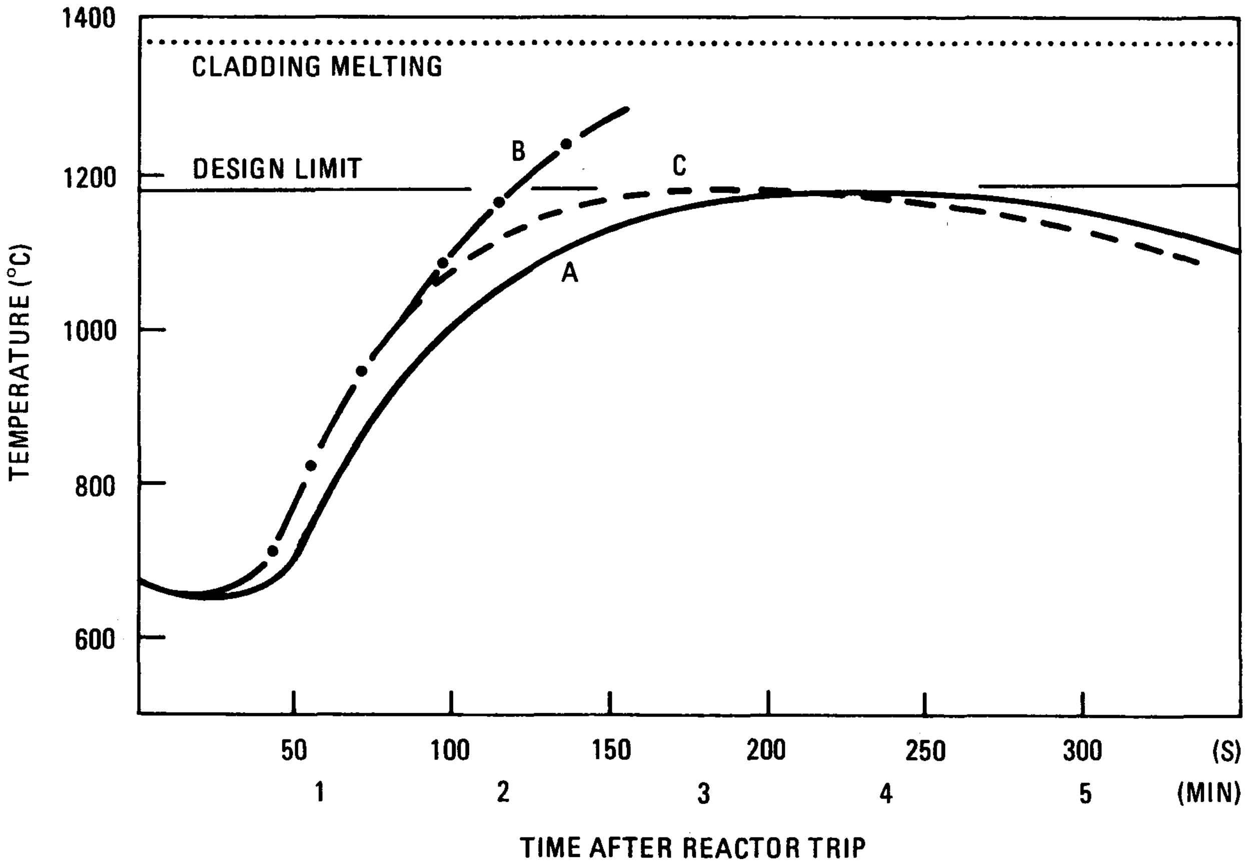

Fig. 5-2. Cladding temperature responses for cases shown in Fig. 5-1

A in Fig. 5-2 and will not exceed the design limit. Therefore, CACS transfer time is unimportant in this case.

In Case B, the main circulator overspeed is not allowed. As a result, the core cooling with main loops is not adequate and the cladding temperature for the corresponding case is shown to exceed the design limit in Fig. 5-2.

In Case C, the inadequate main loop function is replaced by an ample CACS to prevent the cladding temperature escalation. In case of inadequate main loops, the later the transfer occurs, the higher the CACS capability is required to prevent the cladding temperature from exceeding the design limit. If CACS transfer occurs early enough (e.g., 30 s), an inadequacy of the main loops will have no effect on the CACS requirement.

Various other cases of different main loops and CACS capabilities were studied to determine the effect of the transfer time on the auxiliary circulator power required to achieve satisfactory core cooling. The results are plotted in Figs. 5-3 through 5-6. Each point on the curves in these figures indicates the set of conditions which results in the maximum cladding temperature reaching but not exceeding the design limit as indicated by Curves A and C in Fig. 5-2.

Figure 5-3 shows the required auxiliary circulator power as a function of the CACS transfer time for two base cases in which the main loop core cooling is adequate. As indicated in this figure, the required auxiliary circulator power is not sensitive to the transfer time, and the main loop cooling alone can cover the period beyond the time of peak cladding temperature at around 200 s. It is seen that Case A with three main loops and no circulator overspeed requires slightly more auxiliary circulator power than Case B. The performance characteristics of the current main circulator indicate that the circulators would stall at about 100 s if three loops were used with no overspeed. This stall problem should be solved by redesign of

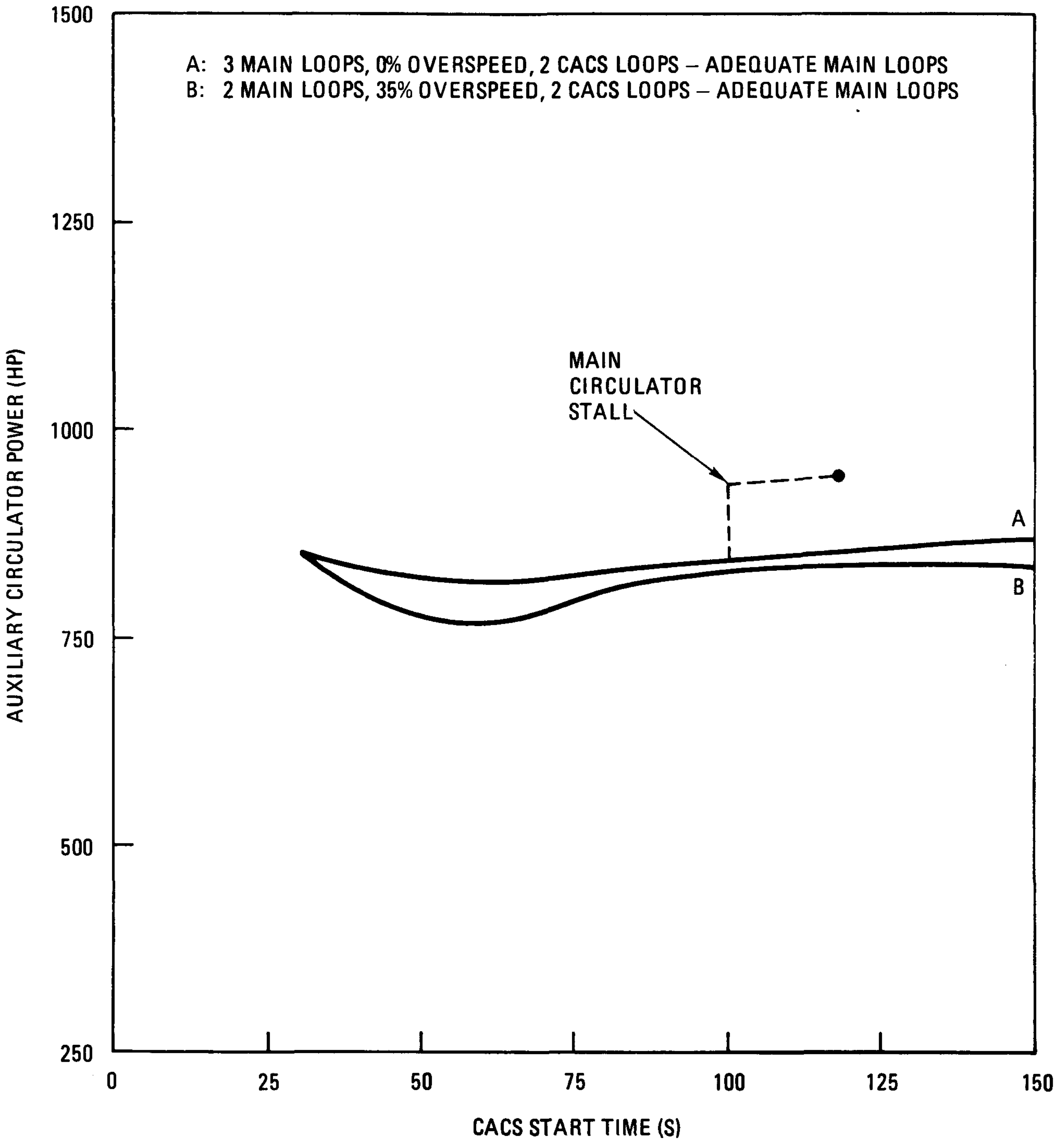

Fig. 5-3. DBDA cooling case study: cases of adequate main cooling loops

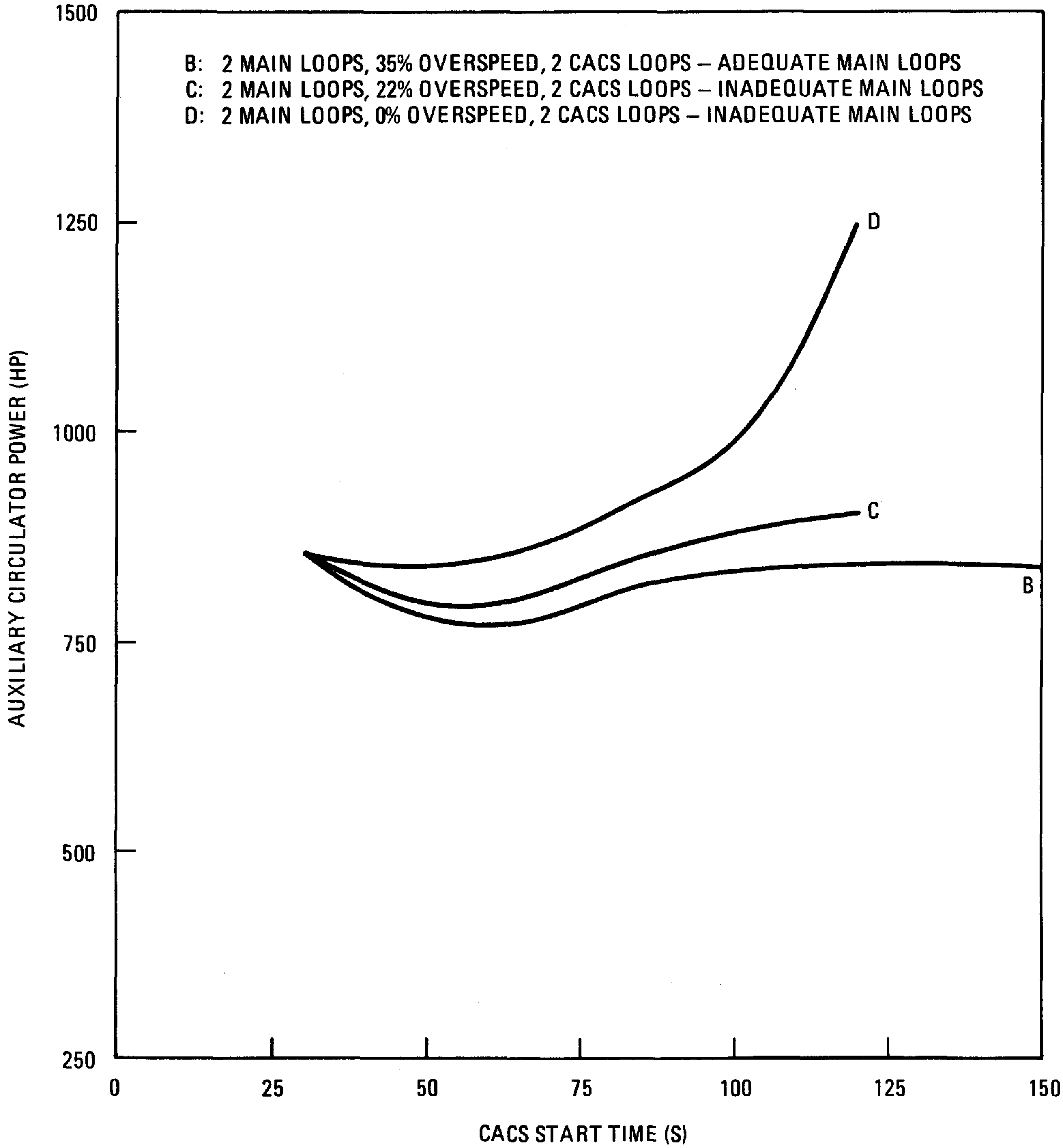

Fig. 5-4. DBDA cooling case study: cases of transfer to two CACS loops

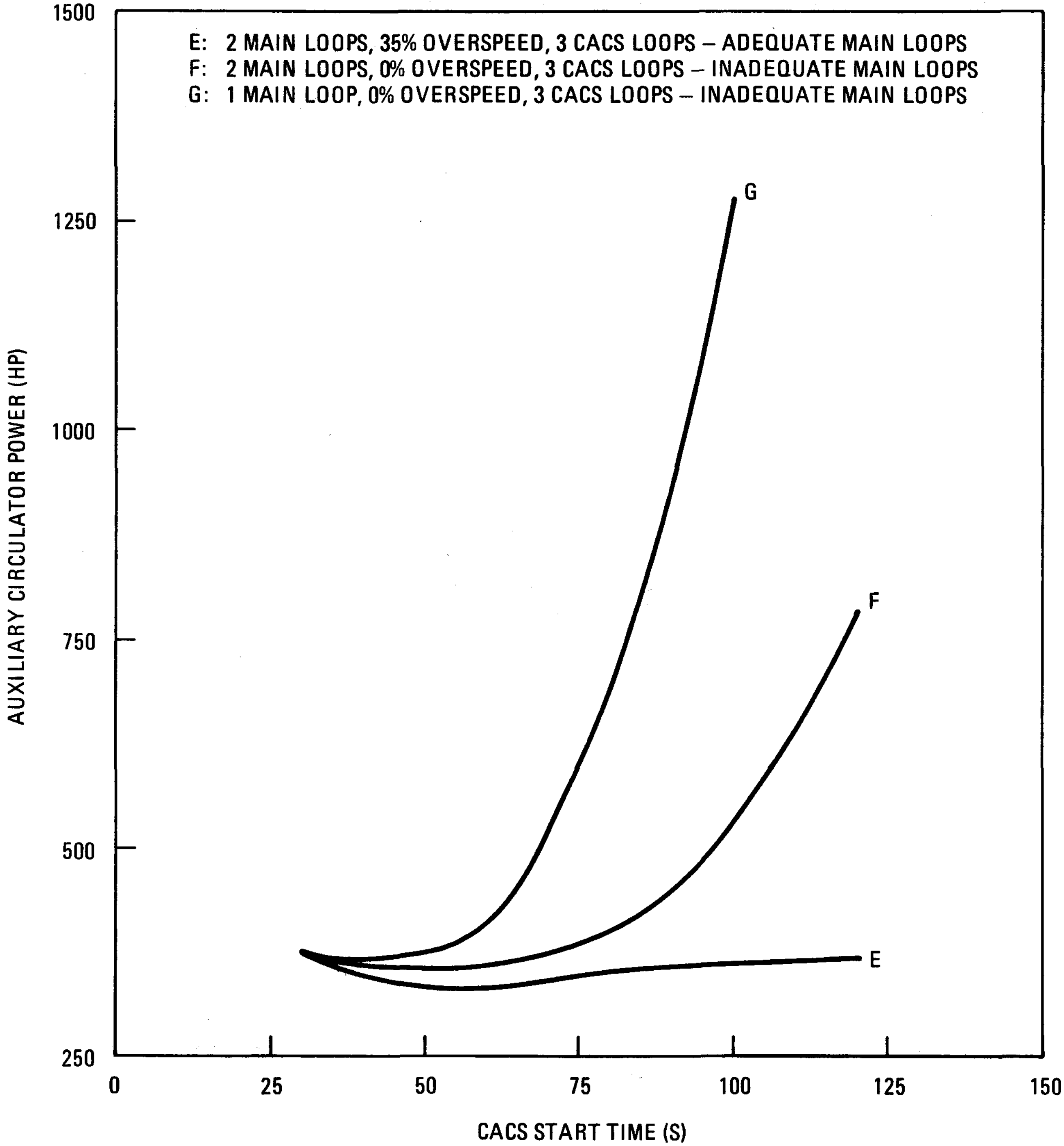

Fig. 5-5. DBDA cooling case study: cases of transfer to three CACS loops

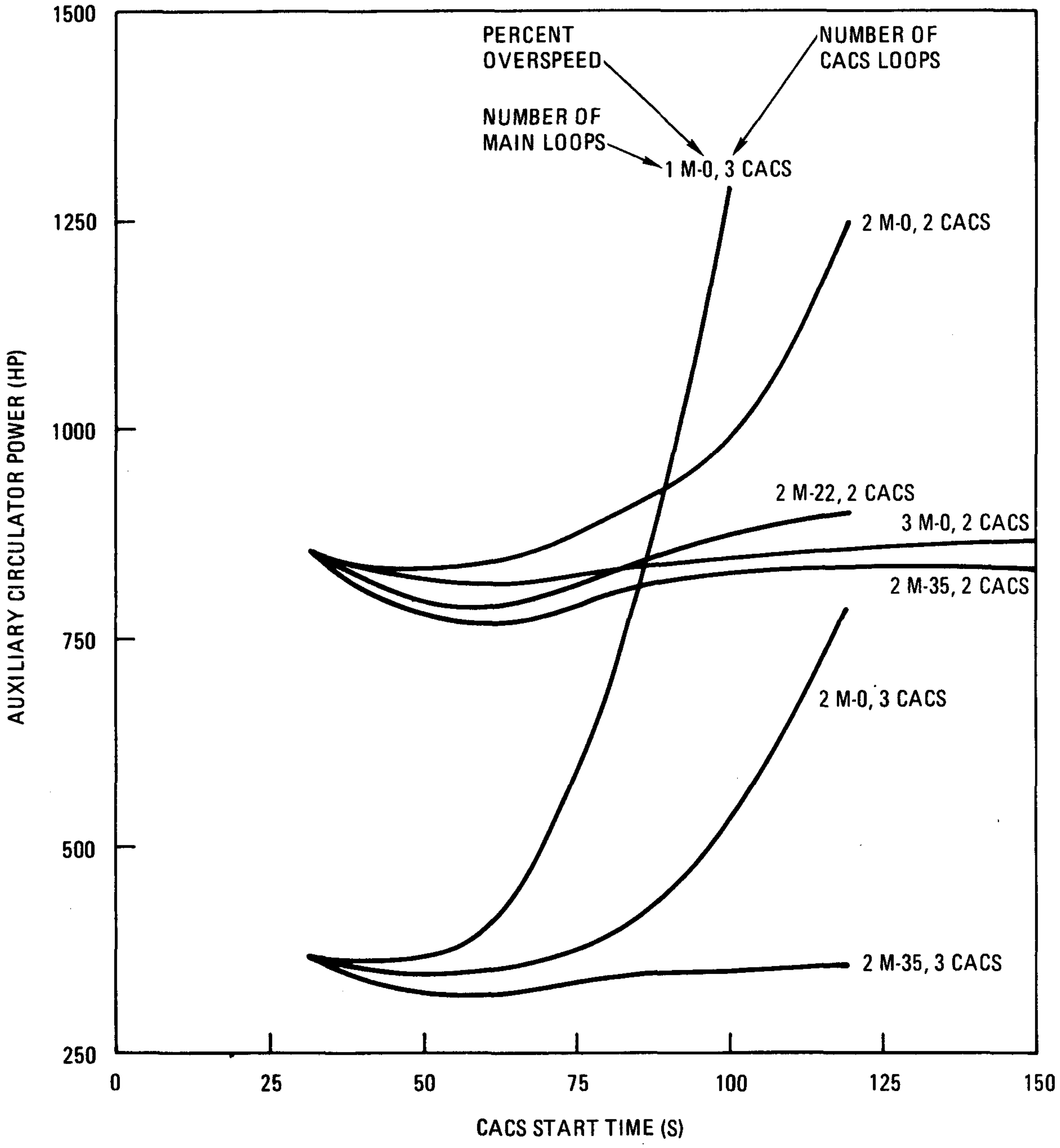

Fig. 5-6. DBDA cooling case study summary

the circulator. Case B has two main loops and a main loop overspeed of 35%, which also gives adequate core cooling with the main loops alone.

Figure 5-4 shows Cases B, C, and D having various degrees of main loop inadequacy. The less adequate the main loop is, the higher the auxiliary circulator power is required after the transfer to compensate for the earlier undercooling. In case of a highly inadequate main cooling, the later the transfer occurs, the higher is the burden for the CACS, as indicated by Curve D.

Figure 5-5 shows similar trends for cases with three CACS loops available. In case of an adequate main loop cooling (Case E), each of the auxiliary circulators requires a low power [280 kW (375 hp)] because three loops are working. With only one main loop available, Case G constitutes a case of grossly inadequate main loop cooling. An early transfer to the CACS is important in this case in order to limit the required auxiliary circulator power within a practical and effective range.

Figure 5-6 summarizes all the cases studied. It appears that a versatile and conservative CACS requirement that would satisfy various cases and allow some margins is a 7.46-MW (1000-hp) auxiliary circulator capable of being started up within 1 min of a DBDA.

REFERENCES

5-1. "Gas-Cooled Fast Breeder Reactor Preliminary Safety Information Document," General Atomic Report GA-10298 Vol. II, February 15, 1971, Fig. 14.8-3.

5-2. "Preapplication Safety Evaluation of the GCFR Project No. 456," USAEC, Directorate of Licensing, August 1, 1974.

5-3. "Gas-Cooled Fast Breeder Reactor Preliminary Safety Information Document," General Atomic Report GA-10298, Amendment 7, Appendix B, February 1976.

5-4. Chung, H., "Thermal Response of Fuel Element Edge Rods Following a Depressurization Accident," General Atomic Company, unpublished data.

5-5. Baxi, C. B., "Heat Transfer Friction Factor and Spacer Loss Coefficients for Bundle Analysis During Laminar Flow," General Atomic Company, unpublished data.

6. CACS DESIGN UNCERTAINTY FACTORS

The design of the CACS loop is based on the results of a detailed analysis which considered the effects of system uncertainties and of air ingress following a depressurization accident.

The system uncertainty factors are discussed in this section. However, effect of air ingress is more closely related to the system responses during the depressurization accident and therefore is discussed in Section 4. A conservative model for the depressurization analysis is defined by incorporating uncertainty margins for the CACS and related systems. The system uncertainty values were obtained primarily from similar studies done for the HTGR and reported in Ref. 6-1. In the conservative model it is assumed that each uncertainty factor is in its most detrimental direction insofar as core cooling is concerned, whereas it would be more technically correct, although less conservative, to combine the independent factors statistically.

6.1. OVERALL CONDUCTANCE OF HEAT EXCHANGERS

The overall conductances (UAs) of the CAHE and the ALC are parameters significantly affecting the heat removal capability of the CACS loop following a depressurization accident. Uncertainties in these quantities are evaluated below for each of the two heat exchangers. Also considered are the methods by which the uncertainties were imposed upon the analytical model to assess their ultimate effect upon the fuel cladding temperatures.

6.1.1. Core Auxiliary Heat Exchanger

The uncertainty in the UA of the CAHE was obtained by directly combining the uncertainties in its unit conductance (U) and in its effective heat transfer surface area (A).

A part of the uncertainty in the conductance (U) was that associated with the calculation of the gas-side convective film coefficients. The same modified Grimison correlations (Ref. 6-2) were used for both the main steam generator and the CAHE, and their applicable uncertainty band is ±10%. The water-side convective film coefficient is much higher than that on the gas side. An additional uncertainty in the conductance results from the 5% design allowance for the fouling of the water-side heat transfer surface of the CAHE by scale deposits (fouling allowance). The heat transfer area will be affected by tube plugging, and a 5% tube plugging design allowance is allowed in the CAHE designs. With the water chemistry specified for the CACWS, it is expected that fouling will not reach the 5% allowed even at the end of plant life. Therefore, the 5% allowance for tube fouling is considered to be conservative. The plugging allowance may be used at any time during the life of the unit. The expected value of UA was chosen as halfway between the minimum and maximum values, because this was considered to best approximate the conditions which would apply over the life of the plant. In the analytical model, the expected value of U was always used, and the combined uncertainties in both U and A were introduced through the effective heat transfer surface area. Thus, the heat transfer areas used in the best estimate and conservative models are 95% and 81% of the installed area, respectively.

6.1.2. Auxiliary Loop Cooler

The ALC transfers heat to the ultimate heat sink, which is air. Its required performance is defined by the loop heat duty and the maximum CAHE water inlet and outlet temperatures, but the actual design is not yet definitely specified at this conceptual stage. The ALC, shown schematically in Fig. 6-1, is a counter cross flow heat exchanger with water on the tube side and air on the shell side. Some descriptive material on the ALC is given in Section 4.7 and Section B.3.4 of Ref. 6-3. In the absence of any firm design information, the uncertainty band in the UA of the ALC was established by making the further assumption that it was equal to that derived above for the CAHE.

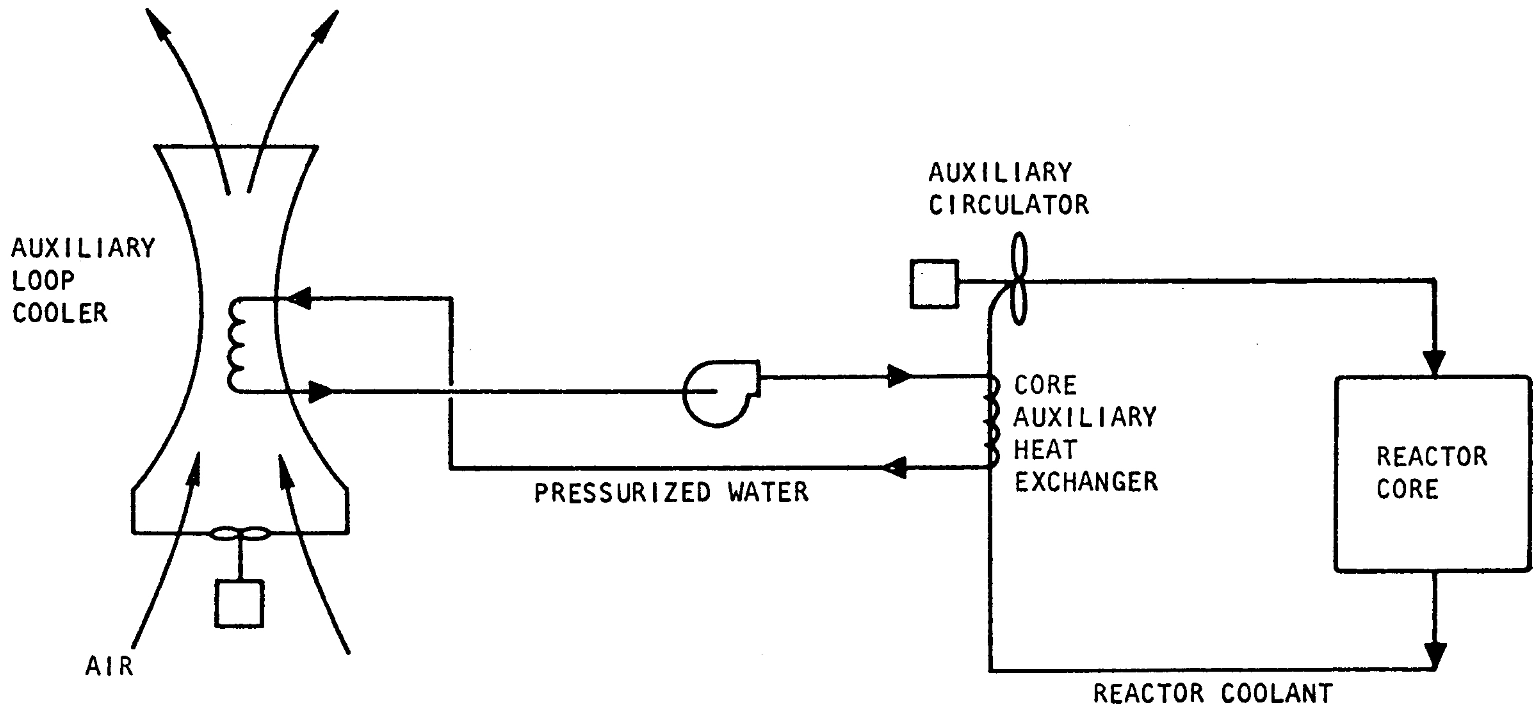

Fig. 6-1. CACS schematic

6.2. OVERALL LOOP PRESSURE DROP

The flow delivered by the auxiliary circulator to cool the core following a depressurization accident is affected by both the speed and torque limitations imposed by the drive motor (Section B.3.4, Ref. 6-3). The circulator torque required depends upon the overall loop pressure drop which must be overcome. Generally, the uncertainty bands were distributed among the various components which comprise the overall pressure drop. A statistical combination of the component pressure drop uncertainties was taken as a ±20% uncertainty in the overall loop pressure drop calculated by the analytical model for the best estimate.

6.3. DECAY HEAT

An uncertainty band on decay heat rates of ±20% for the first 1000 s after reactor trip was applied to the expected decay heat function, as recommended by the ANS-5 subcommittee (Refs. 6-4, 6-5). This same factor was also applied to the breeding product heating rates. The function and the coefficients for the fission and breeding product decay heats are described in Section B.3.2 of Ref. 6-3.

6.4. NUCLEAR POWER

The nuclear power uncertainty was assumed to be ±5% in predicting the local power, in accordance with current practice in the thermal reactor industry. The accuracy of calculation of local core power in the GCFR is expected to be higher than for a thermal reactor because in the hard neutron spectrum of the GCFR, the core is neutronically very homogeneous. For the same reason, flux shifts due to fission product buildup are not expected to occur in the GCFR.

6.5. THERMOPHYSICAL PROPERTIES OF PRIMARY COOLANT

The uncertainty associated with the thermophysical properties of the primary coolant gas is attributed to two sources. One is the measurement techniques used in generating the property values. The other is the method used in combining constituent properties when a mixture of gases is involved.

The heat capacity of gases is accurately derived from reliable pressure-volume-temperature data with certainty to within a few tenths of a percent (Refs. 6-6, 6-7).

The coolant transport properties and the thermal conductivity and viscosity values are more difficult to measure. Although conductivity and viscosity data presented in the literature exhibit some scatter, the mean of these data represents the actual properties with little uncertainty. For conservatism, however, an uncertainty band equivalent to the total data scatter observed in the literature was applied. A comprehensive review of thermal conductivity and viscosity data (Refs. 6-6, 6-7) indicates a maximum deviation in thermal conductivity of 5% and in viscosity data of 3%. These dispersions were independently applied.

The thermophysical properties of the gas mixture present under air ingress conditions were derived from the individual constituent properties as described in Section B.3.2 of Ref 6-3. No uncertainty was allowed for the method used in combining the constituent properties, since the overall CACS core cooling capability was found to be rather insensitive to air ingress.

6.6. CORE BYPASS FLOW

The bypass flows through the various seals within the coolant circuit and through the non-operating main and auxiliary loops are parasitic with regard to CACS performance, since they remove no heat from the core. The core bypass flow fraction is assumed to be 1% of the auxiliary circulator output for the best estimate model. The bypass flow fraction will be determined more accurately as more detailed component design and test data become available. For the conservative model, the core bypass flow fraction is assumed to be 2% of the auxiliary circulator output.

6.7. CONTAINMENT BACKPRESSURE

The containment backpressure during the critical period (<3 min) after the depressurization accident is significantly higher than the final equilibrium pressure, which is 0.172 MPa [25 psia (11.3 psig)] (Ref. 6-2). However, no credit is taken for the improved cooling this would provide, and the best estimate model conservatively assumes the reactor coolant to be at the equilibrium containment backpressure once the blowdown phase is complete. Furthermore, the conservative model assumes 90% of the best estimate containment absolute equilibrium backpressure to provide margin for either uncertainty in the containment void volume estimation or for a possible delay in actuation of the containment isolation valves. This 10% reduction in the absolute pressure represents a 23% reduction in the gauge (or helium partial) pressure.

The specific effect of the backpressure on the maximum cladding temperature is examined for the total range of uncertainties including the atmospheric backpressure in Section B.2.3.3 of the PSID, Amendment 7.

6.8. EFFECTS OF SYSTEM UNCERTAINTIES

The system uncertainty factors discussed above are summarized in Table 6-1. The conservative and the best estimate models are defined by multiplying the respective parameters by these factors. As described earlier, the conservative analyses reported in the PSID, Amendment 7 assume each of these uncertainties to act in its worst way, whereas it would be more realistic to combine the effects statistically.

TABLE 6-1
SYSTEM UNCERTAINTY FACTORS USED FOR BEST
ESTIMATE AND CONSERVATIVE MODELS

Parameter	Best Estimate Model	Conservative Model
Decay heat	1.0	1.2
Local power uncertainty	1.0	1.05
Overall conductance of CACS heat exchangers (CAHE and ALC)	1.0	0.85
Loop pressure drop	1.0	1.2
Coolant thermal conductivity	1.0	0.95
Coolant viscosity	1.0	1.03
Containment absolute backpressure	1.0	0.9
Core bypass flow fraction	0.01	0.02

REFERENCES

6-1. Malek, G. J., et al., "Back-Pressure for CACS Core Cooling," General Atomic Report GA-A13325 (GA-LTR-19), March 7, 1975.

6-2. Grimison, E. D., "Correlation and Utilization of New Data on Flow Resistance and Heat Transfer for Cross Flow of Gases Over Tube Banks," Trans. ASME 59, 583 (1937).

6-3. "Gas-Cooled Fast Breeder Reactor Preliminary Safety Information Document," General Atomic Report GA-10298, Amendment 7, February 1976.

6-4. Shure, K., "Fission Product Decay Energy," USAEC Report WAPD-BT-24, Westinghouse Atomic Power Division, 1961.

6-5. "Proposed ANS Standard Decay Heat Release Rates Following Shut-down of Uranium Fueled Thermal Reactors" ANS-5.1, American Nuclear Society Standards Committee, 1971.

6-6. Hilsentath, J., and Y. S. Touloukian, "The Viscosity, Thermal Conductivity and Prandtl Number of Air, O_2, N_2, NO, H_2, CO, CO_2, H_2O, He and A," Trans. ASME 76, 967 (1954).

6-7. Goodman, J., et al., "The Thermodynamic and Transport Properties of Helium," General Atomic Report GA-A13400, March 1975.

7. AUXILIARY CIRCULATORS

The auxiliary circulators are part of the auxiliary core cooling system and provide helium flow for decay heat removal. Three circulators are provided, any two of which can supply the necessary flow in the most severe operating condition. Each auxiliary circulator unit will consist of an electric-motor-driven centrifugal compressor and diffuser. The auxiliary circulators are to be operable at all pressure levels from full helium inventory down to refueling (depressurized) status.

Normal use of the auxiliary circulators will be during the following conditions:

1. Plant shutdown,

2. Refueling (approximately atmospheric pressure),

3. Functional checkout (reactor at full load, auxiliary loop isolation valve closed).

The design basis for the auxiliary circulators is principally determined by the reactor shutdown cooling requirement that occurs in the design events during accidental depressurization (Section 2.3.4) and by design parameters, as discussed in Section 4. Because of the wide range of required operating conditions, the electric motor drives will be capable of variable speeds, and each motor will be operated by an independent control system and will be supplied from an essential bus.

7.1. DESIGN AND PERFORMANCE REQUIREMENTS

The design of each auxiliary cooling loop is based upon the results of detailed depressurization accident analyses which considered the effects of system uncertainties and of air ingress. The circulator design parameters for these conditions are shown in Table 7-1. The design life and duty cycle requirement is discussed in Section 3.6.9.

The auxiliary circulators shall be capable of startup or shutdown with the auxiliary loop isolation valve closed and at reactor helium operating pressure and temperature conditions. This will provide for functional checkout with the main circulators operating in addition to the normal startup and shutdown sequence.

The circulators shall be capable of operating throughout the operating speed range without flow instability or surge. The critical speed of the rotor shall be at least 40% above the maximum operating speed, and the natural frequencies of the compressor blades shall be at least 40% above the excitation frequencies throughout the operating speed range.

The normal speed control of the circulators shall be by means of the variable-frequency power available to the drive motor. The control system and power supply for each circulator shall be independent of the others. Each circulator shall be driven by its own power supply and shall be controlled through its own control system. The motor shall be capable of restarting following any voltage interruption.

The single failure criterion shall be met in that failure in any one control system or power supply will not cause a failure or inhibit operation of the other auxiliary cooling loop systems.

Power supplies, service systems, and related equipment shall be located either in the reactor containment building or in the reactor service building.

Each auxiliary circulator shall be equipped with a lubrication system for the bearings, a cooling system for the lubrication system and motor stator, and a buffer gas system as required to meet the performance and environmental conditions.

TABLE 7-1
AUXILIARY HELIUM CIRCULATOR DESIGN DATA

	Depressurized Primary System	Pressurized Primary System
Type	Centrifugal	Centrifugal
Drive	Electric	Electric
Fluid	Helium/air	Helium
Speed, rpm	3600	640
Inlet temperature, °C (°F)	221 (430)	341 (645)
Inlet pressure, MPa (psia)	0.1744 (25.3)	8.8256 (1280)
Outlet pressure, MPa (psia)	0.1896 (27.5)	8.8270 (1280.2)
Mass flow, kg/s (lb/sec)	9.12 (20.1)	14.74 (32.5)
Efficiency, %	80	
Tip diameter, d_2, m (in.)	1.344 (52.9)	
Tip width, w, m (in.)	0.088 (3.47)	
Eye diameter, d_{1s}, m (in.)	0.767 (30.2)	
Hub diameter, d_{1h}, m (in.)	0.305 (12)	
Power, kW (hp)	794 (1064.8)	2.98 (4.0)

The circulators shall be provided with a service system to deliver the required supply of cooling media for the circulator motor and lubricating oil system together with buffer gas. The service system shall be designed on an independent module basis with respect to motor stator and lubricating oil cooling. The buffer helium compression, purification, and distribution sections of the system shall be designed as an integrated centralized facility which is common to all three auxiliary circulators.

The entire circulator unit and its control system shall be functionally tested to verify their operability with the reactor plant under full load and with the three main cooling loops in operation.

7.2. DESIGN DESCRIPTION

The general arrangement of the auxiliary circulator mounting and primary closure is shown in Fig. 7-1. The primary closure consists of an outer ring that is bolted to a thermal sleeve formed in the upper section of each of the three auxiliary loop PCRV penetration liners and the upper bell casing of the circulator, which forms the major part of the primary closure.

The outer ring that is bolted to the penetration incorporates a double concentric O-ring seal and an array of water tubes entering and leaving the auxiliary heat exchangers located below the circulator and diffuser.

The circulator is placed above the auxiliary heat exchanger. The diffuser and other helium ducting are installed so that the helium travels from the outlet of the heat exchanger and through the circulator compressor and then exits horizontally into the core inlet duct. A loop isolation valve is installed in the cold helium side, upstream of the circulator inlet duct to prevent backflow when the associated circulator is shut down.

The drive motor bell housing is bolted to the outer closure ring and also incorporates a double concentric O-ring seal. The interspace between both seals is pressurized with clean helium at 34.47 kPa (~5 psia) above the

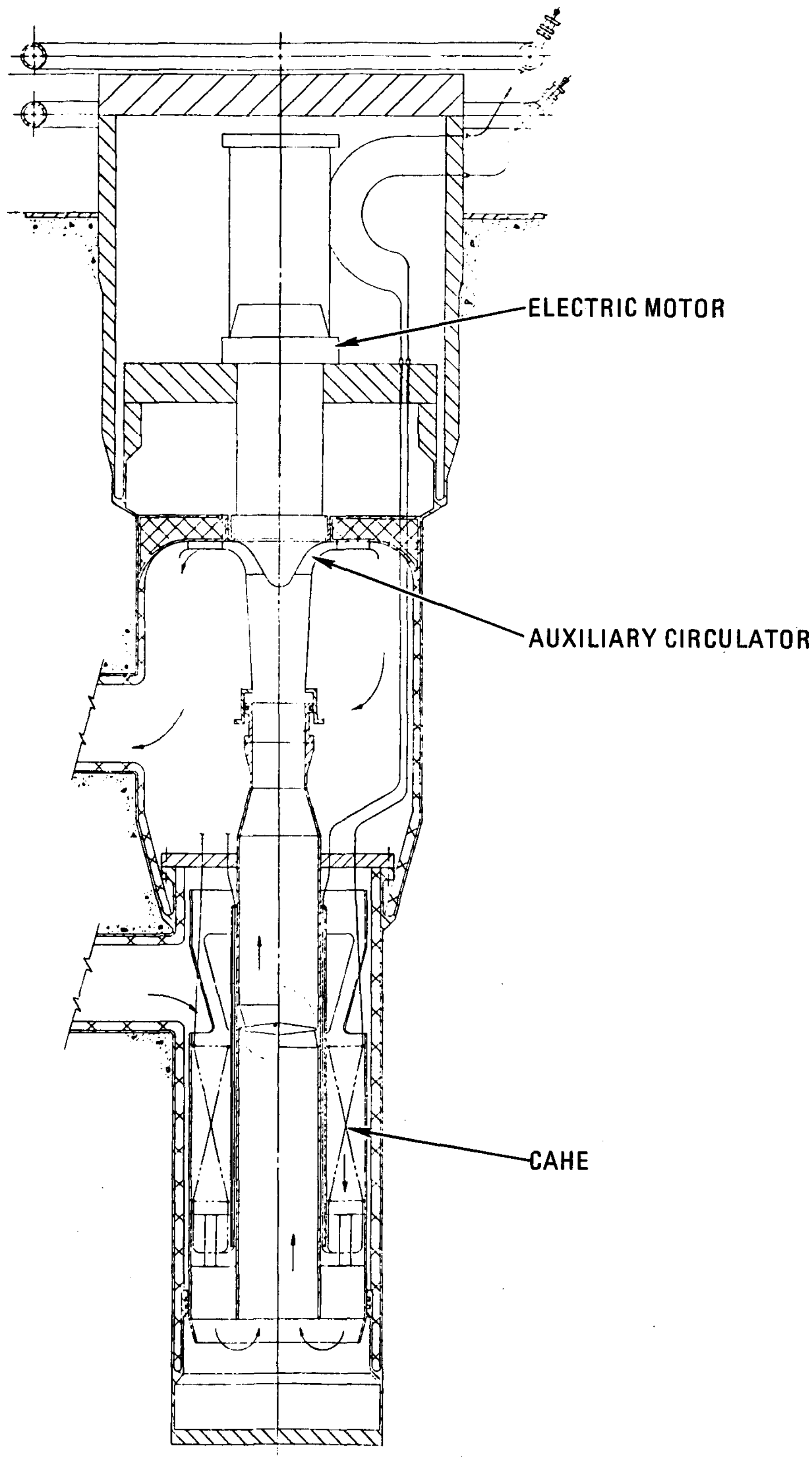

Fig. 7-1. CACS assembly

reactor coolant pressure. The double seal also permits the seals to be tested at any time during the life of the reactor without disturbing the closure. Penetrations in the motor bell housing are for piping for cooling water, motor windings and bearings, return helium supply, and electrical connections.

Thermal insulation is provided on the underside of the closure, and provision is made to remove the circulator without disturbing the auxiliary heat exchanger and its piping or the diffuser and isolation valve.

A flow restrictor, which consists of a thick steel plate, is installed above the primary closure. This restrictor is supported in the penetration liner and is held in place by a split ring. Holes are provided in the plate for piping and other circulator services to pass through. The flow restrictor will ensure that in the event of a failure of the primary seal, structure, or holddown, the flow area in and around the restrictor plate will not exceed the area compatible with acceptable depressurization rates. In addition, the plate will form a missile protection device against any fragments from a failure of the primary closure.

A structure extends down from the primary closure to support the diffuser ring surrounding the compressor. This ring serves the dual purpose of providing a diffuser and incorporating a missile protective buffer for both the inlet and outlet water pipes for the auxiliary heat exchanger and the penetration liner.

7.3. DESIGN EVALUATION

An electric motor drive is provided for the auxiliary circulators as a different motive source from the steam turbine drive used on the circulators for the main loops. The design of the auxiliary circulators is based on well-established technology. Because of its fundamental simplicity, the electric-motor-driven centrifugal compressor of moderate size and power does not pose any particular new problems or require development.

Three circulators are provided where two are adequate to meet the most severe performance requirements in the event of a depressurization accident. Each circulator is self-contained, and failure of one cannot cause failure in the other units. The service systems will be based on the modular concepts for each unit for essential services.

Electric power for the motor may be obtained from either the normal or the emergency power sources. Availability of the auxiliary circulators can be assured in the time available in the event of main loop loss.

The closure design is in accordance with the ASME nuclear code, as is the flow restrictor. A qualification and testing program will be carried out on the auxiliary circulators and drives.

8. CORE AUXILIARY HEAT EXCHANGER (CAHE) DESIGN

The purpose of the auxiliary heat exchangers is to remove heat from the reactor helium coolant when the main cooling loops are shut down or unavailable for this purpose. Helium at high temperature leaves the bottom of the core and enters the bottom end of the heat exchanger. It flows vertically upward through the heat exchanger, where heat is transferred to the cooling water inside the tubes (Fig. 7-1). Cooled helium leaving the top of the heat exchanger enters the auxiliary circulator and is circulated through the core to repeat the cycle.

8.1. DESIGN AND OPERATING REQUIREMENTS

The auxiliary heat exchanger must provide cooling for both pressurized and depressurized cooldown conditions. The design is based on the pressurized condition, unlike the auxiliary circulator, which is designed for maximum power and speed under depressurization accident conditions as described in Section 7. Design parameters for the heat exchanger are summarized in Table 8-1. The heat removal capacity of each loop provided by this design is consistent with the CACS design parameters discussed in Section 4.

Boiling in the auxiliary heat exchangers shall be prevented by maintaining the water under a pressure sufficient to assure approximately 17°C (30°F) subcooling at the maximum expected operation temperature.

Safety relief valves shall be provided for the auxiliary heat exchangers to protect them from overpressurization when a heat exchanger is isolated on the water side.

TABLE 8-1
DESIGN DATA FOR CAHE

	Pressurized Cooldown	DBDA	Standby
Helium Frontal Area, m^2 (ft^2)	3.08 (33.18)	3.08 (33.18)	
Heat Duty, MW (Btu/hr)	20.1 (68.7×10^6)	16.21 (55.3×10^6)	0.557 (1.9×10^6)
Logarithmic Mean Temperature Difference, °C (°F)	176 (349)	261 (501)	
Overall Heat Transfer Coefficient, W (Btu/hr-ft^2-°F)	24.06 (82.1)	13.48 (46.0)	
Heat Transfer Area, m^2 (ft^2)	222.96 (2400)	222.96 (2400)	
Helium Side			
Flow rate kg/s (lb/hr)	14.7 (117,000)	9.07 (72,000)	1.13 (9,000)
Inlet temperature, °C (°F)	604 (1120)	832 (1530)	316 (600)[a]
Outlet temperature, °C (°F)	342 (647)	218 (424)	221 (430)
Average pressure, MPa (psia)	8.8256 (1280)	0.1793 (26)	
Pressure drop, kPa (psi)	0.1379 (0.02)	1.172 (0.17)	
Water Side			
Flow rate, kg/s (lb/hr)	75.9 (602,300)	75.9 (602,300)	2.39 (19,000)
Inlet temperature, °C (°F)	234 (454)	132 (270)	149 (300)
Outlet temperature, °C (°F)	289 (550)	182 (359)	204 (400)
Average pressure, MPa (psia)	8.9632 (1300)	8.9632 (1300)	
Pressure drop, MPa (psi)	0.2365 (34.3)	0.2068 (30.0)	

[a] Helium gas reverse flow.

TABLE 8-1 (Continued)

	Pressurized Cooldown	DBDA	Standby
Tube			
Number of tubes	50	50	
Tube size, m (in.)	0.0318 x 0.0034 (1.25 x 0.135)	0.0318 x 0.0034 (1.25 x 0.135)	
Tube length, m (ft)	44.71 (146.7)	44.71 (146.7)	
Longitudinal tube pitch, m (in.)	0.0508 (2.0)	0.0508 (2.0)	
Transverse tube pitch, m (in.)	0.0508 (2.00)	0.0508 (2.00)	
Tube bundle height, m (ft)	0.1560 (6.14)	0.1560 (6.14)	

Conditions in the auxiliary heat exchangers and heat dump systems shall be maintained such as to reduce thermal transients on auxiliary loop startup and to minimize parasitic heat losses to the loops while maintaining flow stability.

During reactor refueling, the reactor coolant pressure is essentially atmospheric.

The design life of the heat exchangers is based on a 30-yr plant life, during which the heat exchangers are subjected to a variety of operating conditions in addition to the particular service conditions for which they are rated.

The heat exchangers shall be designed so that they will not be damaged or caused to malfunction either by internally generated vibrations, such as flow-induced vibrations, or by environmental vibrations.

8.2. DESCRIPTION

Each auxiliary heat exchanger, together with an auxiliary circulator and isolation valve, is located in a PCRV penetration.

The auxiliary loop coolant is pressurized water. Each heat exchanger is a helically wound, axial-flow tube bundle with an integral shroud. The tube bundle is about 1.98 m (6.5 ft) in outside diameter and 1.83 m (6 ft) long and is made of carbon or low-alloy steel. Inlet water enters from the top of the heat exchanger tube bundle and flows downward, crossing the upward flow of helium. The outlet tube ends are routed through the inner shroud and return to the top of the cavity. A drawing of an auxiliary heat exchanger installed in a PCRV cavity is shown in Fig. 7-1.

The helium flow path from the core through the auxiliary cooling loop cavities is similar to that through the main cooling loop cavities, except that there are no flow reversals and the helium passes directly upward across the tube bundle. The water supply to and from the auxiliary heat exchanger is connected to the auxiliary cooling heat dump system located outside the containment building. During normal reactor plant operation, there is a small leakage of helium from the core inlet plenum through the closed auxiliary loop isolation valves. A small flow of cooling water through the heat exchangers maintains the auxiliary cooling loops at close to the cold helium temperature. This reduces thermal transients on loop startup and minimizes parasitic heat losses. During use for shutdown cooling, the design inlet water temperature is 132°C (270°F) and the outlet water temperature to the heat dump system is 182°C (359°F) (Section 4).

Wear protection is provided on the heat transfer tubes at contact points between the tubes and tube supports. The tubes are free to move through the tube supports as thermal expansion occurs. Tube surfaces will be protected with a hard facing, such as chromium carbide, at support locations to preclude tube damage and to facilitate the relative motion between the two surfaces. The corresponding surfaces of the tube supports will not be coated because the degree of wear over the 30-yr life is expected to be negligible.

The support structure for the tube bundle is suspended from the primary closure at the upper end of the auxiliary loop cavity. The closure ring incorporates thermal sleeves to accommodate the individual inlet and outlet water tubes. The inlet and outlet tubes that extend outside the primary closure pass through a closure flow restrictor plate and are then collected into their respective ring headers or tubesheets, in which access for tube plugging is provided. Connection from the header or tubesheets is then made to the inlet and outlet lines of the water supply and heat dump system. The inlet and outlet ends of the tubes in the heat transfer bundle are grouped together into headers outside the flow restrictor plate. Pipes from each of the inlet and outlet headers are routed to the auxiliary heat dump system located outside the containment building. Each inlet header pipe includes a remotely actuated shutoff valve located outside the PCRV upstream of the supply ring header. Check valves are included in each pipe upstream of the return ring header.

8.3. DESIGN EVALUATION

The auxiliary heat exchanger is conventional with regard to design, material, and duty and presents no difficult problems.

The minimum thickness of all pressure-containing parts will be determined in accordance with the applicable portions of Section 3 of the ASME Code and the Nuclear Power Piping Code, USAS B 31.7. The design is determined from the conditions given in Table 8-1. The controlling design conditions are established based on the most severe coincidental conditions of temperatures and differential pressures. All pressure parts categorized as Class A will be analyzed in accordance with the requirements of Section 3 of the ASME Code. Stresses produced by earthquake loadings will be analyzed according to the requirements delineated in Section 3 of the ASME Code. Parts classified as part of the heat exchanger piping (external to the primary system) will be designed and analyzed in compliance with the Nuclear Power Piping Code, USAS B 31.7. Load-carrying support structures classified as non-code parts will be analyzed in a manner similar to code parts using Section 3 of the ASME Code as a guide to ensure their structural adequacy for a 30-yr life.

Since the auxiliary heat removal loops may be used for cooldown under emergency conditions, the heat exchangers will be analyzed as if the plant emergency were a normal operating transient imposed on them (Section 13).

With the cooling water supply entering the PCRV divided among numerous separate pipes, the water inleakage resulting from a rupture of a single cooling water supply line is inherently limited. Outlet cooling water lines will have check valves to prevent continued leakage from the outlet end of the ruptured line. In order to limit the total water leakage from a tube rupture, moisture detectors located in each auxiliary loop, which are similar to those in the main loops, produce an automatic isolation signal for the auxiliary loop.

All unsupported lengths of pipes and tubing will be analyzed to determine their vibration characteristics. Measures will be incorporated to prevent undesirable and/or damaging vibrations or amplitudes thereof from occurring as a result of the various excitations that might be present.

Dynamic flow stability problems do not exist in the auxiliary heat exchangers, since no boiling occurs.

9. ALTERNATE DRIVE AND CONTROL SYSTEM FOR AUXILIARY CIRCULATORS*

The auxiliary circulator drive and control system for the GCFR 300-MW(e) Demonstration Plant (Refs. 9-1, 9-2) is similar to that used in the large HTGR. The motor is a squirrel-cage induction motor supplied with variable frequency power by an independent control system for each circulator. Each circulator control system is connected to the essential power buses, which have multiple sources of power including a standby diesel generator. The circulator motor is contained within the primary coolant envelope and is protected from excess temperature by thermal insulation and cooling water supplied by the auxiliary circulator service system.

In this section, alternative drive and control system design concepts that differ from the system discussed earlier will be investigated. The requirements for the drive are based on PSID Amendment 7 (Ref. 9-2). They include accelerating the motor to 4900 rpm in less than 85 s following a depressurization accident and operating at that speed with an output of 1000 hp. One of the important requirements is that the drive must have the potential of being scaled up to 3000 to 5000 hp for a future commercial-size

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* For Sections 9 and 10, which are based on subcontractor reports, the following conversion factors should be used to convert into SI units:

1 hp = 745.7 W

1 psi = 6894.757 Pa

1 lb = 0.4536 kg

1 in. = 0.254 m

1 gpm = 6.309×10^{-5} m^3/s

1 ft^3 = 0.0283 m^3

1 Btu/hr = 0.2931 W

1°C = (1°F - 32) 1.8

GCFR plant. The low-speed requirement for the motor is about 4 hp at 300 rpm for operation during reactor shutdown with full reactor coolant pressure, thus imposing a 50:1 speed range requirement for both depressurized and pressurized cooldown operating conditions. The drive and control system must be designed to meet the safety Class I qualification and must also operate through seismic disturbances, power failures, and other design basis events listed in Table 2-1. A summary of the requirements is given in Table 9-1.

Twelve alternate auxiliary circulator drive system design concepts were established: five electric motor drives, one gas drive, two hydraulic drives, and four steam turbine drives.

9.1. ELECTRICAL DRIVE SYSTEMS

9.1.1. Frequency-Controlled a.c. Induction Motor Drive (Fig. 9-1, SK-6440-77-434)

The frequency-controlled a.c. induction motor drive is the reference case for this study. It is the system that was to be employed for the HTGR auxiliary circulators. The system employs a rectifier-inverter combination to convert 60-Hz supply power to variable frequency power for the motor. The motor runs within a few percent of the synchronous speed determined by the excitation frequency. This decrement below synchronous speed, the slip, increases with load.

The motor is a squirrel-cage induction motor and therefore has no slip rings, commutator, or brushes. Of the variety of electric motors, it is best suited for installation inside the PCRV.

The controller is a "d.c. link system." The d.c. link between the rectifier and inverter is at a nearly constant d.c. voltage and therefore can be connected to a backup battery system. This combination of components forms what is commonly known as an uninterruptible power supply. Such

TABLE 9-1

GCFR AUXILIARY CIRCULATOR ALTERNATE DRIVE AND CONTROL SYSTEM REQUIREMENTS

Requirements

1. Horsepower at maximum speed: 1000 hp.
2. Maximum speed: 4900 rpm.
3. Continuously variable speed range: 100 to 4900 rpm.
4. Maximum torque required at 2500 to 4900 rpm: 1050 ft-lb.
5. Output power at 300 rpm: 4.0 hp to be achieved within 30 s after startup.
6. Startup time to 4900 rpm: 85 s (maximum).
7. Total life: 30 yr.
8. Qualification as Class I equipment per IEEE Standards 323 and 334 as applicable to provide assurance that such equipment will meet or exceed its performance requirements throughout its installed life.
9. Duty cycle
    9.1. Faulted Condition: Full power and full speed for 10 min, reducing to approximately 50% power after 1 day. This condition to occur once in lifetime of drive.
    9.2. Emergency Condition: 300 rpm, 4.0 hp with speed decreasing to 100 rpm similar to pattern of Faulted Condition.
    9.3. Normal Operations: 1000 hr continuous operation at varying loads with averages of 50% torque and 50% speed, once a year (during refueling).
10. Speed regulation

    1000 to 4900 rpm ± 4% of set speed.

    100 to 400 rpm ± 10% of set speed.
11. Environment
    11.1. Drive

        Option E1: Drive inside pressure vessel.

        a. Helium atmosphere at 650°F and 1250 psi.
        b. Radiation rate of 100 rads/hr with a total integrated dose of 2×10^8 rads.

TABLE 9-1 (Continued)

c. Nominal 45-in. diameter.

d. Vertical operation

Option E2: Drive outside pressure vessel coupled to circulator by means of a sealed shaft. Normal industrial type environment except during accident conditions when conditions similar to those described in IEEE STD 323, Appendix B, may prevail.

11.2. Controller: For both Options E1 and E2, the controller is in a normal industrial type environment, as noted in Option E2.

12. Seismic loads: Drive and controller are to operate during seismic disturbances as follows:

12.1. Without damage:

Horizontal load = 2.4 g.

Vertical load = 1.6 g.

12.2. Without loss of function:

Horizontal load = 4.0 g.

Vertical load = 3.0 g.

12.3. Disturbance frequency range:

0.125 to 50 cps.

IEEE STD 344 shall serve as a guide for seismic considerations.

13. Input: 4 - 20 mA speed control signal.

14. Power input (for electric drive): up to 4160 V, three phase, 60 Hz, and 250 V d.c.

15. Single direction operation only.

16. Normal protective and detection features required, including protection for:

16.1. Overloads.

16.2. Any reverse motion.

17. Normal speed controller signal compensation circuits and limits required.

TABLE 9-1 (Continued)

Options

1. Power and torque 115% of nominal values at maximum speed of 4900 rpm.
2. Power and torque 130% at 4900 rpm.

Information Requested From Suppliers

1. Estimated price for base unit and options for quantity of three units of each size.
2. Outline drawings.
3. Availability.
4. Exceptions.
5. Power and/or fuel requirements.
6. Cooling requirements.
7. Failure modes.

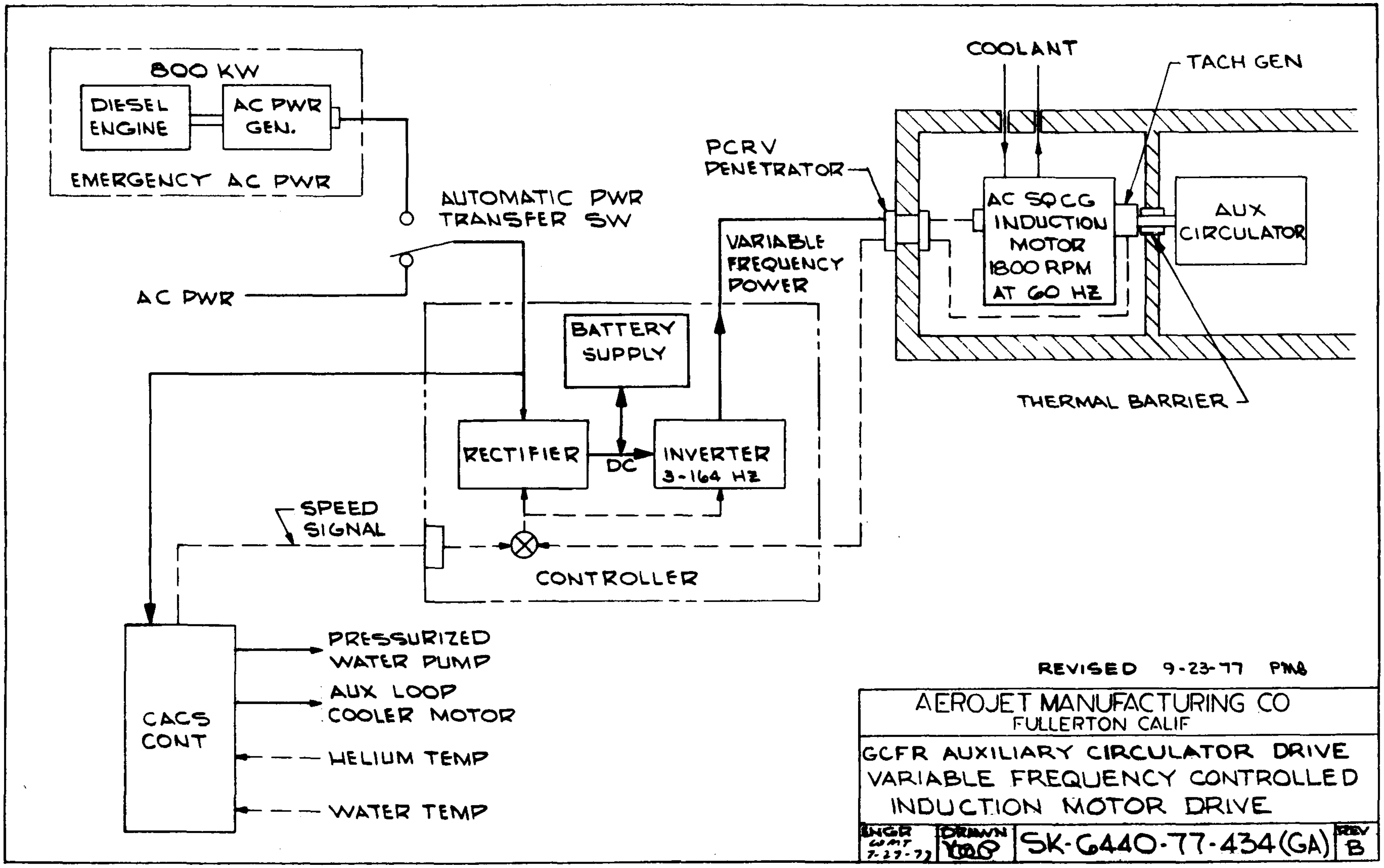

Fig. 9-1. Frequency-controlled a.c. induction motor drive

systems are used extensively in supplying a.c. power without interruption of critical systems in the event of failure of normal a.c. power.

The speed-torque characteristic of this drive system appears to be appropriate for the circulator load. In the upper power range, the maximum speed and full load torque cover the load requirements of the DBDA. In the low-speed range, the available steady-state torque is considerably less than maximum but is sufficient for operation for the pressurized cooldown accident. There appears to be no requirement for large steady-state torque at low speed.

The torque available for accelerating the motor and circulator to 4900 rpm for a DBDA is limited by the controller design and is in the range of 100% to 150% of full load torque. Based on the full load torque value and the estimates of motor and circulator inertia, the acceleration time to 4900 rpm was calculated to be about 30 s (Ref. 9-3).

The required speed range of this application, about 50:1, is somewhat beyond the state of the art capability for this type of system. The lowest speed, 100 rpm, requires frequencies of 1.66 Hz for a two-pole motor and 3.33 Hz for a four-pole motor. Vendors hedge on guaranteeing operations below 10 Hz. In addition, there have been reports in the literature of instabilities in the low-speed range. These were unexpected instabilities and the vendors have claimed cures.

The top speed of 4900 rpm is also beyond the state of the art. The normal maximum speed for a 60-Hz two-pole motor is slightly less than 3600 rpm. The conventional design of the shaft and rotor takes into account a possible overspeed condition of 25% (possibly due to an overhauling load). Therefore, any speed requirement over 4500 rpm is outside the range of normal design and testing. In addition, the 4900-rpm speed is outside the normal commercial product range, and vendors are reluctant to pursue any development that does not lead to a commercial product.

Figure 9-1 shows the motor located in the PCRV cavity but with a thermal barrier between the motor cavity and the auxiliary circulator. The motor would be in the high-pressure helium environment, but it is expected that its cavity would be temperature conditioned.

Figure 9-1 also indicates that the auxiliary circulator components are parts of the CACS and all the CACS components are controlled by the CACS control system. The source of normal and emergency power for all the CACS components is also indicated.

There are variations of this basic system. Instead of the solid-state rectifier-inverter system, the variable frequency could be generated by rotating machinery. This was conventionally done prior to the development of solid-state devices. The system would consist of a constant speed motor driving a synchronous generator through a variable speed fluid coupling or eddy-current clutch. Such equipment is larger, is less reliable, and operates less well at low frequencies than the solid-state equipment.

9.1.2. Direct Current Motor Drive (Fig. 9-2, SK-6440-77-433)

A speed-controlled d.c. motor system was considered as an alternate that would provide stable speed control over the required range at any torque up to the full load value. The speed is controlled by varying the armature voltage of the motor. The variable d.c. voltage is produced by controlling a silicon-controlled rectifier (SCR) (thyristor) controller. This is a widely used, simple, and reliable method of achieving excellent speed control over a wide range. Speed ranges of 100:1 or more are possible.

In this application, however, there are significant disadvantages. In addition to the expected difficulties associated with operating brushes and a commutator in the PCRV environment, vendors have indicated other problems. In their proposed systems, the top speed is achieved by a stepup gear box with a ratio of about 4:1. In addition to the added complexity of the system, the load inertia reflected through this gear ratio has an enormous effect on acceleration time. Also, for this size drive, vendors will not

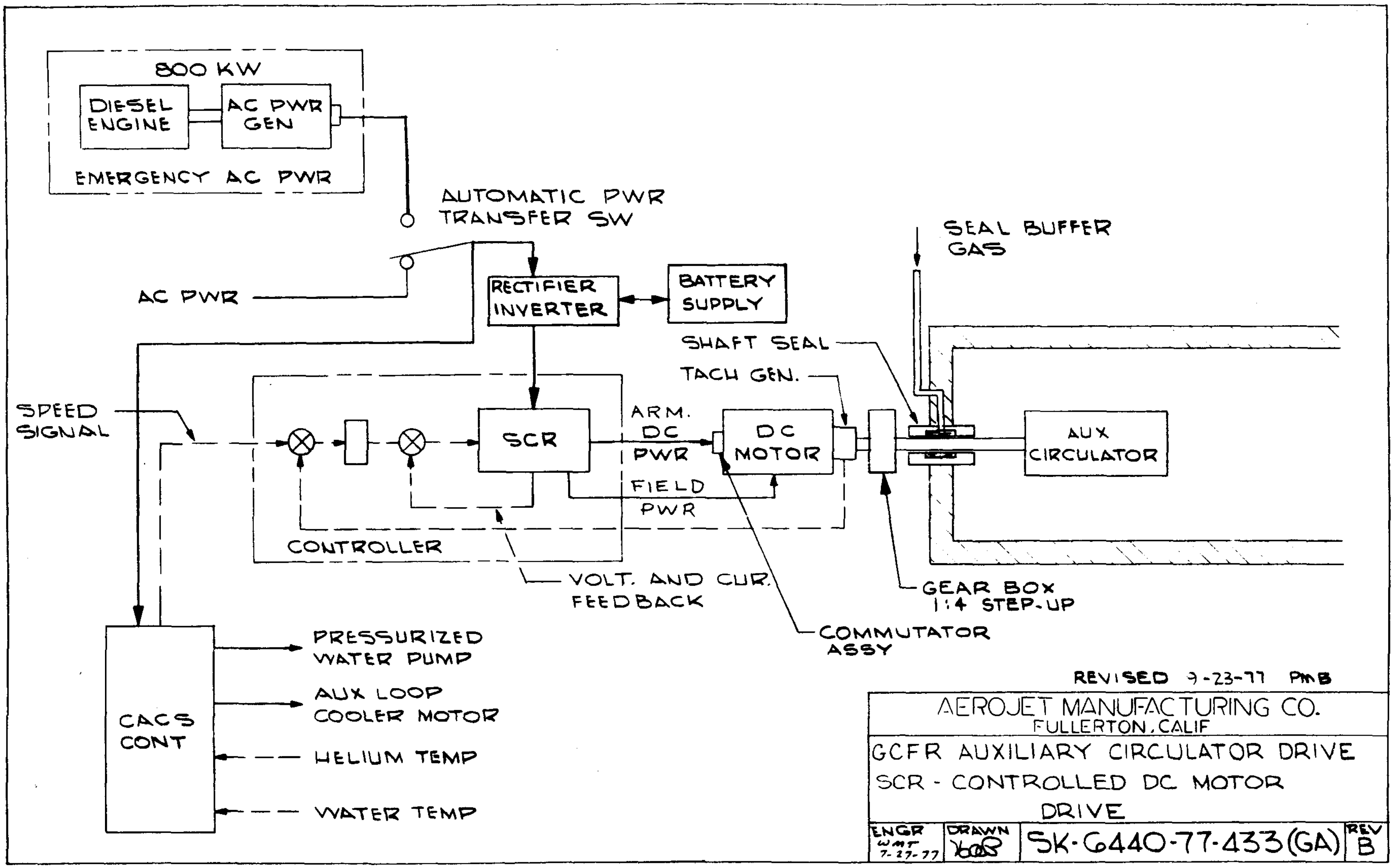

Fig. 9-2. Direct current motor drive

provide the 50:1 speed range with a single motor. They propose dual motor systems. Another problem is operation from a battery source. To achieve this operation with speed control, an inverter or similar equipment must be added to the system.

9.1.3. Variable Frequency-Controlled Synchronous Motor Drive (Fig. 9-3, SK-6440-77-468)

This is a variation of the reference system that employs a synchronous motor instead of an induction motor. This system would provide more precise speed control and could enable the use of a less costly rectifier-inverter system. These potential advantages are not appropriate for the GCFR Demonstration Plant application or the extrapolation to a commercial plant. A break point will occur somewhere between 3000 and 7000 hp where the induction motor cooling will be too severe a problem and also the cost of the controller may become very significant.

As shown in Fig. 9-3, the system employs a forced-commutation type inverter that operates from a fixed input d.c. voltage. Such an inverter can be operated from batteries as shown. The less costly non-forced-commutation type inverter cannot be operated from a fixed battery supply. Therefore, a battery backup system would include an additional rectifier and inverter system.

The system is shown with slip rings for field excitation. Elimination of the slip rings by use of a rotary transformer and rectifiers on the motor rotor is not practical for the motor size in this application. This system with the rotary transformer excitation appears to be a leading candidate for applications of 10,000 hp and above.

9.1.4. Frequency-Controlled Dual Induction Motor Drive (Fig. 9-4, SK-6440-77-437)

This is a backup alternate to the reference system that would compensate for any of its difficulties in the low-speed range. The system consists

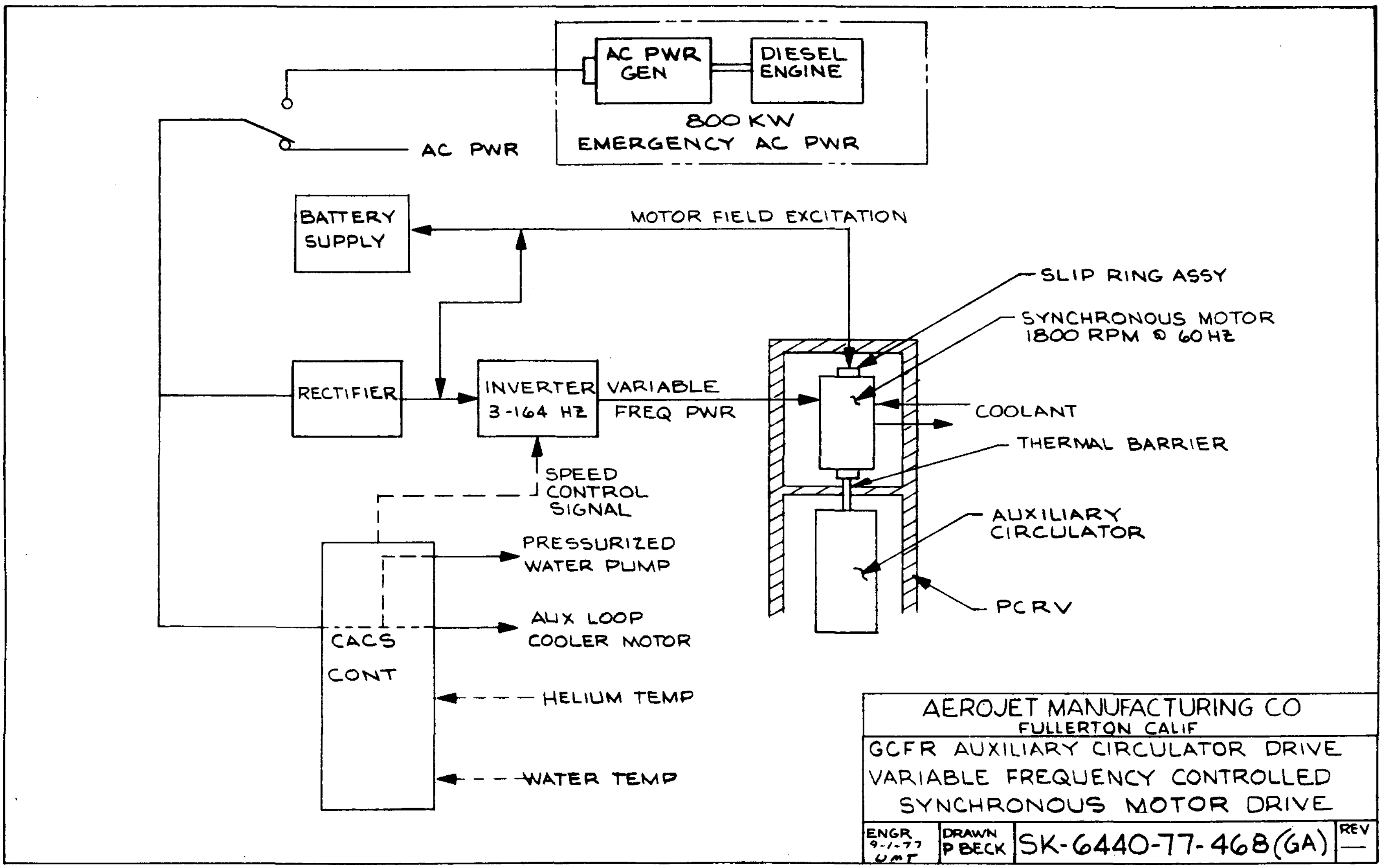

Fig. 9-3. Variable frequency-controlled synchronous motor drive

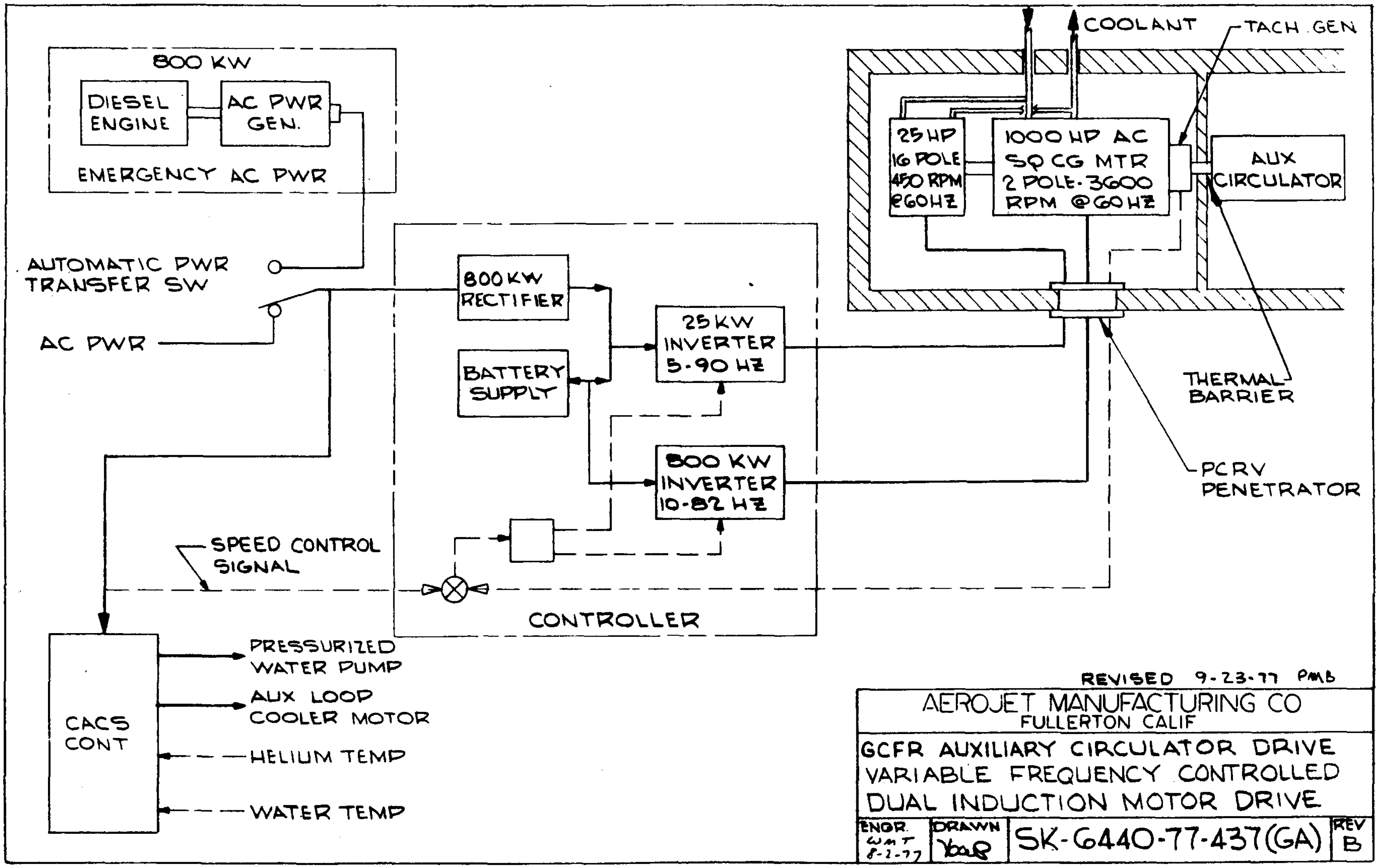

Fig. 9-4. Frequency-controlled dual induction motor drive

of two motors, coupled together so that they drive the same shaft, and two inverters, each supplying power to one motor. A single rectifier system would provide power for both inverters.

The second, smaller drive motor in the system would be designed specifically to provide for the load requirements of the pressurized cooldown accident without having to stretch the state of the art for a single motor drive. This advantage is partially offset by the additional complexity of the motor package and controller.

9.1.5. Converter Cascade Wound-Rotor Induction Motor Drive (Fig. 9-5, SK-6440-77-431)

This is an alternate that employs a wound-rotor induction motor. One variation is the supersynchronous system shown in Fig. 9-5. Below synchronous speed, part of the 60-Hz power supplied to the motor stator is converted to mechanical power output. The remainder is transferred to the rotor winding. This lower-frequency power is converted back to 60 Hz by a thyristor converter and delivered back to the 60-Hz supply. The speed is varied by controlling the converter and the amount of power returned to the line. For speed above synchronous speed, the power flow through the converter is reversed and power at the appropriate frequency is fed to the rotor. At or near synchronous speed, a special operating mode is required to produce torque.

Another variation is a subsynchronous system. It operates only in the range below synchronous speed, and therefore the motor must be geared up to produce 4900 rpm. However, the subsynchronous system employs a simpler, single-mode controller.

Both of these systems have excellent control characteristics at nonsynchronous speeds. These systems are applicable to very large drives, i.e., 10,000 hp and above. However, for this application, they have no advantages over the reference system and the motor has the disadvantage due to slip rings. In addition, operation from batteries would require special additional equipment.

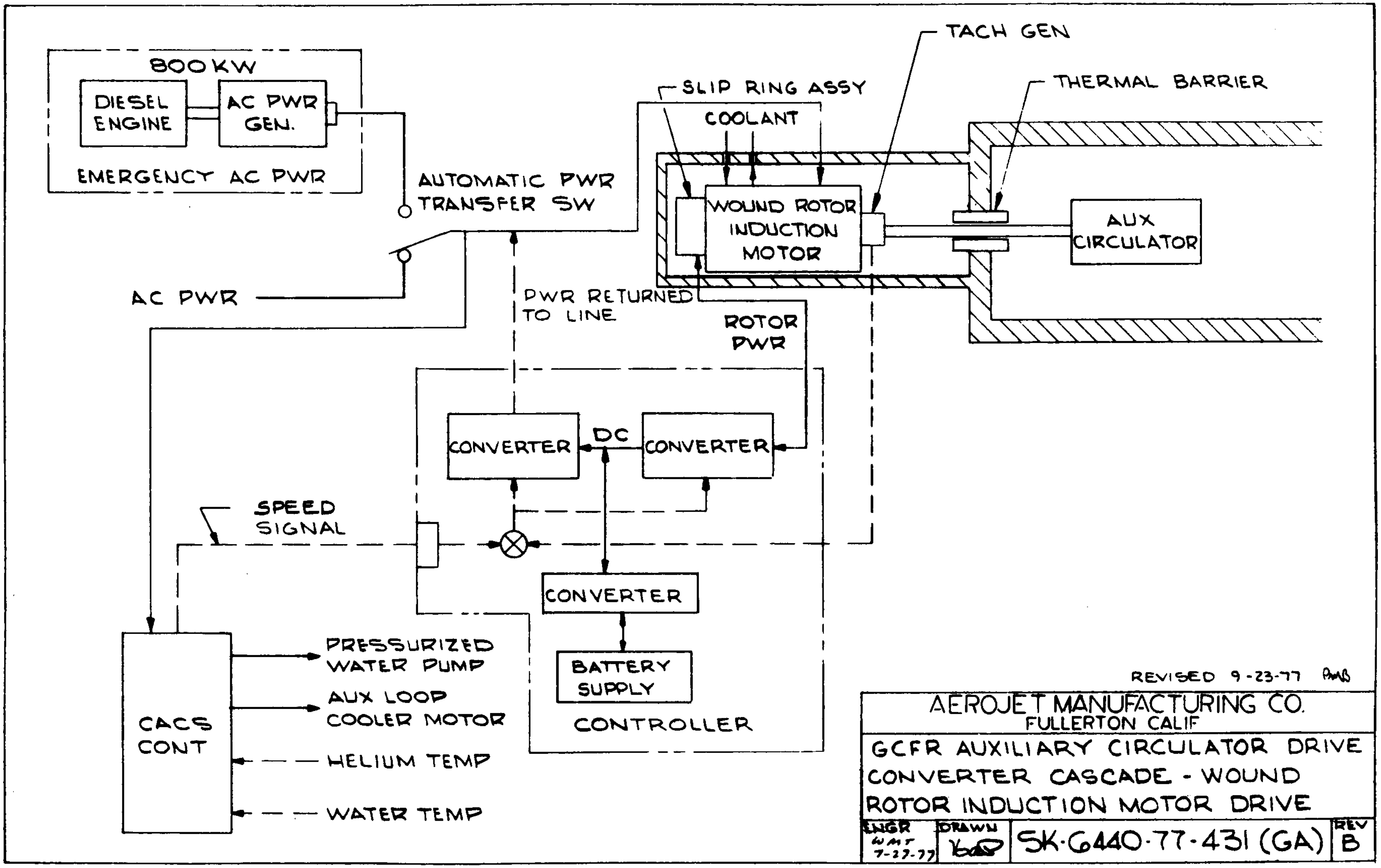

Fig. 9-5. Converter cascade wound-rotor induction motor drive

9.1.6. Other Systems

Other electrical drive systems were considered but were found not to be applicable. One consisted of an electric drive motor coupled to the circulator by a variable speed coupling such as an eddy-current clutch. A leading manufacturer of eddy-current clutches (Eaton) would not propose such an application. The clutches are made for horizontal shaft application only. They have too small a range of speed control and would require the addition of a stepup gear box. There appears to be no advantages in pursuing this system.

A similar hybrid system that employed a fluid coupling instead of an eddy-current clutch was considered. Such a system is equivalent to the hydraulic turbine systems described in Section 9.2. The latter have the significant advantage of separating the drive turbine from the pump and drive motor and thereby requiring only the turbine in the PCRV.

Other systems considered included variable frequency generators driven through variable speed couplings. These systems are variations of the reference system as discussed in Section 9.1.1.

9.1.7. Typical Electric Drive Installation

An installation arrangement of a typical electric motor drive in the PCRV cavity is shown in Fig. 9-6. The motor envelope size should include all the motors being considered except the separate d.c. motor system proposed by one of the vendors.

The approximate sizes of the control equipment outside the PCRV for an electric drive are shown in Fig. 9-7. The sizes shown are based on the equipment required for the reference system.

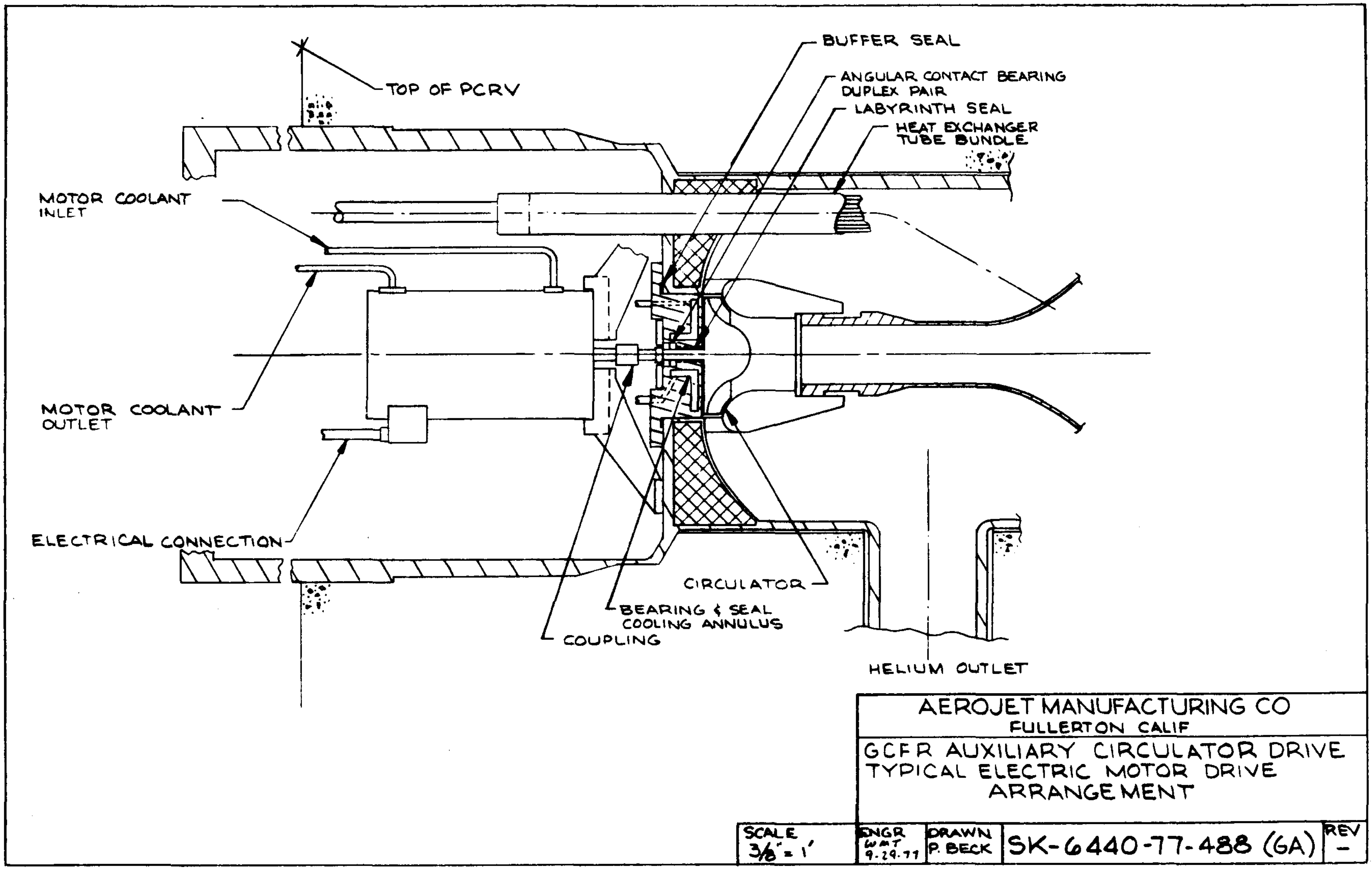

Fig. 9-6. Typical electric motor drive arrangement

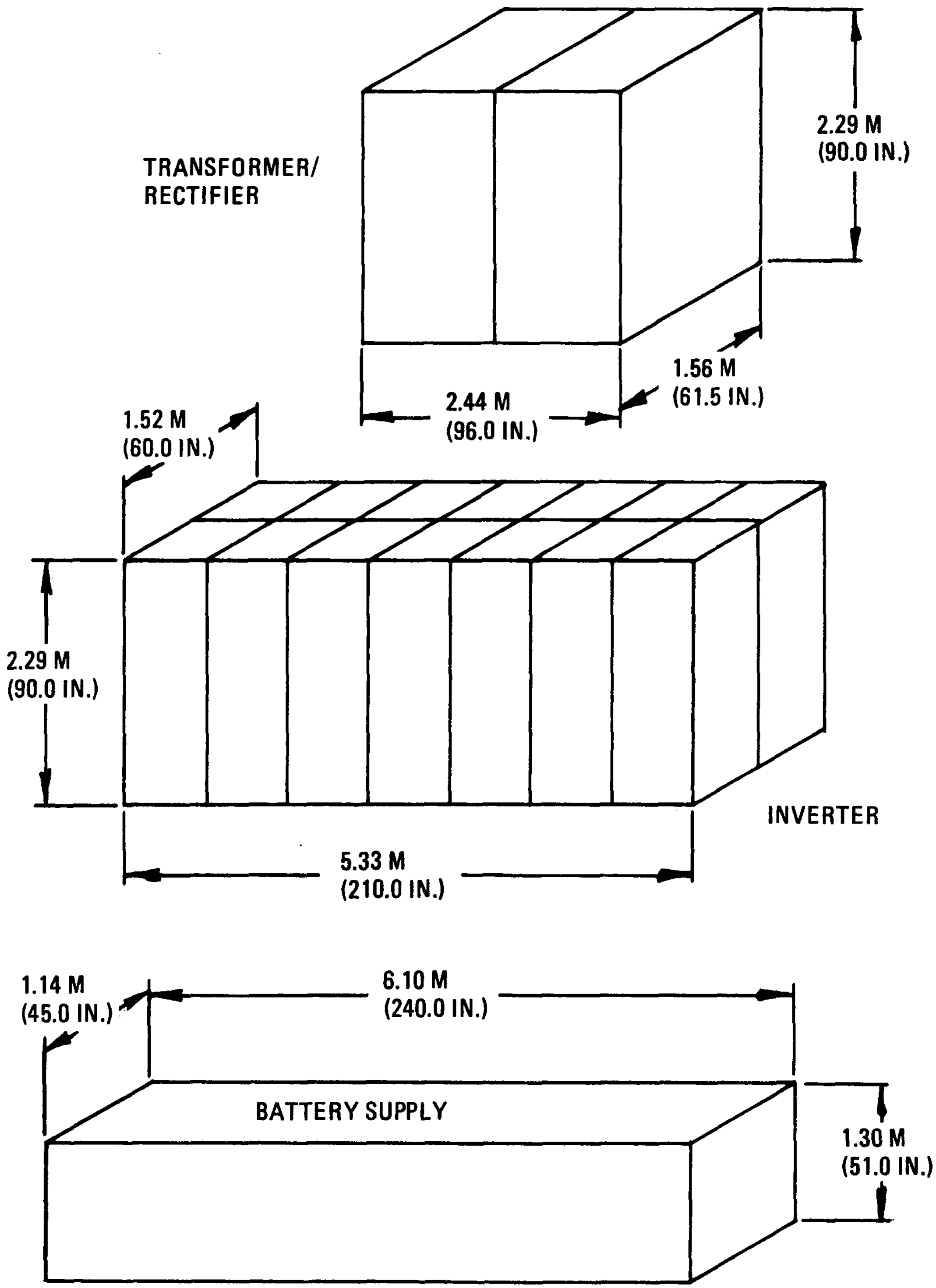

Fig. 9-7. Typical electrical drive control component outlines

9.2. MECHANICAL DRIVE SYSTEMS

Three types of mechanical drives were evaluated in this study: the hydraulic turbine, the steam turbine, and the gas turbine. All of these mechanical drives involve the use of working fluids (e.g., water, steam, or air) to drive them. If the turbine is located within the PCRV, then the working fluid must also be introduced into the PCRV. This poses problems, such as the size of inlet and return or exhaust lines required and the protection of the reactor coolant from contamination. Also, electrically, pneumatically, or hydraulically operated valves subject to various failure modes must be used in the working fluid lines. These problems do not exist or are less severe for the reference electrical drive, since no working fluid is involved and the electrical power cables used are considerably smaller than the required fluid lines. Mechanical drives start quicker and have better speed torque characteristics for this application. Scaling the system up to higher power levels is much less of a problem for the mechanical drives than for the contemplated electrical systems. The mechanical drives are probably more reliable and less subject to catastrophic failure modes (winding insulation failure due to loss of coolant or quality control, etc.) within the PCRV. Also, 4900 rpm is well below the proven maximum speed of all the mechanical drives evaluated, while it is above the upper limits for the existing electrical motor types contemplated for this application.

The required operating speed range of 50:1 is beyond the normal application of mechanical as well as electrical drives and may be difficult to achieve with good speed control over the entire speed range. In the hydraulic turbine applications, cavitation in the low-speed range must also be considered.

Some of the mechanical systems evaluated (i.e., the hydraulic turbines) involve the use of electrically driven pumps and blower drives, which introduces additional failure modes into the system. In addition, most of the instrumentation and controls will probably be electrically operated. For these systems the integrity of the backup electrical supply is of vital importance.

Brief descriptions of the mechanical drives evaluated in this study are given below.

9.2.1. Hydraulic Turbine Drive (Figs. 9-8 and 9-9, SK-6440-77-456 and -457)

Hydraulic turbines, such as the Pelton wheel or Francis turbine, provide an attractive drive mechanism for the GCFR auxiliary circulators since they are very reliable, start quickly, and can be contained within a very small space for the power developed compared with alternative driving devices. Their main disadvantage is the need to supply them with a large quantity of water under high pressure to meet the high-speed, high-torque operating requirement.

9.2.1.1. System Description. The hydraulic turbine auxiliary circulator drive system shown in Figs. 9-8 and 9-9 consists of hydraulic turbine(s) located within the PCRV on a vertical shaft and a high-head, high-capacity pump for the DBDA condition and a low-head, low-capacity pump for the pressurized cooldown accident. Both pumps are driven electrically from site power or backup electrical power and are located outside the PCRV but connected in a closed loop. A backup supply of water with the required head (to cover a 2-hr blackout of emergency electrical power) can be provided by placing a reservoir of the required capacity at the required elevation. Alternatively, this can be accomplished by using an uninterruptible electrical power supply with batteries as the energy source. All the pump and blower drives in the auxiliary cooling system should be provided with the same driving mode.

Layout drawing SK-6440-77-471 (Fig. 9-10) shows the installation of a hydraulic turbine in the PCRV. The hydraulic turbine housing cavity is pressurized by an inert gas (nitrogen). The turbine shaft is sealed from

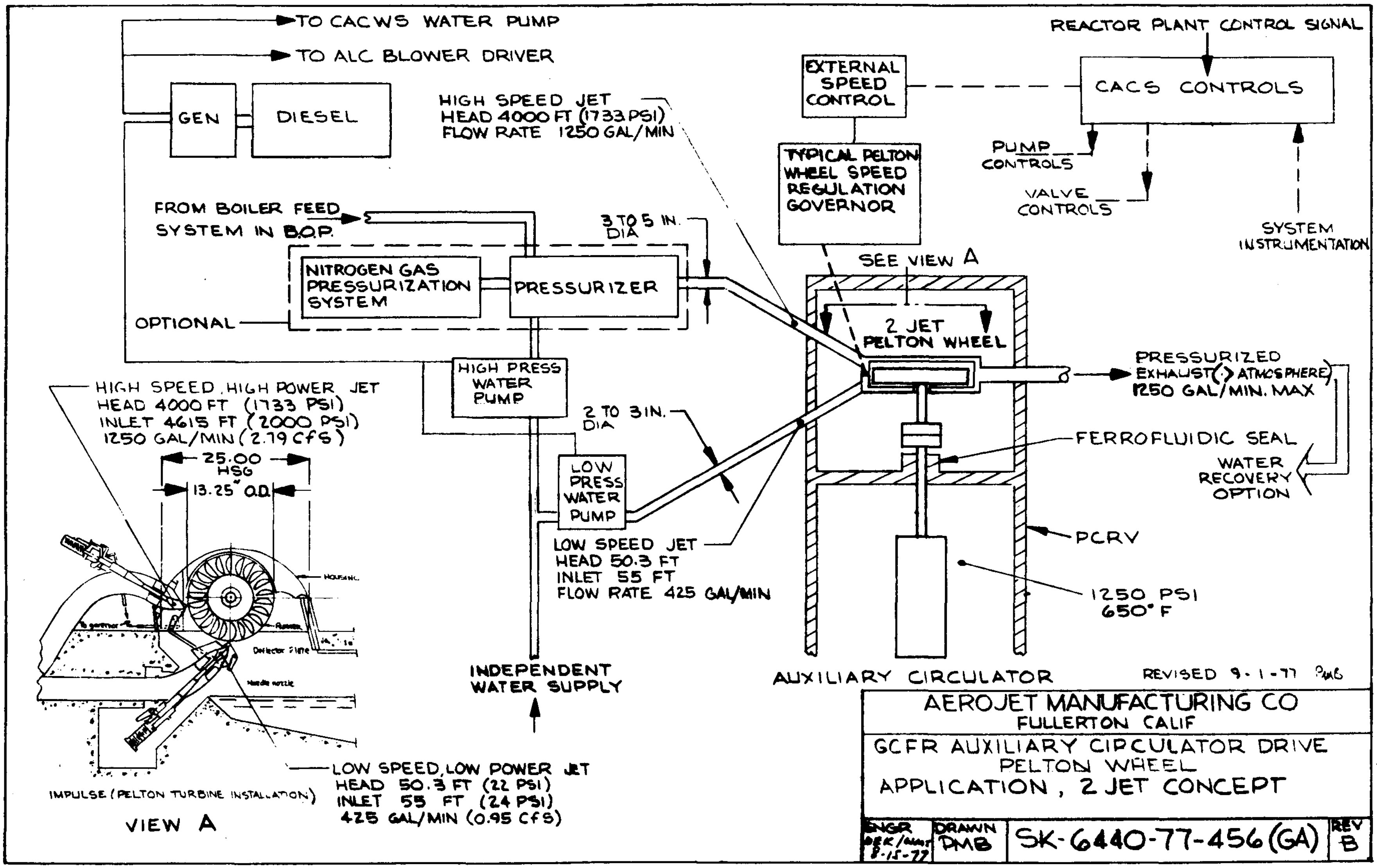

Fig. 9-8. Hydraulic turbine drive, 2-jet concept

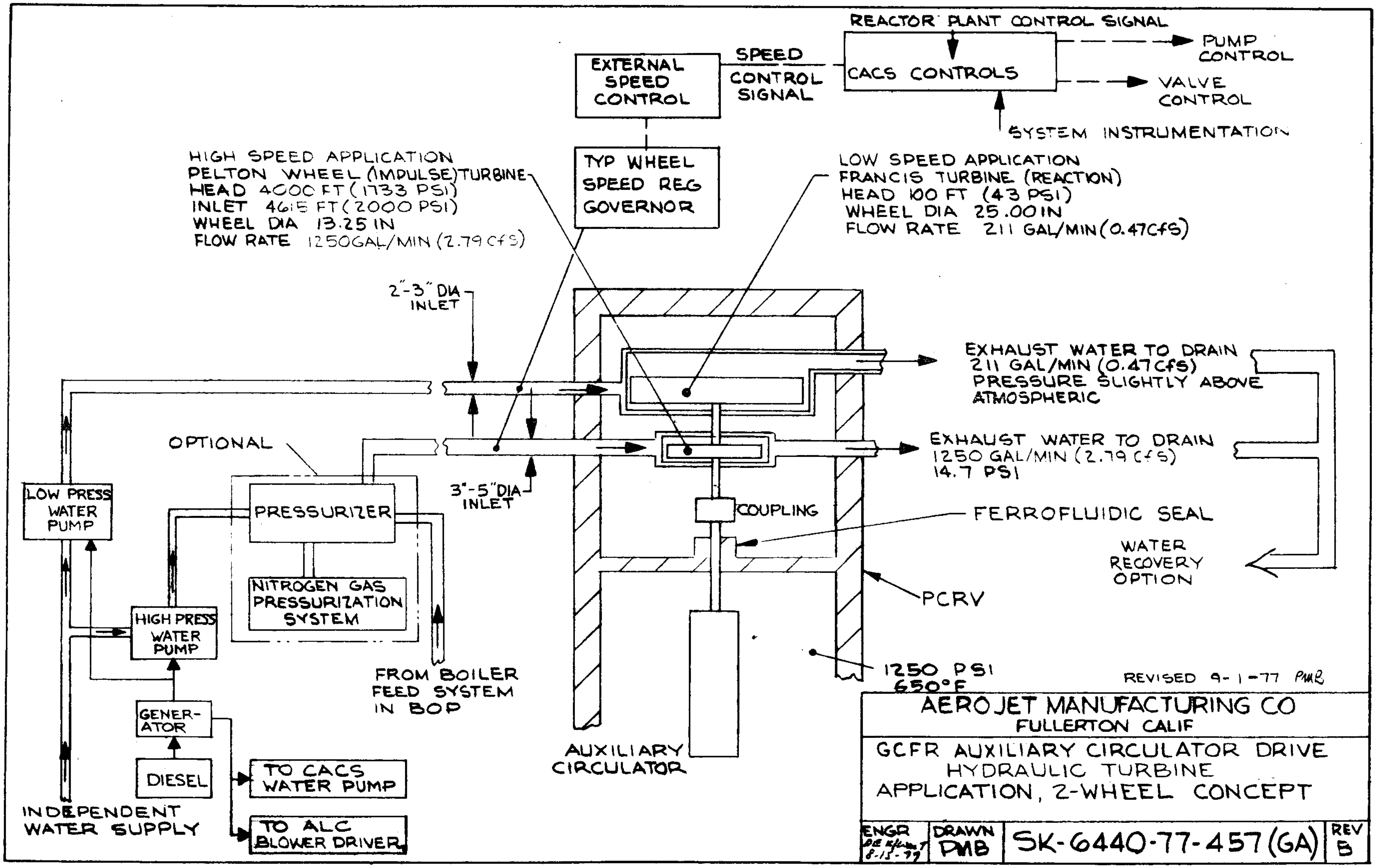

Fig. 9-9. Hydraulic turbine drive, 2-wheel concept

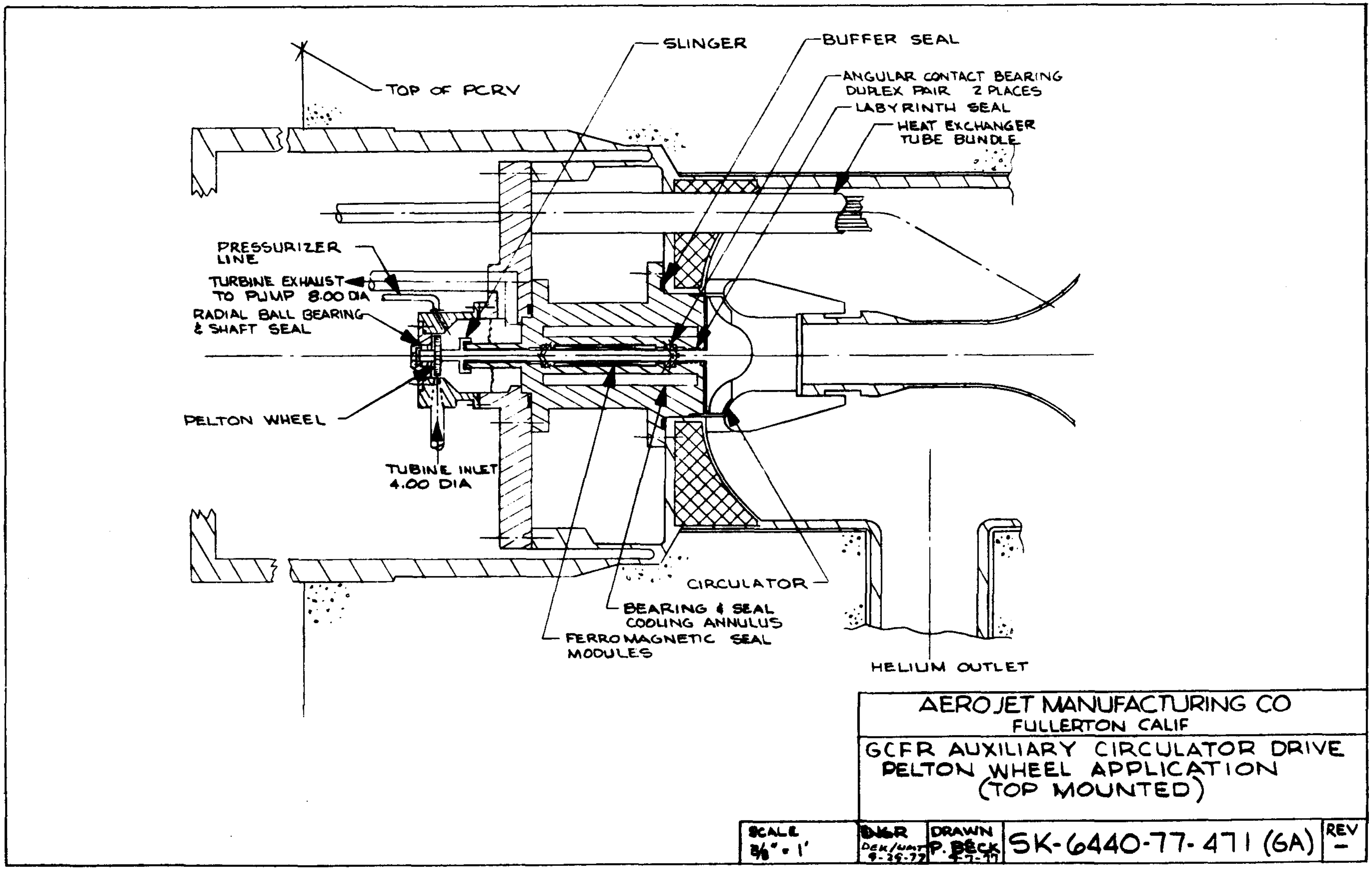

Fig. 9-10. Hydraulic turbine installed in PCRV

the reactor coolant (helium) using a labyrinth ferrofluidic seal. A slinger on the shaft prevents water from entering the seal. The heat generated in the working fluid bearings and seals must be removed either by natural or forced cooling as determined in the preliminary design. Also, means will be provided in the design and in the control equipment to prevent the submergence of the Pelton wheel in water.

9.2.1.2. Design Selection. The Pelton wheel impulse turbine could best satisfy the high-speed, high-power operating requirements, since the use of a high-head water supply which is available from the balance of the plant (for startup if required) will minimize the water flow rates needed to satisfy these requirements. Table 9-2 compares a Pelton wheel operating with a high head and a Francis turbine operating on a medium head. The Francis turbine would require nearly six times the water flow rate to meet the subject requirements, assuming that both of the hydraulic turbines are operated within their normal specific speed range.

It is not practical, however, to use the highly pressurized water (2000 psi) needed for the high-speed, high-power requirements to meet the low-power, low-speed operating requirements (Ref. 9-3). Instead, one of the following concepts should be considered:

1. Two-Jet Concept. In the two-jet concept, a second jet fed from a separate lower-pressure water source would be added to the Pelton wheel design. One jet would be used to meet the high-speed, high-torque requirements, while the other would be used to meet the low-speed, low-torque requirements. The two jets would not be operated at the same time. The disadvantage of this concept is that the Pelton wheel could only be designed to meet the most severe of the requirements and would therefore not be optimum to satisfy the low-speed requirements.

TABLE 9-2
COMPARISON OF PELTON WHEEL AND FRANCIS TURBINE
FOR HIGH-SPEED AND HIGH-TORQUE REQUIREMENTS

Drive Mechanism	Wheel Outer Dia. (in.)	Head Required		Water Flow Rate Required (gpm)	Rotor Speed (rpm)	Horse-power
		Ft	Psi			
Pelton wheel	13	4000	1750	1250	5000	1000
Francis turbine	10	631	273	7000	5000	1000

Actually, on a vertical shaft Pelton wheel it may be advantageous to use more than one jet to satisfy the high-speed, high-torque requirements only. In that case, one or more additional jets would be used to satisfy the pressurized cooldown requirements.

2. Two-Wheel Concept. In the two-wheel concept, a second hydraulic turbine, probably of the reaction type (e.g., a Francis turbine), would be added to the shaft and supplied from a separate, much lower-pressure water source. The advantage of this concept would be that each turbine could be designed to operate within a given limited operating envelope. The disadvantages, which do not appear prohibitive for the application, would be the added cost of the additional turbine, the increased envelope required, and the windage losses from the non-operating wind milling turbine.

A more detailed investigation will be required to determine if the two-jet concept is feasible. The two-wheel concept is certainly feasible and will therefore be used initially as the reference design for the hydraulic turbine drive.

9.2.1.3. Design Considerations for Hydraulic Turbines.

9.2.1.3.1. Shaft Orientation. Both Francis turbines and Pelton wheels have been designed for operation with a vertical shaft, but the Francis turbine is preferred for that operation.

9.2.1.3.2. Location. The preferred location for a hydraulic turbine drive is at the bottom of the cavity to prevent water leakage along the rotating shaft. It is probable, however, that this problem can be avoided by judicious design. The Francis turbine probably requires the bottom location.

9.2.1.3.3. Submerged Operation. The Pelton wheel cannot operate submerged, whereas that is the normal operating mode for the Francis turbine. The system can be designed so that the exhaust water level never reaches the wheel unless the driving pump fails, in which case the wheel has no driving force.

9.2.1.3.4. Pressurized Water Source - Startup Source (If Required). The pressurized (2000 psi) water needed to drive the Pelton wheel to meet the DBDA requirements can be obtained from the balance of plant (BOP) feedwater system for the first 2 min of operation if required. It appears, however, that the system is quick enough starting to eliminate the need for a startup pressurized water source.

9.2.1.3.5. Sustaining Source. The pressurized water needed to sustain the system once the BOP water source falls below the required pressure can be obtained from an electric motor or mechanically driven water pump. The electricity for the pump can be obtained from the site power using a diesel driven (or other mechanical drive) generator as backup. A redundant backup unit can be provided if required to satisfy safety requirements. A plenum can be provided in the line to allow time for the backup unit to come on line if the site power is lost. The remaining pumps and blower drives in the auxiliary cooling system could be powered in the same manner. The backup electrical power would probably be a part of the plant emergency power system. The water would be recirculated through the system with cooling provided.

The use of an elevated water source to provide the required head for the DBDA function would be impractical. An elevation greater than thousands of feet for a Pelton wheel and hundreds of feet for a Francis turbine would be required. Similarly, providing a sufficient quantity of pressurized water independent of the sources given above would be impractical. A pressurized water tank of greater than 150,000-gal capacity would be required for a 2-hr supply. The water inlet line would have to be schedule 80 or greater pipe with a 3.5- to 5-in. diameter owing to the high line pressures involved, but would not be subjected to severe thermal gradients. A water flow rate of approximately 1250 gpm would be required.

9.2.1.3.6. Low-Speed, Low-Torque Application. The pressurized water (50 psi) for the low-speed, low-torque application can be obtained from an electric motor driven water pump. A 2- to 3-in. schedule 40 supply line would be sufficient. A 500-gpm (Pelton wheel) or 250-gpm (Francis turbine) water flow rate would be required.

A 50,000-gal water tank located 50 ft above the Pelton wheel could be used to provide a 2-hr supply of pressurized water for the pressurized cooldown condition.

9.2.1.3.7. Speed Control. The rotor speed of a Pelton wheel can be readily controlled by restricting the flow of water to the turbine (needle nozzle) and/or deflecting the jet stream (deflector plate).

The rotor speed of a Francis turbine is controlled by the use of a movable wicket gate.

9.2.1.3.8. Rotor Sizes. The rotor diameter for a Pelton wheel to meet the high-speed, high-torque requirements would be approximately 13 in. using a water flow rate of about 1250 gpm with a 4000-ft head. A 26-in.-diameter housing would be required.

The rotor diameter for a Francis turbine for the low-speed, low-torque requirements in the two rotor concepts would be approximately 25 in. using a water flow rate of about 250 gpm with a 100-ft head.

9.2.2. Steam Turbine Drive

A steam turbine can be used to drive the GCFR auxiliary circulators. AMCO has produced four concepts using a steam turbine drive:

Concept 1 - Using a system steam source, a non-boiling CACWS.

Concept 2 - Using a system steam source, a boiling CACWS.

Concept 3 - Using an independent steam source in a closed loop.

Concept 4 - Using an independent steam source in an open loop.

Concept 1 is shown in Fig. 9-11 (SK-6440-77-467), Concept 2 in Fig. 9-12 (SK-6440-77-472), and Concepts 3 and 4 in Fig. 9-13 (SK-6440-77-464).

In all the concepts, the steam turbine(s) is based upon existing commercial models. A typical steam turbine drive arrangement (except for Concept 2) is shown in Fig. 9-14 (SK-6440-77-486). Concepts 1, 2, and 3 use a closed loop system (Rankine cycle), while Concept 4 is an open loop system. The differences between the concepts lies in the way the steam to drive the system is produced.

In Concepts 1 and 2, the steam is produced from heat rejected from the reactor by the auxiliary cooling system using a steam generator (in the CACWS loop in Concept 1, and replacing that loop in Concept 2). In Concepts 3 and 4, the steam is produced in a boiler operating from an independent fuel supply. In Concept 4, the steam exhausted from the turbine is rejected to the atmosphere.

In all the concepts, the startup steam source will be provided from the main steam generators. Since this source will be available for only a short time (i.e., the first 2 min of an emergency or faulted condition), a steam accumulator is included in the line to provide a supply of steam until the sustaining steam source can be brought on line.

The size of the steam accumulator required (a function of the time required for the steam generator to go from idle to full steam production) has not been determined for Concepts 1 and 2. Approximately a 7-min supply of steam (1000 ft^3 at 1200 psi) will be required to run the steam turbine until the boilers in Concepts 3 and 4 can be brought to full production from idle.

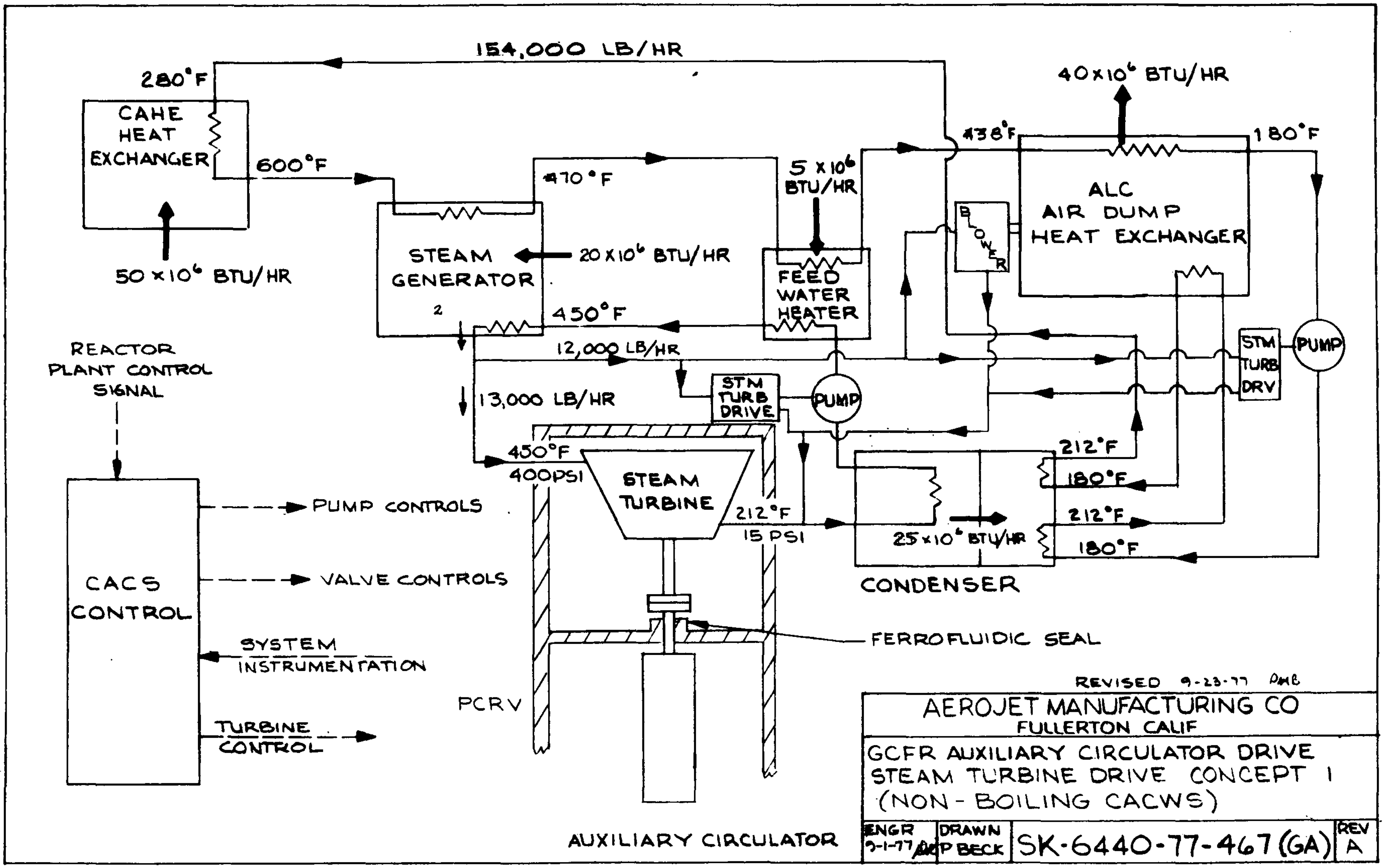

Fig. 9-11. Steam turbine drive: Concept 1, non-boiling CACWS

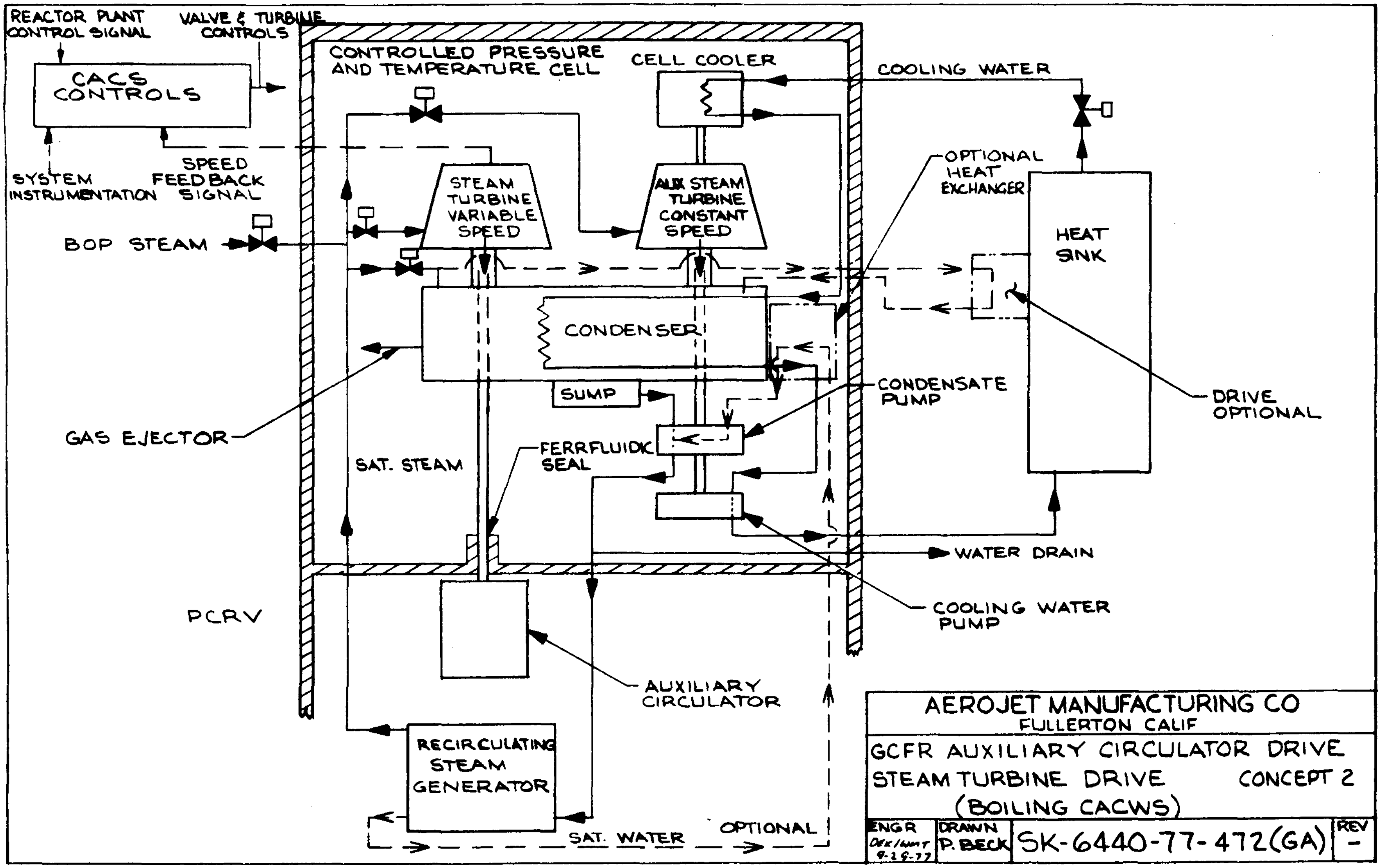

Fig. 9-12. Steam turbine drive: Concept 2, boiling CACWS

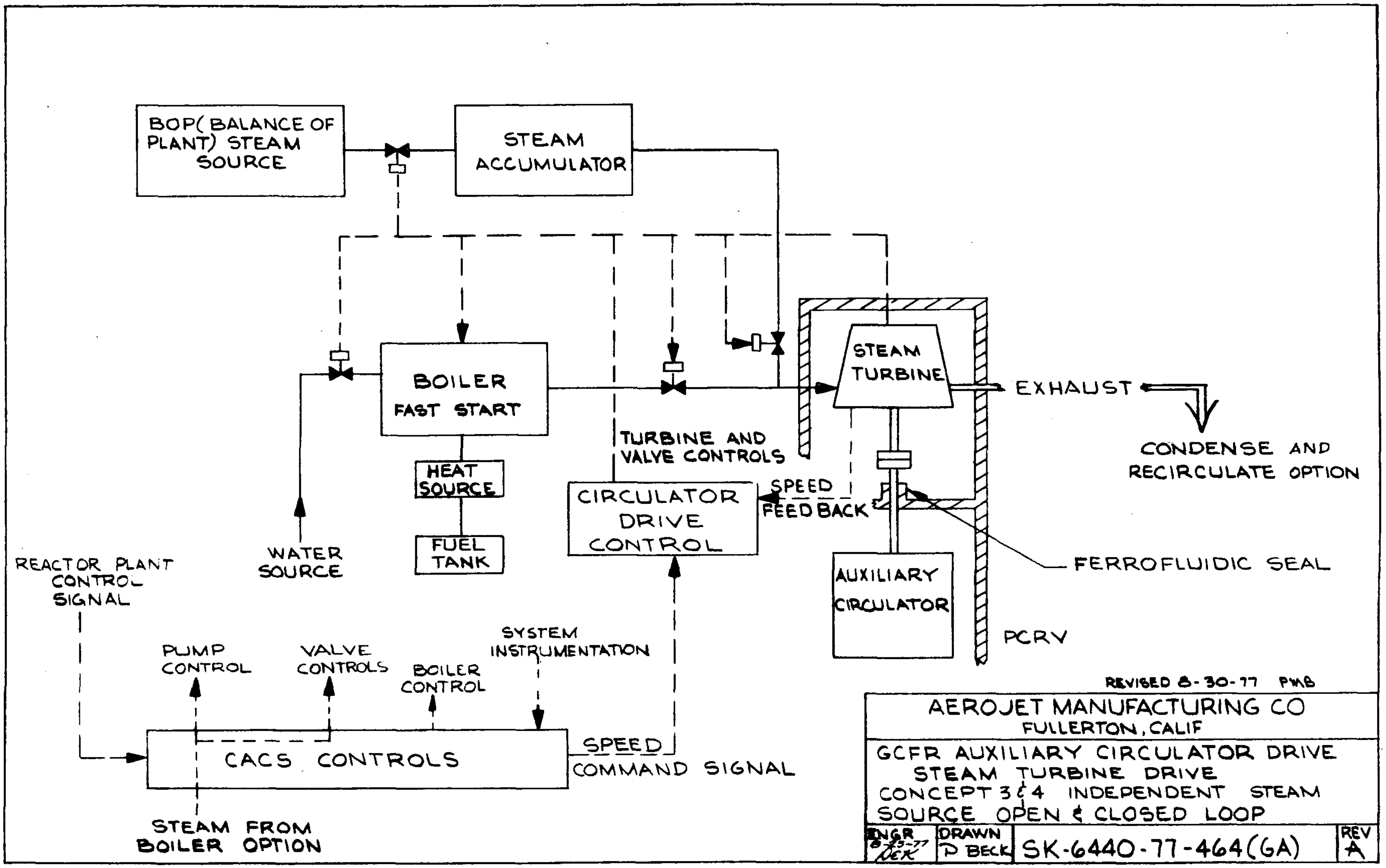

Fig. 9-13. Steam turbine drive: Concept 3, independent steam source in a closed loop, and Concept 4, independent steam source in an open loop

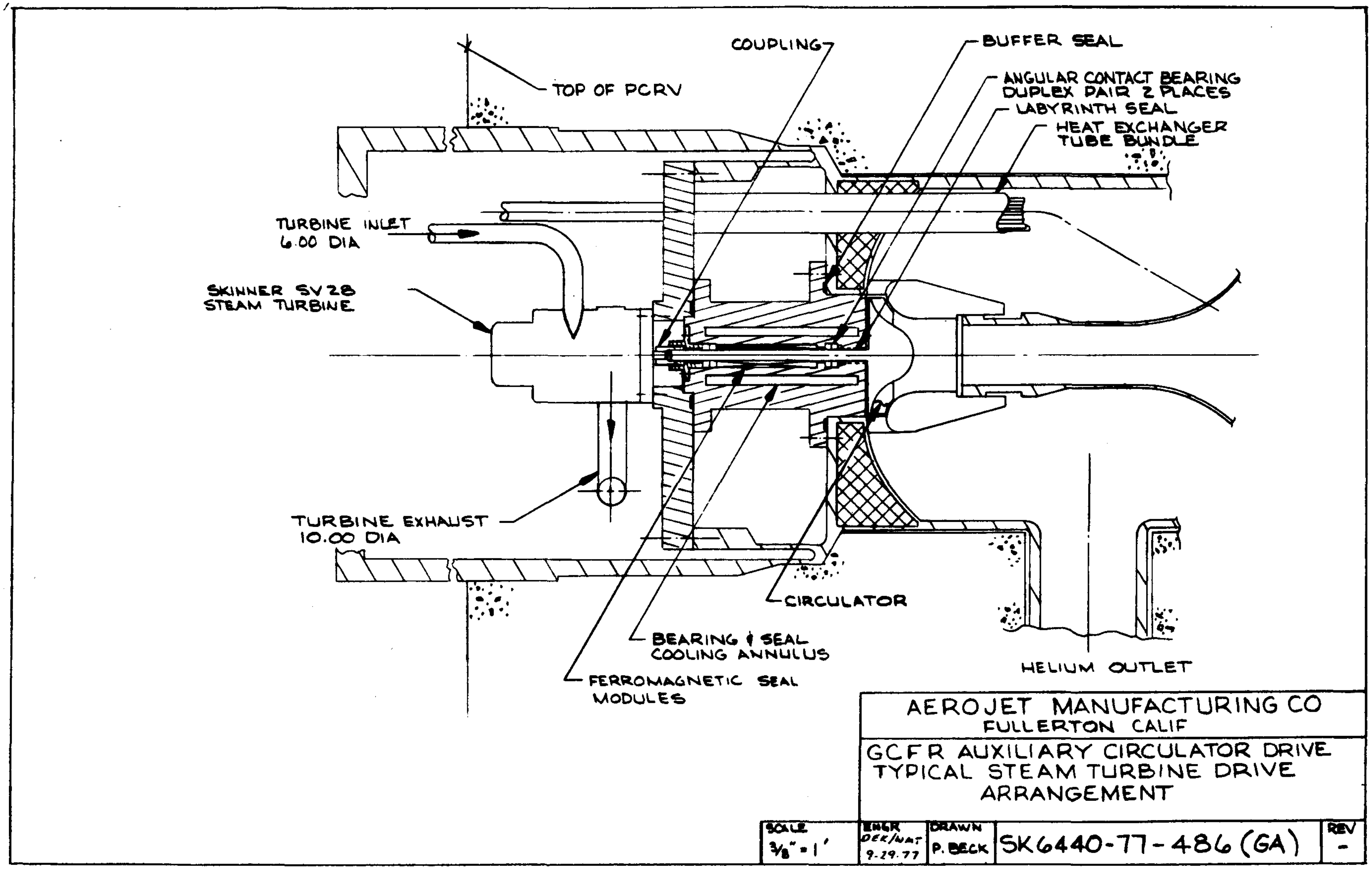

Fig. 9-14. Typical steam turbine drive arrangement

Descriptions of the four steam turbine drive concepts, with particular emphasis on the sustaining steam source for each, are given below.

9.2.2.1 Concept 1, Non-Boiling CACWS (Fig. 9-11).

9.2.2.1.1. System Steam Source. The objective of Concept 1 is complete independence from outside power sources after the startup phase. In Concept 1, the sustaining steam source is provided by placing a steam generator in the CACWS loop in series with the ACL dry heat rejection exchanger. The steam side of the steam generator would be connected in a closed loop consisting additionally of the steam turbine, a condenser, and a water pump.

In order for the GCFR CACS to be self-sustaining, all the pumps and blower drives in the system, e.g., the CACWS pump, the ACL cooler blower drive, and the steam turbine loop water pump, should be driven by steam produced in the steam generator. The loss of any of the pumps and/or blower drives mentioned above would shut down the system. Thus, nothing is to be gained in reliability by driving any of them from a separate power source; in fact, the opposite is true. Unfortunately, as presently proposed the CACWS loop does not provide sufficient high-availability energy to the steam generator to drive a completely independent system. The energy available is probably not even sufficient to drive the steam turbine to meet the maximum requirements of the DBDA condition. However, this would change if the hot leg temperature of the CACWS loop were increased to nearly 600°F from the 500°F presently contemplated. The cold leg temperature of the system could then also be raised by a like amount. The overall affect of this concept on the ACL dry exchanger would be considerable, since after extracting 7% or 8% of the heat to drive the system, it would return most of the remainder to the ACL dry heat rejection exchanger at a considerable lower temperature. This, in effect, would reduce the hot side average temperature in the exchanger by a hundred degrees or more.

Startup time and, consequently, steam accumulator size can be reduced by keeping the steam turbine loop operating at idle, as is contemplated for the auxiliary heat rejection loop. This would also reduce the thermal shock problems associated with startup from ambient conditions. The steam turbine could be located within the PCRV if it were especially designed to operate within that environment.

9.2.2.1.2. Steam Turbine Design. A number of steam turbines are commercially available that operate within the defined steam conditions and power and speed requirements. (However, none of these steam turbines are designed to operate in the PCRV environment.) An example is the Skinner S-Series Vertical Turbine described below:

Rating:	1000 hp, 4900 rpm (also 4 hp at 300 rpm)
Steam conditions:	1000 psig, 550°F; exhaust: 10 psig
Turbine type:	SV-2B-3
Efficiency:	Approximately 50%
Steam rate:	17.9 lb/hp hr at 1000 hp, 4900 rpm
Approximate price:	$25,000

9.2.2.1.3. Summary. Concept 1 cannot be considered a viable candidate for consideration unless the hot leg temperature in the CACWS loop is increased. It might also become feasible if an alternative to the dry cooler (e.g., steam or pond cooling) is used to reduce the system sink temperatures.

9.2.2.2. Concept 2, Boiling CACWS (Fig. 9-12).

9.2.2.2.1. Description. The objective of this concept is independence from external power sources.

In Concept 2, the sustaining steam source is provided by placing a recirculating steam generator in the PCRV to pick up the decay heat. The steam side of the steam generator would be connected by piping to a variable speed steam turbine driving the auxiliary circulator and a constant speed turbine driving the condensate pump, the cooling water pump, and the cell cooler fan. The condenser would be of a unique design located below the two steam turbines. The steam not needed to drive the system would be dumped directly to the condenser. An optimal addition would be a heat exchanger using saturated water from the steam generator to heat the cooling water to near saturation temperature. The steam generator also would be a unique design, with steam being generated in finned tubes with a steam dome and separator and a saturated water downcomer. Hot helium would be circulated outside the tubes. The system would not be required to operate at idle since the environment for the system could be controlled. The BOP startup steam could be used to charge the loop, if needed and if feasible.

Concept 2 would require a redesign of the CACWS loop to convert it into a boiling loop at a different flow rate and hot leg temperature and loop pressure. No attempt has been made to size this concept, since changing the CACWS loop is outside the scope of this study. It has not been determined if this concept could be used with a dry air dump heat exchanger.

9.2.2.2.2. Summary. Concept 2 cannot be considered as a candidate system unless the decision is made to use a boiling CACWS, replacing the heat exchanger with a larger steam generator.

9.2.2.3. Concept 3, Independent Source, Closed Loop (Fig. 9-13).

9.2.2.3.1. Description. In Concept 3, the sustaining steam is provided by an auxiliary boiler operating on an independent fuel supply. The boiler would take the place of the steam generator in Concept 1. The pumps and blower drives in the system would also be operated at idle (producing a small amount of steam at the system operating pressure) to minimize thermal shock problems associated with startup from ambient and to ensure that the boiler could be brought on line quickly. This would reduce the size of the steam accumulator needed for starting the system. Concept 3 would also impact the ACL cooler, since cooling water would have to be provided to the condenser. A boiler with a capacity of about 1.5 MW (5×10^6 Btu/hr) would be required to drive the system. This would require about 100 gal/hr of kerosene or the equivalent in other fuels for the maximum operating condition. This concept is very attractive from the standpoint of simplicity, reliability, and cost. Its main disadvantages are the qualifying of a boiler for this application, the need to continuously power the system at idle, and the added heat load on the ALC heat exchanger produced plus the need to provide a steam accumulator.

9.2.2.3.2. Steam Turbine Design. There are a number of existing commercial steam turbines that operate within the steam conditions possible for Concept 3 and the power and speed requirements of the system. As noted previously, a special adaptation of an existing design or a new steam turbine design would be required if the steam turbine were to be submerged in the PCRV.

9.2.2.3.3. Summary. Concept 3 can be considered a viable candidate for this application as long as continuous idle operation of the system and the impact on the ALC can be accepted and an auxiliary boiler can be qualified for Class 1 operation.

9.2.2.4. Concept 4, Independent Source, Open Loop (Fig. 9-13). Concept 4 is similar to Concept 3, except that the exhaust steam from the steam turbine and pump drives would be exhausted to the environment after having heated up the feedwater to near saturation temperature. In this concept, the problems associated with rejecting low-availability heat are avoided. However, a supply of up to 25,000 lb/hr (50 gpm) of fresh Class 1 water would be required. Exhausting the steam to the environment might also pose a problem. Concept 4 has the advantage of simplicity, low cost, and reliability (as long as the integrity of the water supply can be guaranteed). There would be no adverse affect on the ALC heat exchanger in this concept.

9.2.3. Gas Turbine Drive (Fig. 9-15, SK-6440-77-432)

A gas turbine drive system for the auxiliary circulator is shown in Fig. 9-15. It consists of a vertically mounted gas turbine engine, the associated fuel and air supplies, an exhaust stack, and necessary controls. The engine incorporates a combination axial-centrifugal compressor driven

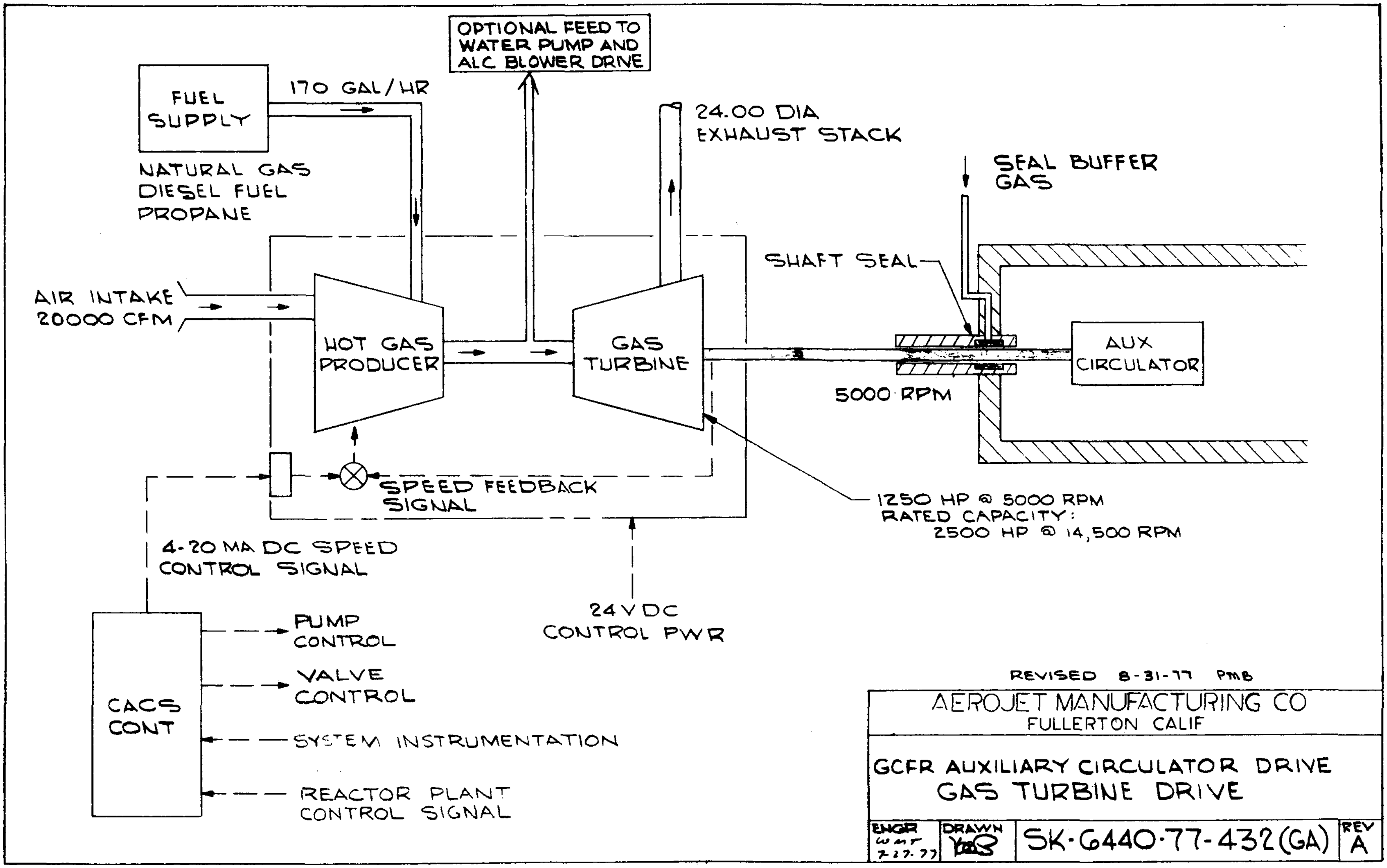

Fig. 9-15. Gas turbine drive

by an axial turbine (the hot gas producer) and an independent free-shaft power turbine driving the output shaft. The turbine would likely be located outside the PCRV. Therefore, the turbine shaft would be coupled to the circulator through an elaborate penetration seal, such as a ferrofluidic seal.

This alternate gas turbine drive design is based on a commercial unit, Model Super TF25, manufactured by AVCO Lycoming Company. Similar units have been applied with vertical mounting in a vertical take-off aircraft. The unit is rated for 2500 hp at 14,500 rpm. At 5000 rpm it delivers about 1250 hp and therefore could be applied without any gearing.

At 1000-hp output, the engine requires 170 gal/hr of liquid propane (or the equivalent in other fuels). It requires about 20,000 cfm of fresh air. A 24-in. exhaust stack would be needed to exhaust the combustion products to the atmosphere. Both the fresh air intake and the combustion product exhaust ducts would penetrate the secondary containment.

Speed control is available down to a base idling speed. However, the output shaft can be stopped completely with an external brake. Meeting the low-speed requirements may require some development work.

There are various starting options for these engines. The starter can be electric, pneumatic, or hydraulic. The starter automatically disengages when the unit has started. Typical time to run from standstill to full output is 9 to 11 sec.

The unit is FAA approved and has an extensive history of reliable operation. It is 50 in. long with a 35 x 44 in. base. The cost of the commercial unit is about $250,000.

9.2.4. Comparison of Steam Turbine, Gas Turbine, and Hydraulic Turbine

1. High-Speed, High-Torque Requirements. All of the mechanical drives should be easily capable of handling this condition.

2. Low-Speed, Low-Torque Requirements. The steam and gas turbines will be able to operate in this regime, but the degree of speed control possible (and required) must be determined. Potential cavitation problems must be considered for the hydraulic turbines when operating in the low-speed regime. The low-speed lubrication and shaft flexibility problems must also be addressed.

3. Reliability. All of the mechanical drives are highly reliable so long as they are specifically designed to operate at the condition and in the environment required.

4. Space Requirements. The space available within the PCRV is more than adequate to accommodate all of the mechanical drives. Additional space outside the PCRV will be required to house the peripheral equipment associated with each of the concepts.

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9-2. "Gas-Cooled Fast Breeder Fast Reactor Preliminary Safety Information Document," General Atomic Report GA-A10298, Amendment 7, Appendix B, February 1976.

9-3. "Conceptual Design Evaluation of Alternate Auxiliary Circulator Motor Drive and Control System Components for the Gas Cooled Fast Reactor (GCFR)," Aerojet Manufacturing Company Report AMCO-1968-77-(01)ER, September 1977.

10. AUXILIARY CIRCULATOR DRIVE AND CONTROL SYSTEM EVALUATION

The 12 auxiliary circulator drive and control systems discussed in Section 9 have been evaluated in a systematic manner. This section discusses the methods of evaluation and presents all the evaluators and weighting factors in tabulated form. The evaluation results are presented in both a qualitative and a quantitative form, and a cost estimate for each system is considered.

10.1. EVALUATION METHODS

Two evaluation methods were employed: one is qualitative and the other is numerical. The first method resulted in the tabulation of the advantages and disadvantages of each alternate system described in Section 10.2. The second method resulted in the numerical values presented in Section 10.3.

The second method is based on the principles of classical decision theory modified to include estimates of relative weights of parameters. The 12 systems selected for evaluation can be considered as a set of alternatives

$$A = \{a_1,\ a_2,\ \ldots\ldots\ldots, a_m\}$$

for which there is a set of goals or objectives

$$O = \{o_1,\ o_2,\ \ldots\ldots\ldots, o_n\}\ .$$

In the present case, the objectives are 11 evaluators that include such items as system performance for the DBDA, performance for the pressurized cooldown accident, suitability for submergence of the drive in the PCRV, cost, and feasibility (see Table 9-1). For each alternative there is a rating, r_{ij}, of its relative capability of meeting each objective. These values, r_{ij}, form an 11 x 12 matrix. For the objectives (evaluators), a set of relative worths or weighting factors

$$W = \{w_1, w_2, \ldots\ldots\ldots, w_n\}$$

was established. Using the ratings and the weighting factors, the optimal course of action can be specified as the alternative that yields the maximum expected worth, or utility,

$$E(U) = \max_i \sum_{j=1}^{n} r_{ij} w_j .$$

Associated with each of the evaluators there is a set of specific aspects, which are shown in Table 10-1. For example, EP1, the performance for the DBDA, has six items. The rating r_{ij} used in the main matrix was established from another, smaller matrix that included ratings of each alternative with respect to the several aspects of each evaluator. Each of these aspects was also given a weighting factor. The individual item ratings and weighting factors were combined in the same manner described for the main matrix to produce a list of total scores for each evaluator. The scores were normalized to a value between 0 and 10 and thereby became the ratings, r_{ij}, used in the main matrix.

The weighting factors for both the individual items and the groups are listed in Table 10-1. These were established jointly by AMCO and GA, with the final set being determined by GA. The ratings were initially determined by AMCO and then were reviewed and discussed with GA. The final ratings reflect the GA comments. All weighting factors and ratings, except for costs, are based on engineering judgment.

The evaluators were broken into two groups as shown in Table 10-1. One group contains the evaluators related to engineering and performance and

TABLE 10-1
EVALUATORS AND WEIGHTING FACTORS FOR AUXILIARY CIRCULATOR DRIVE AND CONTROL SYSTEM

	Individual Item Weight	Group Weight
EP. ENGINEERING AND PERFORMANCE RELATED EVALUATORS		
EP1 For DBDA Function		4
1. Ability to achieve 4900 rpm.	4	
2. Quick start capability.	5	
3. Stability and control of high speed.	3	
4. Ability to operate from stored energy device for 2 min.	2	
5. Susceptibility to limitations in emergency power systems.	4	
6. Capability of meeting load conditions.	4	
EP2 For Pressurized Cooldown Accident		4
1. Ability to achieve low speed (100 rpm).	2	
2. Ability to accelerate to 300 rpm in 30 s.	4	
3. Stability and control of low speeds.	4	
4. Ability to operate from stored energy device for 2 hr.	5	
5. Susceptibility to limitations of emergency power systems.	2	
6. Capability of meeting load conditions.	3	
EP3 General Engineering and Design Aspects		2
1. Complexity of equipment to achieve speed range.	3	
2. Restrictions on speeds.	2	
3. Capability of meeting load conditions for standby and refueling.	3	
4. Special design problems (e.g., cavitation).	3	
5. Capability for scale-up to 5000 hp.	5	
6. Maintenance requirements.	3	
7. Noise and vibration considerations.	3	
EP4 Submergence Factor		3
1. Suitability for PCRV environment.	4	
2. Number and type of penetrations of PCRV.	3	
3. Size impact on PCRV.	4	
4. Expected maintenance in PCRV.	5	
5. Capability for in-servicing monitoring and inspection.	4	
6. Potential for contamination of reactor helium.	5	

TABLE 10-1 (Continued)

		Individual Item Weight	Group Weight
EP5	Impact on Other Systems		2
	1. Required services from BOP.	2	
	2. Impact on other CACS equipment.	4	
	3. Impact on facility due to size and type of equipment.	3	
EP6	Reliability		4
	1. Complexity of equipment.	5	
	2. Operating history.	4	
	3. Complexity/reliability of power supply.	4	
	4. Complexity/reliability of fluid system.	4	
EP7	Independence Factor		3
	1. Ability to operate without dependence on BOP or emergency power.	5	
	2. Independence from water supply.	3	
	3. Independence from external fuel supplies.	2	
CF.	COST AND FEASIBILITY RELATED EVALUATORS		
CF1	Cost		2
	Total cost from cost estimate	--	
CF2	Feasibility and Availability		3
	1. General feasibility.	5	
	2. Availability (confidence in vendor information).	3	
	3. Relation to state of the art.	3	
CF3	Other Cost and Schedule Impact Factors		2
	1. Required development.	5	
	2. Requirements for system tests and special testing facilities.	5	
CF4	Safety/Licensing Aspects		4
	1. Potential for qualification as safety Class I/Class IE equipment.	5	
	2. Reliability documentation.	5	

the other group contains those related to cost and feasibility. This arrangement permits a strictly technical engineering evaluation that is separate from a more administrative aspect. However, other groupings could be useful.

10.2. QUALITATIVE EVALUATION RESULTS

This section contains the qualitative results of the evaluations of the 12 alternate auxiliary circulator drive and control systems examined. The quantitative results are presented in Section 10.3. The qualitative results are tabulations of the advantages and disadvantages of the systems. The quantitative results are tables and charts derived from the rating method described in Section 10.1.

10.2.1. System Advantages and Disadvantages

10.2.1.1. Electrical Drives. The electrical drives investigated in this study share some common advantages and disadvantages, including the following:

Advantages

1. Power conductors afford easy sealing at the entry to the PCRV. No working fluids are involved.

2. There are few working parts in the drive motor.

3. Electrical drives have a long history of successful and reliable operation in commercial and nuclear applications.

4. Speed control is a commonly used operational requirement.

Disadvantages

1. The electrical drives employ electrical insulation and other motor materials subject to radiation and environmental damage.

2. The high-speed requirement of 4900 rpm is generally beyond the state of the art for motors of this size.

3. Motors have higher rotary moment of inertia than mechanical drives.

4. Because of controller limitations, starting torques are limited to about 1.0 or 1.5 times full load torque.

The unique characteristics of each electrical drive system are described below.

10.2.1.1.1. Converter Cascade Wound-Rotor Induction Motor Drive.

Advantages

1. Low speed control is good.

2. The starting time for the DBDA is adequate (~30 s); the starting torque is high.

3. The drive can be scaled up to over 10,000 hp.

4. The drive has good tolerance for voltage and frequency transients in emergency power systems.

5. A 50:1 speed range is within the state of the art.

6. The drive can be submerged in the circulator cavity but would require special design. Only electrical conductors and motor coolant lines require sealing.

7. The drive has a good commercial operating history.

Disadvantages

1. The drive has difficulty in achieving high speed, requiring a three-mode controller or a step-up gear box.

2. It is difficult to control higher speeds, especially near-synchronous speed.

3. Special equipment is required to operate from a battery supply.

4. The drive has slip rings and brushes.

5. At least six electrical power conductors are required.

6. The controller is more complicated than the reference case controller.

7. The cost is higher than the reference case cost.

8. The drive has no previous history of qualification as Class I equipment.

9. The drive is essentially a torque controller and requires a speed feedback signal for control.

10.2.1.1.2. SCR-Controlled d.c. Motor.

Advantages

1. Speed control is good over the normal design range.

2. The drive has a simple, most reliable controller.

3. The drive has a good and extensive commercial operating history.

4. The motor reliability is good with proper periodic maintenance.

5. The basic system is the least costly of any electric drive.

Disadvantages

1. A speed of 4900 rpm cannot be achieved directly in this size range; gearing up with ratios up to 4:1 is required.

2. A 50:1 speed range cannot be achieved in this size range; two motors are probably required.

3. The drive has brushes and a commutator.

4. The drive has relatively high inertia and therefore a longer startup time.

5. The prospects for scaling up are not good.

6. The drive is difficult to operate from a battery supply.

7. There is no record of previous qualification.

10.2.1.1.3. Variable Frequency-Controlled Induction Motor.

Advantages

1. The starting time is adequate for the DBDA (~30 s).

2. Speed control is excellent at high speeds.

3. Speed control is good at low speeds.

4. The 50:1 speed range appears to be within the state of the art.

5. The system has intrinsic speed control because frequency is controlled; it can operate with an open loop.

6. The simple motor construction is adaptable to submergence in the PCRV.

7. The simple squirrel-cage rotor construction with no brushes, slip rings, or commutator requires no maintenance.

8. Only three power conductors are required.

9. Only electrical conductors and coolant lines require sealing.

10. The drive is adaptable to battery operation with little or no additional equipment.

11. A controller and motor of this type have been partially qualified as Class I equipment.

12. Vertically mounted squirrel-cage induction motors of 1000-, 2000-, and 3000-hp (1800 rpm) size have been qualified for light water reactor (LWR) emergency core cooling systems.

13. The system presents a favorable starting load to an emergency power system.

14. Although all vendors are reluctant to make any firm commitments, the most likely ones seem to favor this system.

15. Some good commercial operating history is developing.

Disadvantages

1. To achieve speeds above 4400 rpm (nominal 3600 rpm + 25%) will require development. There is no operating history or test results at speeds around 4900 rpm.

2. Scaling up may be limited. The indicated size limit is in the range of 2500 to 7000 hp.

3. The controller is relatively complex.

4. There may be some correctable instabilities in the low-speed range.

10.2.1.1.4. Variable Frequency-Controlled Synchronous Motor Drive.

Advantages

1. The starting time is adequate for the DBDA (~30 s).

2. Speed control is excellent at high speeds.

3. Speed control is good and probably excellent at low speeds.

4. The 50:1 speed range appears to be within the state of the art.

5. Construction is adaptable to submergence in the PCRV.

6. Only electrical conductors and coolant lines require sealing.

7. The drive has potential for a simpler and cheaper controller.

8. Scaling up to over 10,000 hp is feasible.

9. The drive has a good commercial operating history.

Disadvantages

1. To achieve speeds above 4400 rpm will require development.

2. Slip rings and brushes for the rotary transformer and rectifiers on the rotor are required for field excitation.

3. There may be some correctable instabilities in the low-speed range.

4. Adapting to battery operation may require additional equipment if a simpler controller is used.

10.2.1.1.5. Variable Frequency-Controlled Dual Induction Motor Drive.

Advantages

1. The starting time is adequate for the DBDA (~30 s).

2. Speed control is excellent at high speeds.

3. Speed control is excellent at low speeds.

4. A speed range of more than 50:1 is feasible.

5. The system can operate with an open loop.

6. The simple motor construction is adaptable to submergence in the PCRV.

7. The drive has a simple squirrel-cage rotor construction.

8. Only electrical conductors and coolant lines require sealing.

9. The drive is adaptable to battery operation with little or no additional equipment.

10. Similar equipment has been qualified or partially qualified.

11. Components of this system are developing a good commercial operating history.

12. The system presents a favorable starting load to an emergency power system.

Disadvantages

1. Two motors and associated coupling are required.

2. The controller is more complex; two inverters are required.

3. There is no record of system qualification.

4. To achieve speeds above 4400 rpm will require development.

5. The system is more expensive than the reference case.

10.2.1.2. Mechanical Drives. The mechanical drives investigated in this study (hydraulic, steam, and gas turbines) share many characteristics in common, including the following:

Advantages

1. The drives are quick starting with good speed-torque characteristics.

2. They have good growth potential with scaleup to higher power posing minimum problems.

3. They are compact, with high power output for the space occupied.

4. The drive motors are reliable.

5. The drives have rotational speed capability; 4900 rpm is well within their proven operating speed range.

Disadvantages

1. The drives have sealing problems involving protection of the reactor cavity from the working fluids (e.g., water, steam, combustion products) and vice versa.

2. The low-speed control characteristics are unknown. AMCO has found no applications of mechanical turbines covering a range of speed control as wide as that (50:1) required in this application.

The unique characteristics of each type of mechanical drive are described below.

10.2.1.2.1. Hydraulic Turbine Drive.

Advantages

1. The system is quick starting (<8 s) with high starting torque and linear speed-torque characteristics.

2. High power output is obtained for the space occupied.

3. The system has high reliability with simple rugged construction and simple design.

4. Speed control is achieved over a wide range of speeds using simple and reliable techniques (needle nozzle and/or deflector for Pelton wheel; Wicket gate for Francis turbine). However, the system may not adequately cover the 50:1 speed range required for this application.*

5. Expansion of the power requirements to 3000 or even 5000 hp would have minimal impact on the hydraulic turbine or supporting system design.

6. It is possible to consider the use of an elevated storage tank (50-ft elevation) to provide a 2-hr backup supply of energy (50,000 gal, 6500 ft^3) in the Pelton wheel concept or half that using the dual turbine concept** for the pressurized cooldown application.

7. The hydraulic turbine drives, using electrically driven pumps, should be among the least costly of the auxiliary circulator drives proposed.

*AMCO has found no application of a Pelton wheel where such a wide range of speeds was used.

**But with a 100-ft head.

8. There is no maximum speed limitation. Hydraulic turbines have been operated at considerably higher rotating speeds than required for this application.

Disadvantages

1. The system requires the introduction of large quantities of water into the PCRV (1200 gpm max.) (4-in. inlet line, 6- to 8-in. exit line).

2. Pumps are required. These can be electrically or mechanically driven, but all the pumps and blowers in the CACS should be driven by the same means.* This will probably weigh in favor of electrical drive motors since the grid power can be used and backup electrical power has to be supplied for other systems.

3. It has not yet been demonstrated that a hydraulic turbine designed for the high-speed, high-torque requirement can give satisfactory service for the low-speed, low-torque operations required for this application.**

4. Potential cavitation problems must be considered in the Pelton wheel and system design for the low-speed, low-torque operating conditions.

5. The Pelton wheel housing must be sealed against the high-pressure, high-temperature helium in the PCRV. Since the electric motor drive for this application will be allowed to see the PCRV cavity pressure, this problem applies only to the mechanical drives. In addition, if the Pelton wheel is top mounted, the PCRV cavity

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*This is a reliability requirement, since the loss of any pump or blower will shut the system down in any case.

**AMCO has found no application of a Pelton wheel where such a wide range of speeds was used.

will have to be sealed against water leakage. If the Pelton wheel is bottom mounted, the second sealing problem mentioned above will not apply.

10.2.1.2.2. Steam Turbine Drive.

Advantages

1. The system is quick starting* (<5 s) with the high starting torque and linear speed-torque characteristics for steam turbines (all concepts).

2. High power output can be obtained for the space occupied (although not as good as with a hydraulic turbine) (all concepts).

3. No outside energy source is required once the system is started.** The system is self-sustaining, since it utilizes the reject heat from the auxiliary heat removal system as the energy source to drive it (Concepts 1 and 2).

4. Steam turbines are highly reliable. However, the remainder of the system, owing to its complexity and the presence of a steam generator or boiler in the system, is less reliable than hydraulic turbine drives (all concepts).

5. There are a number of existing commercial steam turbines that could be adapted for this application so long as a conditioned cavity (lower temperature and pressure) was provided within the PCRV (all concepts).

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*Balance of plant steam can be used for quick starting until the sustaining source is brought on line.

**Requires increasing the CACWS maximum loop temperature to 575° to 600°F from 500°F.

6. Expansion of the power requirements to 3000 or even 5000 hp would have minimal impact on the concept,* although it will affect the turbine and the balance of the loop design (all concepts).

7. Good speed control is provided over a wide range of speeds using simple and reliable techniques (steam flow control). However, good speed control over the entire 50:1 speed range may pose a problem.

8. The system has high rotational speed capability; 4900 rpm is well below the maximum proven operating speed of steam turbines.

Disadvantages

1. The system requires increasing the hot leg temperature of the CACWS loop (Concept 1) by 75° to 100°F or converting it to a boiling water loop (Concept 2), also at a higher temperature.

2. The ALC hot-side fluid temperature is greatly reduced, thereby more than doubling the heat transfer surface required if the heat is rejected by a dry cooling tower (Concepts 1, 2, and 3). This problem would be greatly reduced if a cooling stream or pond were used as the heat sink rather than the atmosphere.

3. The boot strap systems (Concepts 1 and 2) and the closed loop boiler system require the use of a number of additional components (e.g., condenser, condensate pump, steam generation, or boiler) which increase the cost and reduce the reliability of the auxiliary cooling system.

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*Assuming that the heat rejection is proportionately increased.

4. Concepts 3 and 4 would require idling the boiler during normal plant operation. All concepts would probably require heat conditioning of all components which would be exposed to the steam and are not located within the PCRV.

5. The boot strap steam turbine concepts would require the greatest amount of development, and that and the number of auxiliary components involved would ensure the greatest costs.

6. Concepts 3 and 4 would require qualifying an auxiliary boiler to nuclear standards. Commercial boiler manufacturers would probably not be willing to do so for a one-of-a-kind boiler.

7. Operation of the steam turbine and its auxiliary equipment in the PCRV will require a conditioned space (lower pressure and temperature) within the PCRV cavity.

10.2.1.2.3. Gas Turbine Drive.

Advantages

1. The system is quick starting with good speed-torque characteristics. Ignition can be achieved using reliable techniques such as start cans with squibs.

2. The gas turbine drive is a simple, self-contained system consisting, in addition to controls, only of the compressed gas generator, the gas turbine, a fuel tank, a speed reduction device (if needed), and the inlet and exhaust ducts.

3. Expansion of the power requirements to 3000 or even 5000 hp would have little impact on the concept feasibility.

4. The gas turbine should be the least costly of all of the drives studied because of its simplicity so long as it is based upon an existing gas turbine design.

Disadvantages

1. A large exhaust stack (24 in.) must be provided to remove the combustion products from the reactor building.

2. About 0.5 lb per horsepower-hour of kerosene (or the equivalent in other fuels) will be needed to run the gas turbine, requiring fairly large storage tanks and periodic refilling during operation.

3. Speed control for the low range of speeds is a potential problem, since this range is far below the normal operating speed range of a gas turbine.

4. If the auxiliary circulator is driven by a gas turbine, the other pumps and blower drives in the system should be driven by the same means. However, transporting hot gases in large ducts over great distances may not be very practical.

Existing Gas Turbine Design Only

5. Most existing gas turbines operate at high speed (20,000 rpm) and may therefore require speed reduction through a gear box or torque converter for this application. A direct drive is possible, however, if the turbine is run below its rated speed.

6. Most gas turbines that AMCO has found have horizontal shafts, and they would therefore require a device to transmit the power to the intersecting right angle circulator shaft. However, a vertical shaft gas turbine of this size has been used for vertical take-off aircraft and is commercially available.

7. Existing gas turbines would have to be located outside of the PCRV cavity, and an elaborate seal arrangement would therefore have to be provided for the rotating shaft penetration.

New Gas Turbine Design Only

8. In order to remove the disadvantages associated with items 5 through 7, a new gas turbine design would be required. The new design would operate on a vertical shaft at the desired speeds. In order to eliminate the rotating shaft penetration seals for the PCRV, the hot gas and compression section of the gas turbine would be physically separated from the turbine wheel driving the auxiliary circulator, which would be located within the PCRV. The cost of developing the new gas turbine for the application could easily exceed one million dollars.

9. Combustion products (hydrocarbons) will be introduced into the PCRV cavity if the turbine wheel driving the auxiliary circulator is located within the PCRV.

10. If the wheel driving the auxiliary circulator is located within the PCRV, shaft seals must be provided to prevent the combustion products from contaminating the reactor coolant helium. Also, large (24-in.) combustion product inlet and exit line penetrations of the PCRV must be provided.

10.3. NUMERICAL RATINGS

The results of the numerical evaluation method described in Section 10.1 are presented in this section. The ratings for the individual items listed for each evaluator in Table 10-1 are presented first on the charts shown in Figs. 10-1 through 10-11.

In these charts, the rating for each system with respect to each individual evaluator item is a number from 0 to 10 in the upper left of each box. The number in the lower right is the product of the rating and the weighting factor. The horizontal sum of these products is the total score for each system. The final column on the right contains the rating normalized to a value from 0 to 10. It is the total rating divided by the maximum possible value.

The individual ratings are based on the information accumulated for each alternate system during the course of the study. The basic information has been presented in Section 9 and in the tabulation of advantages and disadvantages in Section 10.2. The final numbers are based on engineering judgment. Each of the AMCO evaluators scored the systems individually and then compared results and revised them by mutual agreement. The ratings were refined in the light of new information received and as a result of discussions with GA personnel.

In the first column in the charts, the systems are designated by an abbreviated title and the last three numbers of the block diagram sketch number.

In the following sections, the major reasons for some of the ratings are briefly explained.

10.3.1. Performance for DBDA Function (EP1, Fig. 10-1).

This evaluator rates each system with respect to its capability to perform according to the requirements during a DBDA. The system must achieve 4900 rpm well within 85 s. In addition, it must operate through a transition period, perhaps as long as 2 min, when there has been an electrical power failure and the system is switched to a source of emergency power. There may be severe voltage and frequency variations during this period.

The electric drives have generally lower ratings than the mechanical drives because of their high-speed limitations and slower acceleration

DRIVE SYSTEM TITLE & NUMBER	INDIVIDUAL EVALUATORS 1	2	3	4	5	6	7	TOTAL SCORE	0 TO 10 RATING
WEIGHTING FACTORS	4	5	3	2	4	4		220 MAX	
-431(GA) CONVERTER CASCADE	5/20	7/35	5/15	4/8	9/36	7/28	/	142	6.5
-433(GA) CONTROLLED DC MOTOR	2/8	4/20	9/27	4/8	9/36	3/12	/	111	5.0
-434 (GA) VARI FREQ INDUCT MOTOR	7/28	7/35	9/27	8/16	7/28	7/28	/	162	7.4
-468(GA) VARI FREQ SYNCH MOTOR	7/28	7/35	10/30	6/12	7/28	7/28	/	161	7.3
-437 (GA) VARI FREQ DUAL MOTOR	7/28	6/30	9/27	7/14	7/28	7/28	/	155	7.0
-432(GA) GAS TURBINE	10/40	8/40	9/27	10/20	10/40	10/40	/	207	9.4
-456(GA) PELTON WHEEL 2 JET	10/40	10/50	8/24	5/10	10/40	10/40	/	204	9.3
-457(GA) HYDRO TURBINE 2 WHEEL	10/40	10/50	8/24	5/10	10/40	10/40	/	204	9.3
-467(GA) STEAM TURBINE NON BOILING CACWS	10/40	7/35	8/24	10/20	10/40	10/40	/	199	9.0
-472(GA) STEAM TURBINE BOILING CACWS	10/40	7/35	8/24	10/20	10/40	10/40	/	199	9.0
-464(GA) STEAM TURBINE CLOSED LOOP	10/40	6/30	8/24	10/20	10/40	10/40	/	194	8.8
-466(GA) STEAM TURBINE OPEN LOOP	10/40	6/30	8/24	10/20	10/40	10/40	/	194	8.8

Fig. 10-1. Evaluation chart: EP1 DBDA function

capability. The frequency-controlled systems (434, 468, and 437) will be affected by the voltage and frequency variations.

In general, the mechanical systems excel in regard to this evaluation factor. The hydraulic turbine systems received lower ratings because they require special equipment to perform through the transition to emergency power. The steam systems were rated lower because of startup difficulties.

10.3.2. Performance for Pressurized Cooldown Accident (EP2, Fig. 10-2)

This evaluator rates each system with respect to its performance during a pressurized cooldown accident. The mechanical systems generally received lower ratings because of anticipated problems in controlling them at low speeds. The dual electrical and mechanical units (437, 456, and 457) were rated high because of the second drive designed specifically for the low speeds.

10.3.3. General Engineering and Design Aspects (EP3, Fig. 10-3)

This evaluator rates each system with respect to general engineering and design aspects not considered in EP1 and EP2. All the systems are considered generally complex, and hence the ratings did not differ much in this regard. Even the d.c. motor drive, which was expected to be the simplest, was proposed by a vendor as a two-motor system.

All the mechanical systems scored 10 with respect to scaling up for a commercial-size reactor. The electrical systems have definite limitations in this regard. The mechanical systems, however, scored low with respect to maintenance and noise considerations.

10.3.4. Submergence Factor (EP4, Fig. 10-4)

This evaluator rated the difficulty of putting the drive inside the PCRV. Although no system is perfectly suited for the PCRV environment, the

DRIVE SYSTEM TITLE & NUMBER	INDIVIDUAL EVALUATORS 1	2	3	4	5	6	7	TOTAL SCORE	0 TO 10 RATING
WEIGHTING FACTORS	2	4	4	5	2	3		200 MAX	
-431(GA) CONVERTER CASCADE	10 / 20	10 / 40	8 / 32	4 / 20	10 / 20	10 / 30	/	162	8.1
-433(GA) CONTROLLED DC MOTOR	7 / 14	8 / 32	8 / 32	6 / 30	10 / 20	8 / 24	/	152	7.6
-434 (GA) VARI FREQ INDUCT MOTOR	7 / 14	9 / 36	8 / 32	7 / 35	8 / 16	9 / 27	/	160	8.0
-468(GA) VARI FREQ SYNCH MOTOR	7 / 14	9 / 36	8 / 32	7 / 35	8 / 16	9 / 27	/	160	8.0
-437 (GA) VARI FREQ DUAL MOTOR	10 / 20	10 / 40	10 / 40	9 / 45	8 / 16	10 / 30	/	191	9.6
-432(GA) GAS TURBINE	5 / 10	10 / 40	2 / 8	10 / 50	10 / 20	8 / 24	/	152	7.6
-456(GA) PELTON WHEEL 2 JET	7 / 14	9 / 36	6 / 24	8 / 40	9 / 18	8 / 24	/	156	7.8
-457(GA) HYDRO TURBINE 2 WHEEL	10 / 20	9 / 36	8 / 32	9 / 45	9 / 18	10 / 30	/	181	9.1
-467(GA) STEAM TURBINE NON BOILING CACWS	5 / 10	10 / 40	4 / 16	8 / 40	10 / 20	8 / 24	/	150	7.5
-472(GA) STEAM TURBINE BOILING CACWS	5 / 10	10 / 40	4 / 16	8 / 40	10 / 20	8 / 24	/	150	7.5
-464(GA) STEAM TURBINE CLOSED LOOP	5 / 10	8 / 32	4 / 16	7 / 35	10 / 20	8 / 24	/	137	6.9
-464 (GA) STEAM TURBINE OPEN LOOP	5 / 10	8 / 32	4 / 16	7 / 35	10 / 20	8 / 24	/	137	6.9

Fig. 10-2. Evaluation chart: EP2, pressurized cooldown

DRIVE SYSTEM TITLE & NUMBER	INDIVIDUAL EVALUATORS 1	2	3	4	5	6	7	TOTAL SCORE	0 TO 10 RATING
WEIGHTING FACTORS	3	2	3	3	5	3	3	220 MAX	
-431(GA) CONVERTER CASCADE	6/18	7/14	8/24	4/12	7/35	7/21	10/30	154	7.0
-433(GA) CONTROLLED DC MOTOR	5/15	6/12	7/21	5/15	3/15	3/9	8/24	111	5.0
-434 (GA) VARI FREQ INDUCT MOTOR	8/24	9/18	9/27	8/24	6/30	10/30	10/30	183	8.3
-468(GA) VARI FREQ SYNCH MOTOR	8/24	9/18	9/27	7/21	7/35	9/27	10/30	182	8.3
-437 (GA) VARI FREQ DUAL MOTOR	8/24	10/20	10/30	6/18	6/30	9/27	10/30	179	8.1
-432 (GA) GAS TURBINE	8/24	9/18	9/27	6/18	9/45	8/24	7/21	177	8.0
-456(GA) PELTON WHEEL 2 JET	7/21	8/16	9/27	4/12	10/50	8/24	7/21	171	7.8
-457(GA) HYDRO TURBINE 2 WHEEL	6/18	8/16	9/27	5/15	10/50	8/24	7/21	171	7.8
-467(GA) STEAM TURBINE NON BOILING CACWS	8/24	9/18	9/27	8/24	10/50	6/18	7/21	182	8.3
-472(GA) STEAM TURBINE BOILING CACWS	8/24	9/18	9/27	4/12	10/50	4/12	7/21	164	7.5
-464(GA) STEAM TURBINE CLOSED LOOP	8/24	9/18	9/27	5/15	10/50	3/9	6/18	161	7.3
-464(GA) STEAM TURBINE OPEN LOOP	8/24	9/18	9/27	9/27	10/50	3/9	6/18	173	7.9

Fig. 10-3. Evaluation chart: EP3, general engineering and design

DRIVE SYSTEM TITLE & NUMBER	INDIVIDUAL EVALUATORS 1	2	3	4	5	6	7	TOTAL SCORE	0 TO 10 RATING
WEIGHTING FACTORS	4	3	4	5	4	5		250 MAX	
-431 (GA) CONVERTER CASCADE	6/24	8/24	9/36	7/35	5/20	9/45	/	184	7.4
-433 (GA) CONTROLLED DC MOTOR	4/16	7/21	6/24	3/15	4/16	8/40	/	132	5.3
-434 (GA) VARI FREQ INDUCT MOTOR	9/36	9/27	10/40	9/45	8/32	10/50	/	230	9.2
-468 (GA) VARI FREQ SYNCH MOTOR	8/32	9/27	9/36	7/35	5/20	9/45	/	195	7.8
-437 (GA) VARI FREQ DUAL MOTOR	9/36	8/24	8/32	8/40	8/32	10/50	/	214	8.6
-432 (GA) GAS TURBINE	0/0	2/6	3/12	4/20	2/8	0/0	/	46	1.8
-456 (GA) PELTON WHEEL 2 JET	7/28	5/15	9/36	8/40	5/20	3/15	/	154	6.2
-457 (GA) HYDRO TURBINE 2 WHEEL	7/28	5/15	9/36	9/45	5/20	3/15	/	159	6.4
-467 (GA) STEAM TURBINE NON BOILING CACWS	5/20	3/9	9/36	8/40	5/20	3/15	/	140	5.6
-472 (GA) STEAM TURBINE BOILING CACWS	5/20	9/27	4/16	6/30	4/16	3/15	/	124	5.0
-464 (GA) STEAM TURBINE CLOSED LOOP	5/20	3/9	9/36	8/40	5/20	3/15	/	140	5.6
-464 (GA) STEAM TURBINE OPEN LOOP	5/20	3/9	9/36	8/40	5/20	3/15	/	140	5.6

Fig. 10-4. Evaluation chart: EP4, submergence factor

reference system (434) and its variation (437) rate high because of the HTGR background for the reference system. With respect to sealing penetrations, the electrical systems rate high because of the relative ease of sealing the electrical conductors.

Size is not a problem except perhaps with the gas turbine. Maintenance inside the PCRV is expected to be required more often for the d.c. motor and the gas turbine. In-service monitoring would be difficult for any system, but the induction motor drives (434 and 437) rate higher because of their simpler internals. Some thermocouples may be sufficient.

The mechanical systems suffer because of their use of a fluid that has potential for contaminating the reactor helium.

10.3.5. Impact on Other Systems (EP5, Fig. 10-5)

This evaluator rates the impact of each alternate system on the other systems in the reactor plant. The impact could result in a significant change in the design, cost, or performance of the other systems.

The steam systems rated very low in this regard because of their great impact on the CACS and their demands for steam, water, and space from the BOP.

10.3.6. Reliability (EP6, Fig. 10-6)

This evaluator attempts to quantify the reliability of each alternate system. Because many of the requirements are beyond the normal operating modes of the components considered, there are no statistical data available.

All the suppliers contend that their components or systems are highly reliable. Attempts to get quantitative information from them, even for normal operating ranges, were not successful. However, each drive has had a history of successful commercial operation, although little or no

DRIVE SYSTEM TITLE & NUMBER	INDIVIDUAL EVALUATORS 1	2	3	4	5	6	7	TOTAL SCORE	0 TO 10 RATING
WEIGHTING FACTORS	2	4	3					90 MAX	
-431 (GA) CONVERTER CASCADE	9 / 18	10 / 40	7 / 21	/	/	/	/	79	8.8
-433 (GA) CONTROLLED DC MOTOR	9 / 18	10 / 40	9 / 27	/	/	/	/	85	9.4
-434 (GA) VARI FREQ INDUCT MOTOR	9 / 18	10 / 40	8 / 24	/	/	/	/	82	9.1
-468 (GA) VARI FREQ SYNCH MOTOR	9 / 18	10 / 40	7 / 21	/	/	/	/	79	8.8
-437 (GA) VARI FREQ DUAL MOTOR	9 / 18	10 / 40	7 / 21	/	/	/	/	79	8.8
-432 (GA) GAS TURBINE	10 / 20	10 / 40	6 / 18	/	/	/	/	78	8.7
-456 (GA) PELTON WHEEL 2 JET	8 / 16	10 / 40	8 / 24	/	/	/	/	80	8.9
-457 (GA) HYDRO TURBINE 2 WHEEL	8 / 16	10 / 40	8 / 24	/	/	/	/	80	8.9
-467 (GA) STEAM TURBINE NON BOILING CACWS	4 / 8	1 / 4	5 / 15	/	/	/	/	27	3.0
-472 (GA) STEAM TURBINE BOILING CACWS	4 / 8	1 / 4	2 / 6	/	/	/	/	18	2.0
-464 (GA) STEAM TURBINE CLOSED LOOP	4 / 8	1 / 4	3 / 9	/	/	/	/	21	2.3
-464 (GA) STEAM TURBINE OPEN LOOP	4 / 8	9 / 36	6 / 18	/	/	/	/	62	6.9

Fig. 10-5. Evaluation chart: EP5, impact on other systems

DRIVE SYSTEM TITLE & NUMBER	INDIVIDUAL EVALUATORS 1	2	3	4	5	6	7	TOTAL SCORE	0 TO 10 RATING
WEIGHTING FACTORS	5	4	4	4				170 MAX	
-431(GA) CONVERTER CASCADE	7 / 35	7 / 28	7 / 28	10 / 40	/	/	/	131	7.7
-433(GA) CONTROLLED DC MOTOR	7 / 35	9 / 36	10 / 40	10 / 40	/	/	/	151	8.9
-434 (GA) VARI FREQ INDUCT MOTOR	7 / 35	8 / 32	8 / 32	10 / 40	/	/	/	139	8.2
-468(GA) VARI FREQ SYNCH MOTOR	6 / 30	6 / 24	8 / 32	10 / 40	/	/	/	126	7.4
-437 (GA) VARI FREQ DUAL MOTOR	6 / 30	5 / 20	7 / 28	10 / 40	/	/	/	118	6.9
-432(GA) GAS TURBINE	7 / 35	9 / 36	10 / 40	8 / 32	/	/	/	143	8.4
-456(GA) PELTON WHEEL 2 JET	8 / 40	7 / 28	10 / 40	5 / 20	/	/	/	128	7.5
-457(GA) HYDRO TURBINE 2 WHEEL	7 / 35	7 / 28	10 / 40	5 / 20	/	/	/	123	7.2
-467(GA) STEAM TURBINE NON BOILING CACWS	3 / 15	6 / 24	10 / 40	2 / 8	/	/	/	87	5.1
-472(GA) STEAM TURBINE BOILING CACWS	1 / 5	6 / 24	10 / 40	1 / 4	/	/	/	73	4.3
-464(GA) STEAM TURBINE CLOSED LOOP	2 / 10	6 / 24	10 / 40	2 / 8	/	/	/	82	4.8
-464(GA) STEAM TURBINE OPEN LOOP	8 / 40	8 / 32	10 / 40	6 / 24	/	/	/	136	8.0

Fig. 10-6. Evaluation chart: EP6, reliability

history of operation in the environment of this application. Complexity of basic equipment and accessories was the main consideration in these ratings.

10.3.7. Independence Factor (EP7, Fig 10-7)

This evaluator rates the capability of each alternate to function without dependence on another part of the plant. However, even the highly rated and independent gas turbine drive depends on a fuel supply. The electrical systems depend on the diesel-driven generators of the emergency power systems and are a significant load on them. The rating of 1 is not 0 because the electrical systems can operate on their own batteries for a short time.

10.3.8. Cost (CF1, Fig. 10-8)

The cost information is derived from the cost estimates in Section 9. The rating is determined from the relation

$$R = \frac{2500 - C}{175} ,$$

where C is the cost in thousands of dollars. The relation is an arbitrary one and puts the rating on a linear scale with respect to cost so that 10 corresponds to a cost of $750,000 and 0 to $2,500,000.

10.3.9. Feasibility and Availability (CF2, Fig. 10-9)

This evaluator rates the feasibility of employing each drive in this application and estimates how available it would be.

The high ratings in the category were given to the reference system and the Pelton wheel drive because of vendor response and the previous procurement activities for HTGRs, including the Fort St. Vrain reactor.

DRIVE SYSTEM TITLE & NUMBER	INDIVIDUAL EVALUATORS 1	2	3	4	5	6	7	TOTAL SCORE	0 TO 10 RATING
WEIGHTING FACTORS	5	3	2					100 MAX	
-431(GA) CONVERTER CASCADE	1 / 5	8 / 24	10 / 20					49	4.9
-433(GA) CONTROLLED DC MOTOR	1 / 5	8 / 24	10 / 20					49	4.9
-434 (GA) VARI FREQ INDUCT MOTOR	1 / 5	8 / 24	10 / 20					49	4.9
-468(GA) VARI FREQ SYNCH MOTOR	1 / 5	8 / 24	10 / 20					49	4.9
-437 (GA) VARI FREQ DUAL MOTOR	1 / 5	8 / 24	10 / 20					49	4.9
-432 (GA) GAS TURBINE	10 / 50	10 / 30	0 / 0					80	8.0
-456 (GA) PELTON WHEEL 2 JET	4 / 20	8 / 24	5 / 10					54	5.4
-457 (GA) HYDRO TURBINE 2 WHEEL	4 / 20	8 / 24	5 / 10					54	5.4
-467 (GA) STEAM TURBINE NON BOILING CACWS	8 / 40	9 / 27	10 / 20					87	8.7
-472 (GA) STEAM TURBINE BOILING CACWS	8 / 40	9 / 27	10 / 20					87	8.7
-464 (GA) STEAM TURBINE CLOSED LOOP	8 / 40	9 / 27	0 / 0					67	6.7
-464 (GA) STEAM TURBINE OPEN LOOP	8 / 40	0 / 0	0 / 0					40	4.0

Fig. 10-7. Evaluation chart: EP7, independence factor

DRIVE SYSTEM TITLE & NUMBER	TOTAL COST 1000 DOLLARS	0 TO 10 RATING
-431 (GA) CONVERTER CASCADE	1244	7.2
-433 (GA) CONTROLLED DC MOTOR	1186	7.5
-434 (GA) VARI FREQ INDUCT MOTOR	1090	8.1
-468 (GA) VARI FREQ SYNCH MOTOR	1165	7.6
-437 (GA) VARI FREQ DUAL MOTOR	1265	7.1
-432 (GA) GAS TURBINE	1130	7.8
-456 (GA) PELTON WHEEL 2 JET	1210	7.4
-457 (GA) HYDRO TURBINE 2 WHEEL	1310	6.8
-467 (GA) STEAM TURBINE NON BOILING CACWS	2063	2.5
-472 (GA) STEAM TURBINE BOILING CACWS	2148	2.0
-464 (GA) STEAM TURBINE CLOSED LOOP	2018	2.8
-464 (GA) STEAM TURBINE OPEN LOOP	1288	6.9

Fig. 10-8. Evaluation chart: CF1, cost

DRIVE SYSTEM TITLE & NUMBER	INDIVIDUAL EVALUATORS 1	2	3	4	5	6	7	TOTAL SCORE	0 TO 10 RATING
WEIGHTING FACTORS	5	3	3					110 MAX	
-431 (GA) CONVERTER CASCADE	7 / 35	6 / 18	7 / 21	/	/	/	/	74	6.7
-433 (GA) CONTROLLED DC MOTOR	3 / 15	3 / 9	5 / 15	/	/	/	/	39	3.5
-434 (GA) VARI FREQ INDUCT MOTOR	9 / 45	9 / 27	9 / 27	/	/	/	/	99	9.0
-468 (GA) VARI FREQ SYNCH MOTOR	8 / 40	7 / 21	8 / 24	/	/	/	/	85	7.7
-437 (GA) VARI FREQ DUAL MOTOR	7 / 35	5 / 15	7 / 21	/	/	/	/	71	6.5
-432 (GA) GAS TURBINE	3 / 15	8 / 24	9 / 27	/	/	/	/	66	6.0
-456 (GA) PELTON WHEEL 2 JET	6 / 30	6 / 18	6 / 18	/	/	/	/	66	6.0
-457 (GA) HYDRO TURBINE 2 WHEEL	8 / 40	8 / 24	8 / 24	/	/	/	/	88	8.0
-467 (GA) STEAM TURBINE NON BOILING CACWS	3 / 15	7 / 21	5 / 15	/	/	/	/	51	4.6
-472 (GA) STEAM TURBINE BOILING CACWS	5 / 25	7 / 21	5 / 15	/	/	/	/	61	5.5
-464 (GA) STEAM TURBINE CLOSED LOOP	5 / 25	7 / 21	3 / 9	/	/	/	/	55	5.0
-464 (GA) STEAM TURBINE OPEN LOOP	6 / 30	8 / 24	7 / 21	/	/	/	/	75	6.8

Fig. 10-9. Evaluation chart: CF2, feasibility/availability

10.3.10. Other Cost and Schedule Impact Factors (CF3, Fig. 10-10)

This evaluator rates the systems on the basis of the required development and testing. All systems require considerable development because of the requirements as related to the capabilities of available units. With respect to testing, the steam units that involve the CACS received very low ratings because of the anticipated difficulties in testing them in conjunction with the CACS.

10.3.11. Safety/Licensing Aspects (CF4, Fig. 10-11)

This evaluator rates the difficulty that would be associated with qualifying a system as Class I and producing the required documentation.

High ratings in this category were given to the reference system and the Pelton wheel drive because of their previous partial qualification and the existence of previous documentation for their applications in HTGRs, including the Fort St. Vrain reactor.

10.3.12. Total Ratings

The normalized ratings from each of the individual rating charts (Figs. 10-1 through 10-11) were transferred to the master rating chart shown in Fig. 10-12. These ratings were multiplied by the appropriate weighting factors and listed in the lower right corner of each box on the chart. The products were rounded off to the nearest whole number and totaled. The totals for the engineering and performance evaluators, the totals for the cost and feasibility evaluators, and the sums of the two are shown on the chart.

The total ratings are also shown on the bar chart in Fig. 10-13. (The system number refers to the numbers 1 through 12 next to the system titles on Fig. 10-12.) The charts show the two systems with the highest ratings: the electrical induction motor reference system (434) and the

DRIVE SYSTEM TITLE & NUMBER	INDIVIDUAL EVALUATORS							TOTAL SCORE	0 TO 10 RATING
	1	2	3	4	5	6	7		
WEIGHTING FACTORS	5	5						100 MAX	
-431 (GA) CONVERTER CASCADE	4 / 20	8 / 40						60	6.0
-433 (GA) CONTROLLED DC MOTOR	2 / 10	7 / 35						45	4.5
-434 (GA) VARI FREQ INDUCT MOTOR	6 / 30	9 / 45						75	7.5
-465 (GA) VARI FREQ SYNCH MOTOR	5 / 25	8 / 40						65	6.5
-437 (GA) VARI FREQ DUAL MOTOR	4 / 20	8 / 40						60	6.0
-432 (GA) GAS TURBINE	7 / 35	8 / 40						75	7.5
-456 (GA) PELTON WHEEL 2 JET	5 / 25	5 / 25						50	5.0
-457 (GA) HYDRO TURBINE 2 WHEEL	6 / 30	6 / 30						60	6.0
-467 (GA) STEAM TURBINE NON BOILING CACWS	5 / 25	2 / 10						35	3.5
-472 (GA) STEAM TURBINE BOILING CACWS	3 / 15	1 / 5						20	2.0
-464 (GA) STEAM TURBINE CLOSED LOOP	5 / 25	6 / 30						55	5.5
-464 (GA) STEAM TURBINE OPEN LOOP	6 / 30	6 / 30						60	6.5

Fig. 10-10. Evaluation chart: CF3, other cost and schedule impact factors

DRIVE SYSTEM TITLE & NUMBER	INDIVIDUAL EVALUATORS 1	2	3	4	5	6	7	TOTAL SCORE	0 TO 10 RATING
WEIGHTING FACTORS	5	5						100 MAX	
-431(GA) CONVERTER CASCADE	5 / 25	7 / 35						60	6.0
-433(GA) CONTROLLED DC MOTOR	3 / 15	6 / 30						45	4.5
-434 (GA) VARI FREQ INDUCT MOTOR	9 / 45	9 / 45						90	9.0
-468(GA) VARI FREQ SYNCH MOTOR	7 / 35	8 / 40						75	7.5
-437 (GA) VARI FREQ DUAL MOTOR	7 / 35	8 / 40						75	7.5
-432(GA) GAS TURBINE	2 / 10	6 / 30						40	4.0
-456 (GA) PELTON WHEEL 2 JET	7 / 35	8 / 40						75	7.5
-457 (GA) HYDRO TURBINE 2 WHEEL	8 / 40	8 / 40						80	8.0
-467(GA) STEAM TURBINE NON BOILING CACWS	6 / 30	4 / 20						50	5.0
-472(GA) STEAM TURBINE BOILING CACWS	6 / 30	4 / 20						50	5.0
-464(GA) STEAM TURBINE CLOSED LOOP	6 / 30	6 / 30						60	6.0
-464 (GA) STEAM TURBINE OPEN LOOP	6 / 30	6 / 30						60	6.0

Fig. 10-11. Evaluation chart: CF4, safety/licensing aspects

CACS DRIVE SYSTEM — TITLE AND SKETCH NUMBER	EP1 DBDA FUNCTION	EP2 PRESSURIZED COOL DOWN ACCIDENT	EP3 GENERAL ENGINEERING AND DESIGN	EP4 SUBMERGENCE FACTOR	EP5 IMPACT ON OTHER SYSTEMS	EP6 RELIABILITY	EP7 INDEPENDANCE FACTOR	ENGINEERING & PERFORMANCE TOTAL	CF1 COST	CF2 FEASIBILITY AVAILABILITY	CF3 OTHER COST AND SCHEDULE IMPACT FACTORS	CF4 SAFTEY/LICENSING ASPECTS	COST/FEASIBILITY TOTAL	TOTAL RATING	
WEIGHTING FACTORS	4	4	2	3	2	4	3		2	3	2	4			
1 SK6440-77-431(GA) CONVERTER CASCADE-WOUND ROTOR INDUCTION MOTOR DRIVE	6.5 / 26	8.1 / 32	7.0 / 14	7.4 / 22	8.8 / 18	7.7 / 31	4.9 / 15	158	7.2 / 14	6.7 / 20	6.0 / 12	6.0 / 24	70	228	
2 SK6440-77-433(GA) SCR-CONTROLLED DC MOTOR DRIVE	5.0 / 20	7.6 / 30	5.0 / 10	5.3 / 16	9.4 / 19	8.9 / 36	4.9 / 15	146	7.5 / 15	3.5 / 11	4.5 / 9	4.5 / 18	53	199	
3 SK6440-77-434(GA) VARIABLE FREQUENCY CONTROLLED INDUCTION MOTOR DRIVE	7.4 / 30	8.0 / 32	8.3 / 17	9.2 / 28	9.1 / 18	8.2 / 33	4.9 / 15	173	8.1 / 16	9.0 / 27	7.5 / 15	9.0 / 36	94	267	
4 SK6440-77-468(GA) VARIABLE FREQUENCY CONTROLLED SYNCHRONOUS MOTOR DRIVE	7.3 / 29	8.0 / 32	8.3 / 17	7.8 / 23	8.8 / 18	7.4 / 30	4.9 / 15	164	7.6 / 15	7.7 / 23	6.5 / 13	7.5 / 30	81	245	
5 SK6440-77-437(GA) VARIABLE FREQUENCY CONTROLLED DUAL INDUCTION MOTOR DRIVE	7.0 / 28	9.6 / 38	8.1 / 16	8.6 / 26	8.8 / 18	6.9 / 28	4.9 / 15	169	7.1 / 14	6.5 / 20	6.0 / 12	7.5 / 30	76	245	
6 SK6440-77-432(GA) GAS TURBINE DRIVE	9.4 / 38	7.6 / 30	8.0 / 16	1.8 / 5	8.7 / 17	8.4 / 34	8.0 / 24	164	7.8 / 16	6.0 / 18	7.5 / 15	4.0 / 16	65	229	
7 SK6440-77-456(GA) PELTON WHEEL APPLICATION 2-JET CONCEPT	9.3 / 37	7.8 / 31	7.8 / 16	6.2 / 19	8.9 / 18	7.5 / 30	5.4 / 16	167	7.4 / 15	6.0 / 18	5.0 / 10	7.5 / 30	73	240	
8 SK6440-77-457(GA) HYDRAULIC TURBINE APPLICATION 2 WHEEL CONCEPT	9.3 / 37	9.1 / 36	7.8 / 16	6.4 / 19	8.9 / 18	7.2 / 29	5.4 / 16	171	6.8 / 14	8.0 / 24	6.0 / 12	8.0 / 32	82	253	
9 SK6440-77-467(GA) STEAM TURBINE DRIVE CONCEPT 1 (NON BOILING CACWS)	9.0 / 36	7.5 / 30	8.3 / 17	5.6 / 17	3.0 / 6	5.1 / 20	8.7 / 26	152	2.5 / 5	4.6 / 14	3.5 / 7	5.0 / 20	46	198	
10 SK6440-77-472(GA) STEAM TURBINE DRIVE CONCEPT 2 (BOILING CACWS)	9.0 / 36	7.5 / 30	7.5 / 15	5.0 / 15	2.0 / 4	4.3 / 17	8.7 / 26	143	2.0 / 2	5.5 / 17	2.0 / 4	5.0 / 20	43	186	
11 SK6440-77-464(GA) STEAM TURBINE DRIVE CONCEPT 3, CLOSED LOOP INDEP. STEAM SOURCE	8.8 / 35	6.9 / 28	7.3 / 15	5.6 / 17	2.3 / 5	4.8 / 19	6.7 / 20	139	2.8 / 6	5.0 / 15	5.5 / 11	6.0 / 24	56	195	
12 SK6440-77-464(GA) STEAM TURBINE DRIVE CONCEPT 4 OPEN LOOP INDEP. STEAM SOURCE	8.8 / 35	6.9 / 28	7.9 / 16	5.6 / 17	6.9 / 14	8.0 / 32	4.0 / 12	154	6.9 / 14	6.8 / 20	6.0 / 12	6.0 / 24	70	224	

ENGINEERING & PERFORMANCE RELATED EVALUATORS (EP1–EP7)

COST FEASIBILITY RELATED EVALUATORS (CF1–CF4)

Fig. 10-12. Master rating chart

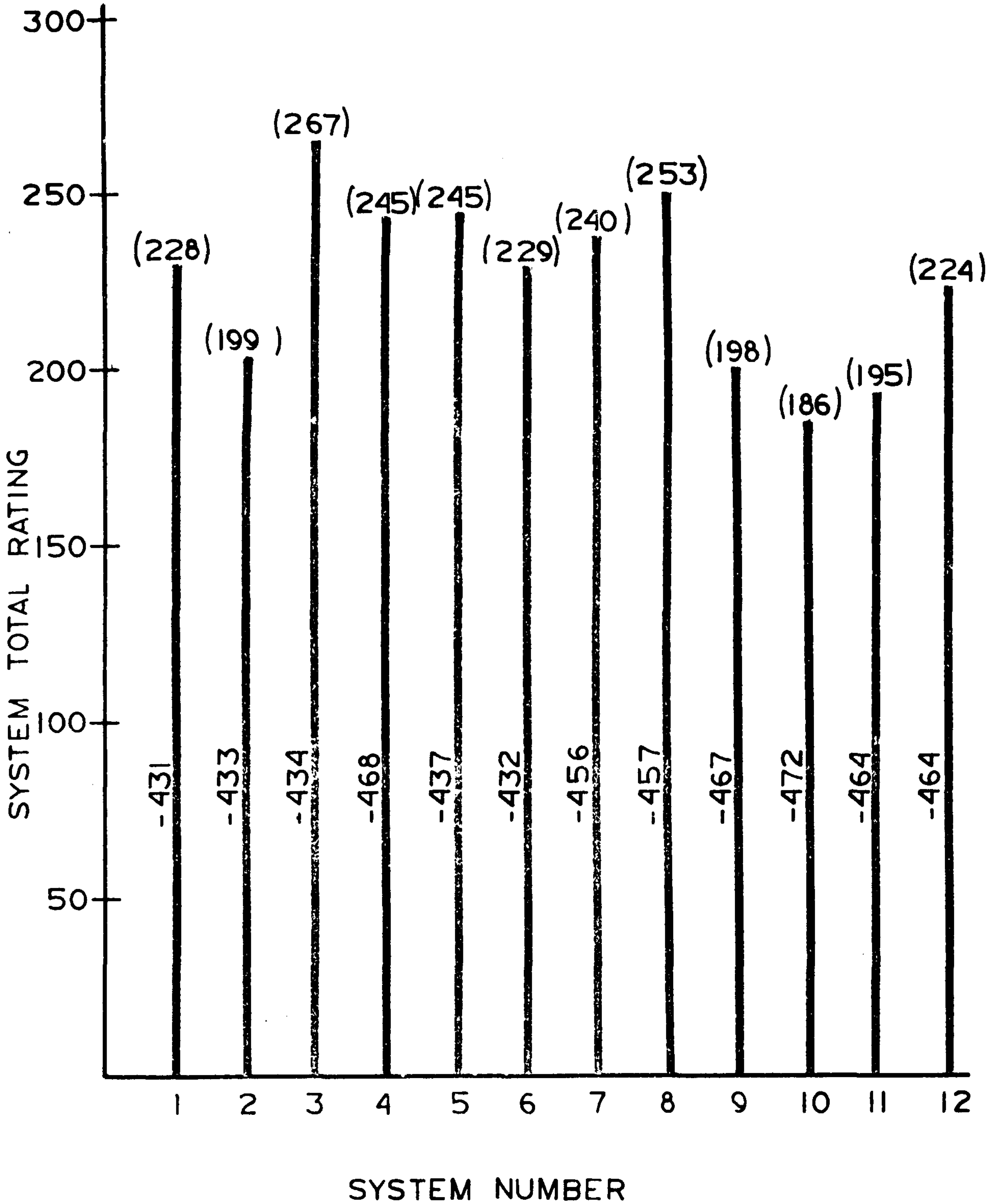

Fig. 10-13. Bar chart of ratings for GCFR auxiliary circulator drives

two-wheel hydraulic turbine (457). However, the difference between these and the other systems does not appear to be great.

The results are presented on another chart in Fig. 10-14. Here the system ratings are shown on a two-axis plot with the engineering and performance rating scale on one axis and the cost and feasibility rating scale on the other. (The system numbers are shown in the boxes and circles.) This chart shows that the electrical reference system 434 (No. 3) rates highest with respect to both performance and feasibility. The two-wheel hydraulic turbine system 457 (No. 8) rates almost as high in performance but rates significantly lower in feasibility.

The remaining systems appear to be clustered in two groups. The first group, Nos. 1, 4, 5, 6, and 7, rates well with respect to the leaders and after some minor changes in technical information or different emphasis as reflected in weighting factors could easily equal or pass the leaders in rating. The second group, Nos. 2, 9, 10, 11, and 12, has significantly lower ratings. This group includes the d.c. motor drive and the steam turbine systems. Considerable changes in ratings or emphasis would be necessary to make these systems attractive alternates.

10.4. COST ESTIMATES

This section presents cost estimates for the GCFR alternate auxiliary circulator drive and control system components for the 12 alternate drive systems (five electrical and seven non-electrical) that have been developed, studied, and evaluated. A cost summary and appropriate backup information are included. The backup information and other supplementary information are included in Appendix A.

10.4.1. Basis of Costs and Assumptions

10.4.1.1. Drive and Controller Costs. Costs for the drive and controller systems were solicited from over 50 suppliers of such equipment. The method

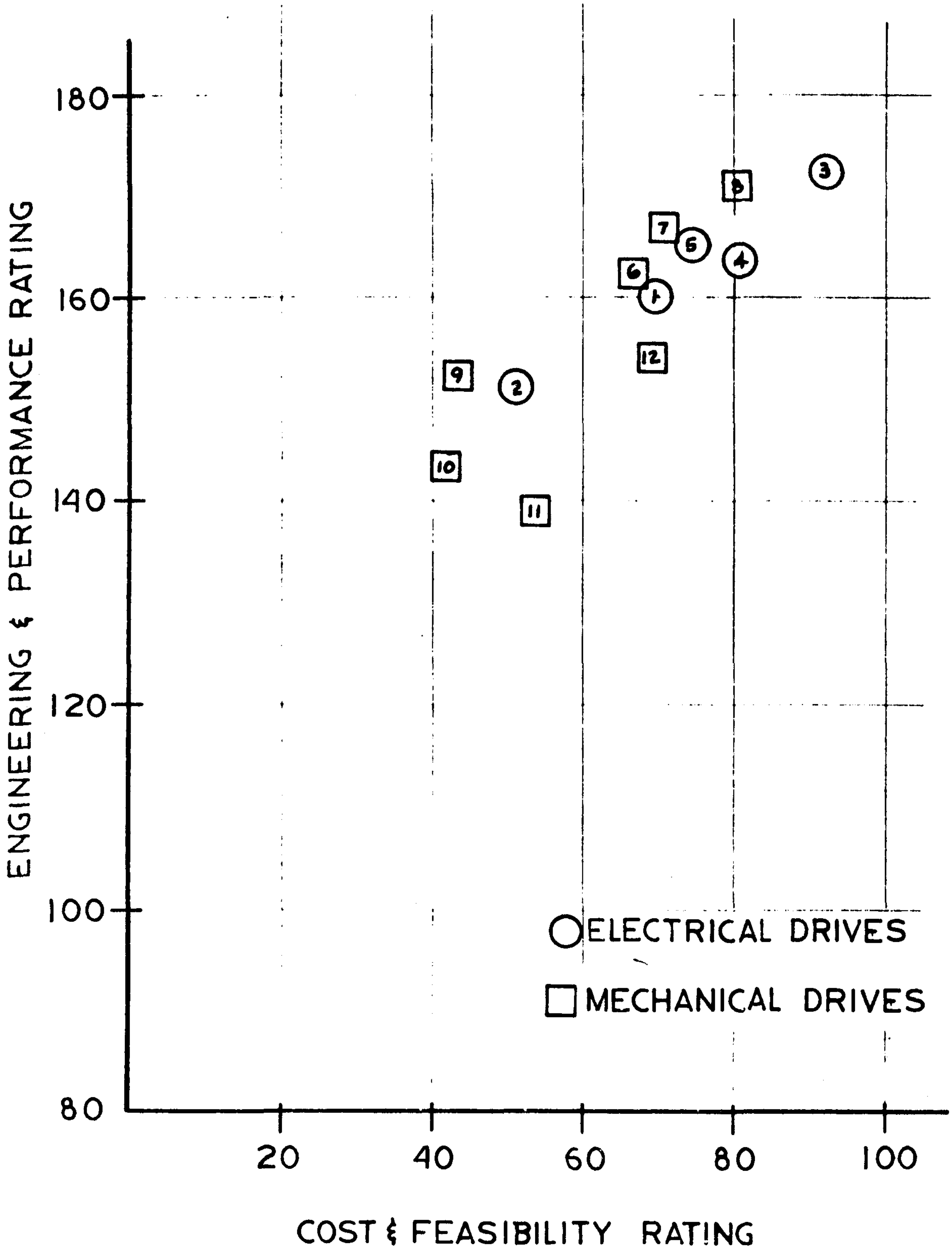

Fig. 10-14. Two-axis rating chart for GCFR auxiliary circulator drives

initially employed was to send Advance Purchase Information Requests (APIRs), essentially requests for quotation of an estimated price, along with the list of drive system requirements that were developed in cooperation with GA. The first batch of about 25 APIRs was sent out August 3, 1977, with a quotation due date of August 26, 1977. Despite constant checking with the vendors, no significant responses were received by the due date. The requirement for Class I qualification was the main reason given for not responding or late response. Despite AMCO's encouragement for suppliers to take exceptions to the certain requirements, few bids were received. In later contacts with vendors, the nuclear requirements were not mentioned and prices were requested for commercial components. These prices are used as the basis for some of the estimates.

10.4.1.1.1. Electrical Drives. The prime candidates for an electrical drive system are Westinghouse, General Electric, Reliance, Louis Allis, Allis Chalmers, and Brown-Boveri. Westinghouse and General Electric have alternately refused to bid, promised to bid, and finally refused to bid. Because of their experience in supplying and qualifying motors, General Electric San Jose and Westinghouse still appear to be good candidates in spite of their current response. Louis Allis and Allis Chalmers did respond with exceptions. Reliance and Brown-Boveri promised to respond but have not.

The prices listed in the electrical drive estimates are scaled up from the responses and other verbal information received from vendors. In every case, it appears that a substantial development contract placed with a vendor may be the only way to assure a firm commitment from one.

10.4.1.1.2. Mechanical Drives. All the cost information on the mechanical drives was received verbally by AMCO. The cost information from vendors on the steam turbine drive components was for commercially available units. AMCO estimated added costs for adapting that equipment for the subject application. The cost of qualifying the equipment to the appropriate Class I standards and of testing and installing it has been estimated separately by AMCO. It is probable that many of the commercial vendors contacted will not be willing (or able) to adapt or qualify their equipment for this application. In that case the prices quoted can only represent the typical price one might expect to pay for such equipment. Allis Chalmers (hydraulic turbines) has requested \$10,000 for a Title I engineering stress analysis to determine material suitability for the rotor and buckets. It is probably appropriate to budget \$25,000 for vendor Title I engineering for all of the mechanical drive concepts.

10.4.1.2. Qualification and Testing Costs. Since no vendor to date has consented to bid a qualified system, AMCO has separately estimated the costs of qualification and associated testing.

This estimate does not include any system testing for the CACS that may be required. Such a test would include the CACS circulating water system and the ALC. The system tests and the other major components of the CACS were not in the scope of the AMCO program.

10.4.1.3. Engineering Costs. Estimates were made of Title I, II, and III engineering costs for the drive and controller systems. They were made on the basis of estimating the number of drawings and other documentation required in each phase and applying the method of manpower breakdown described in Ref. 10-1. The estimates are rough order of magnitude because of the very early state of design. A single typical set of estimates was made for the electrical drives, because at this stage any differences would be negligible compared with the accuracy of the estimates. Similar typical estimates were made for a hydraulic turbine drive and steam turbine drive. Estimates for the other mechanical systems were made by applying a ratio derived from the number of additional drawings required for the more complex systems.

10.4.1.4. Installation Costs. Very rough estimates of the installation costs of the various systems were made to provide a complete cost picture.

10.4.1.5. Emergency Power System Costs. Because some of the mechanical systems include a power source, such as a boiler, an equivalent cost is added in each case to make cost comparisons between the systems meaningful. For example, the cost of a backup power source, a diesel drive generator emergency power unit, is included in each electrical drive. If backup electrical power is already provided for, then this represents the added cost of increasing the capacity of the backup emergency power system to accommodate the auxiliary circulator drive.

10.4.2. Cost Summary

The cost estimate summary sheet (Table 10-2) shows the cost estimates for each of the 12 alternate drive systems considered in this study. The costs shown are for a single drive system. Since the reactor would employ three essentially identical drives for the three auxiliary circulators, the development, qualification, and testing costs for any drive system are divided among the three and the apportioned per unit costs are listed. Similarly, the engineering costs have been spread. The engineering costs took into account the extra drawings involved because of the three different locations for the three drives. Although most of the parts in each location will be identical, such things as wire and pipe routings and identification and the location of equipment outside the PCRV will be different.

All the estimates are for drives in the 1000- to 1300-hp range. Although prices for 1000-, 1150-, and 1300-hp units were specifically requested, no vendor indicated any differences. The qualification, development, and engineering costs are of such a magnitude that the cost differentials among those sizes are insignificant. Scaling up to about 3000 hp, however, would produce significant changes.

More detailed cost estimate information is presented in the AMCO report (Ref. 10-1).

REFERENCE

10-1. "Conceptual Design Evaluation of Alternate Auxiliary Circulator Motor Drive and Control System Components for the Gas Cooled Fast Reactor (GCFR)," Aerojet Manufacturing Company Report AMCO-1968-77(01)ER, September 1977.

TABLE 10-2
SUMMARY COST ESTIMATES FOR GCFR AUXILIARY CIRCULATOR DRIVE
(THOUSANDS OF DOLLARS)

Drive System	Engineering	Procurement and Fabrication	Qual. and Testing	Installation	Emergency Power Source	Total[(a)]
1. SK-6440-77-431(GA), Converter Cascade - Wound-Rotor Induction Motor Drive	180	484	350	100	130	1244
2. SK-6440-77-433(GA), SCR - Controlled D.C. Motor Drive	180	426	350	100	130	1186
3. SK-6440-77-434(GA), Variable Frequency-Controlled Induction Motor Drive	180	380	300	100	130	1090
4. SK-6440-77-468(GA), Variable Frequency-Controlled Synchronous Motor Drive	180	405	350	100	130	1165
5. SK-6440-77-437(GA), Variable Frequency-Controlled Dual Induction Motor Drive	180	455	400	100	130	1265
6. SK-6440-77-432(GA), Gas Turbine Drive	130	500	400	100	0	1130
7. SK-6440-77-456(GA), Pelton Wheel Application, Two-Jet Concept	155	380	350	75	250	1210
8. SK-6440-77-457(GA), Hydraulic Turbine Application-Two-Wheel Concept	155	480	350	75	250	1310

TABLE 10-2 (Continued)

Drive System	Engineering	Procurement and Fabrication	Qual. and Testing	Installation	Emergency Power Source	Total[a]
9. SK-6440-77-467(GA), Steam Turbine Drive, Concept 1 (Non-Boiling CACWS)	180	1333	400	150	0	2063
10. SK-6440-77-472(GA), Steam Turbine Drive, Concept 2 (Boiling CACWS)	225	1373	400	150	0	2148
11. SK-6440-77-464(GA), Steam Turbine Drive, Concept 3 (Closed Loop Independent Steam Source)	180	1188	500	150	0	2018
12. SK-6440-77-464(GA), Steam Turbine Drive, Concept 4 (Open Loop Independent Steam Source)	180	458	500	150	0	1288

[a] Total cost for each of the three drives required.

11. RECOMMENDATIONS FOR AUXILIARY CIRCULATOR DRIVE AND CONTROL SYSTEMS

11.1. PRIMARY AND BACKUP RECOMMENDATIONS

The objective of this study was to make and support recommendations for auxiliary circulator drive and control components that would have the best potential of being successfully designed, specified, procured, installed, and put into operation in the GCFR Demonstration Plant and subsequent commercial plants and would comply with all the plant safety and control requirements.

As a consequence of this study, an electrical drive system and, in particular, the frequency-controlled a.c. induction motor drive (System 434, Fig. 9-1) is recommended for the reference system. The leading reasons for this choice are (1) the previous procurement of the equivalent system for the HTGR, (2) the simplicity of the rotating parts of the motor, and (3) the apparent consensus of the possible vendors.

Procurement will be a problem. In spite of the vendors' reluctance to provide strong positive responses to the inquiries, it is believed that the leading candidates as suppliers, in order of preference, are Westinghouse, Louis Allis, and General Electric. Some potential exists for Reliance Electric and Allis Chalmers. The latter is currently joining with Siemen to form a U.S.-based company for producing large rotating apparatus.

One backup electrical system is recommended, i.e., System 468 (Fig. 9-3), the frequency-controlled synchronous motor drive. This system, particularly with a brushless field excitation system, could be available if cooling of the primary system motor rotor presented extraordinary design difficulty. The wound-rotor induction motor drive, System 431 (Fig. 9-5), or the frequency-controlled dual induction motor drive, System 437 (Fig. 9-4), could be an alternative backup, but the d.c. motor drive, System 433 (Fig. 9-2), is not recommended.

As a backup mechanical system, the two-wheel hydraulic turbine drive, System 457 (Fig. 9-9) is recommended. The leading reasons for this choice are (1) the successful operation of the Pelton wheel on the Fort St. Vrain reactor, (2) the high performance rating for this system, (3) the simple design of the rotating parts, and (3) the simple power source for the 2-hr blackout.

If the main circulator drive is chosen to be an electrical system and diversity is a governing requirement, System 457 could become the primary recommendation. The recommendation is qualified and depends on the diversity requirement. If only the driver inside the PCRV must be diverse, so as to preclude any common-mode failure of equipment particularly susceptible to that environment, such as winding insulation failure, System 457 is recommended.

On the other hand, as pointed out previously, the System 457 pumps and the other CACS pumps and blowers depend on electric power. These components are shown in Fig. 9-9 as being supplied by a diesel-driven generator. This diesel generator could be a separate one for this system, making the system independent of the rest of the plant. However, if the diversity requirement demands that the CACS not depend on electric power (except for instrumentation and control, of course), the hydraulic turbine drive may be impractical.

Alternates that could achieve both complete diversity and independence are the gas turbine and the steam turbine drives. Based on the ratings, it appears that strong consideration should be given to the gas turbine. However, if major redesign of the CACS becomes appropriate, consideration of the boiling CACWS steam turbine drive as shown in System 472 (Fig. 9-12) should be considered.

11.2. RECOMMENDATIONS FOR FOLLOW-ON ACTIVITY

It has been found that if certain requirements were changed or better defined, they would simplify the design, reduce costs, and increase the potential for securing suitable equipment. One example pertains to the electrical drives. If the top speed requirement of 4900 rpm were reduced to 4500 rpm or even better to 3600 rpm, the amount of development and testing would be significantly reduced. Normally, a.c. motors operate at no higher than 3600 rpm and are tested up to 25% above 3600, at 4500 rpm. Most vendors indicated that 4900-rpm speed would require special design and puts the motor outside the commercial application regime.

Another example pertains to all drives and particularly to the mechanical ones. Although the power required is low, most vendors have reservations about the operation of their products at the low-speed end. The 50:1 speed range stretches the state of the art for all drives. It is suggested that the low speed and power requirements be reviewed so that any unnecessary requirements can be eliminated.

Because of the reluctance of vendors to consider performing the Class I qualification and testing, it is suggested that GA consider having this work done by a separate organization. This would apply particularly to the mechanical systems. No supplier of any mechanical component that has been contacted was willing to undertake any of the qualification work.

Finally, it is recommended that any future work on the auxiliary circulator drive not be separated from that on the other pump and blower drives in the CACS, and that a system approach be applied.

12. CACS DYNAMIC SIMULATION

The development of a CACS dynamic simulation code was first brought out when it was required to conduct a CACS trade-off study. The existing GA GAFTRAN code is a safety-oriented code developed to examine safety questions about the CACS with considerable complexity built in to evaluate core temperatures. It appears that a system-oriented code which is constructed in modular blocks allowing changes in the system components will be most advantageous for performing the CACS trade-off and system sensitivity studies. The code that was developed for this purpose is called CASY. Detailed technical discussions and computer test runs for this code are given in Ref. 12-1.

Figure 12-1 shows the components in the system simulation of the CASY code. It illustrates the thermal coupling between the component models and between the gas and water sides in the two heat exchangers. Fluid flow/pressure drop considerations are also included, but fluid inertia effects are neglected. The reactor core model is also used in the overall plant dynamic simulation. Controllers for the auxiliary circulator drive motor and the two water pumps are not shown but are included in the simulation. The complete simulation contains about 90 integration variables.

The CASY code has the following capabilities: (1) to simulate at the system or component input/output level the static and dynamic properties of the system and their relation to interfacing systems and environmental parameters, (2) to calculate system performance parameters during the critical period of startup and switch-over from main loop cooling, (3) to analyze and evaluate component parameter variations encountered in system design and trade-off studies and in sensitivity analyses, (4) to function as a control system analysis and design tool, and (5) to provide component input/output parameter ranges for use in establishing hardware design parameters.

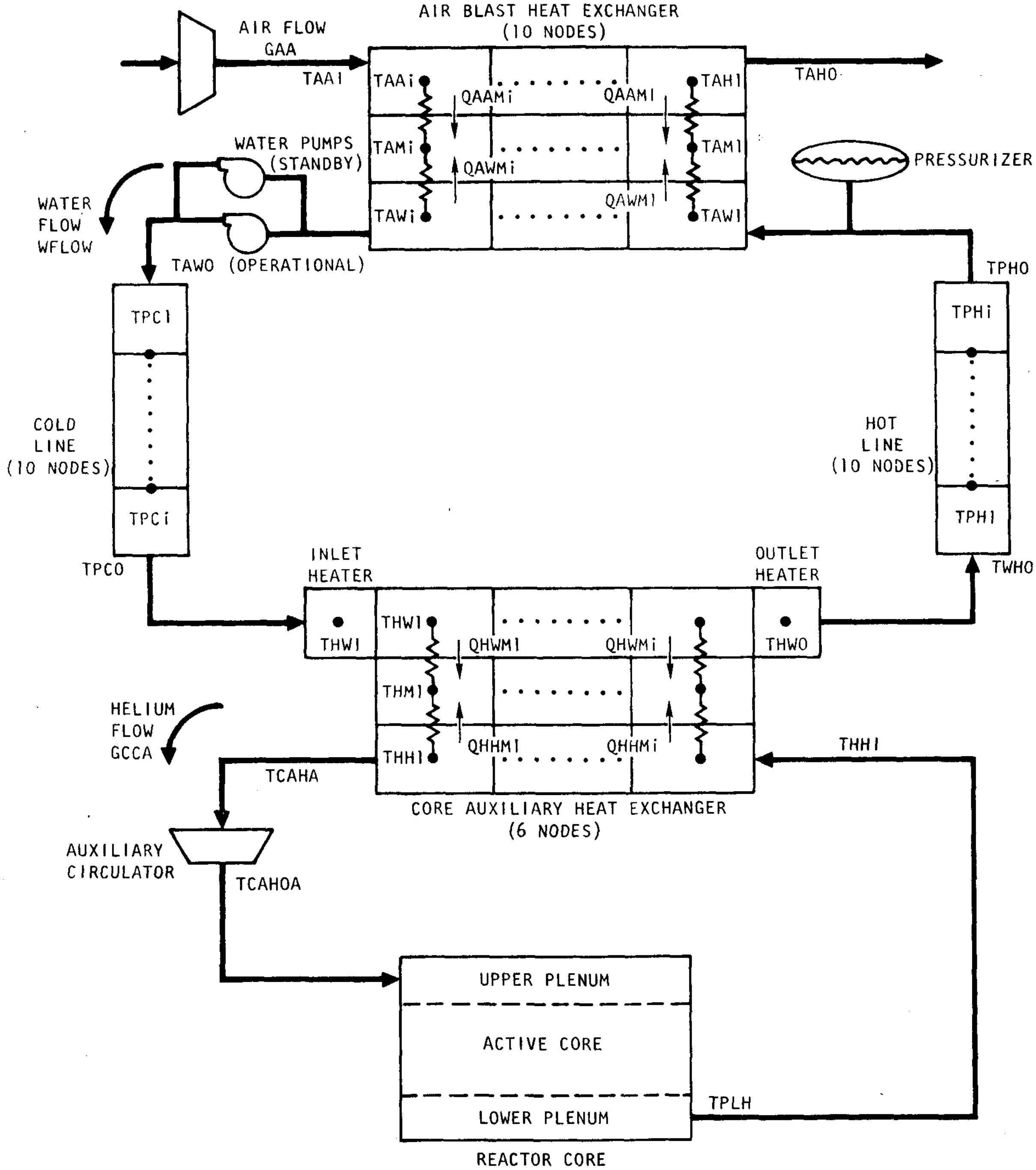

Fig. 12-1. CACS dynamic simulation

REFERENCE

12-1. "CASY - A Dynamic Simulation of the GCFR Core Auxiliary Cooling System," Vol. I and II, Jaycor Reports J77-6046-TR-01 and J77-6046-TR-02.

13. FINAL TRANSIENT ANALYSIS FOR REVISED REFERENCE DESIGN

As a part of the recent effort on the alternate design study for the 300-MW(e) GCFR, revised design data for CACS components were evolved (Sections 7 and 8). The main revision is in the CAHE design. Significant changes are (1) about four times higher water circulating rate and (2) about 2.4 times higher flow area in the CAHE than those of the previous conceptual design that was used for the PSID, Amendment 7 analysis (Ref. 13-1).

To ascertain the adequacy of the revised design, transient analyses have been performed for two base cases: (1) the DBDA and (2) the shutdown cooling for the pressurized core, which will be referred to as the pressurized cooldown henceforth.

The results of the DBDA analysis indicate that adequate core cooling is achieved [the maximum cladding temperature being 1249°C (2280°F)] using two CACS loops, each having a 452-kW (606-hp) auxiliary circulator. The revised power requirement is lower than the 641-kW (860-hp) required for the previous CAHE design to obtain similar DBDA conditions. The reduced power requirement is due to a 50% lower CAHE pressure loss coefficient and lower water temperatures, which resulted from the quadrupled design water flow rate in the revised design. It should be noted, however, that the auxiliary circulator power requirement would vary depending on the scenarios of CACS application for the DBDA, including the transfer time and number of operational loops, etc., as discussed in Section 5.

The results of the pressurized cooldown case indicate that the maximum CAHE water temperature during the transient is low. This permits the water pressure to be reduced as low as the primary coolant pressure without boiling the water.

Both the lower auxiliary power requirement and the lower water pressure possibility are significant design improvements over the previous conceptual design.

13.1. MOCKUP OF REVISED CACS DESIGN

Implementation of the revised design data for the whole GCFR system model is under way. Since the complete mockup is not yet available, only the CACS part of the GAFTRAN mockup has been updated with the revised design data. This means that mockup of the core, steam generator, and main circulator-turbine unit remains identical to that used for the PSID, Amendment 7 analyses (Refs. 13-1, 13-2, 13-3). The conservative analysis model as defined in Ref. 13-1 is chosen, which allows uncertainty margins for several system parameters (Section 6) as well as one failed coolant loop. The updated CACS data and correlations are summarized below.

13.2. HEAT TRANSFER CORRELATIONS FOR CACS

Heat transfer coefficients for the CACS components are represented in GAFTRN by

$$h = A\,\dot{m}^B ,$$

where h = heat transfer coefficient in W/m^2-°K (Btu/hr-ft^2-°F),

$\dot{m}$ = fluid flow rate in kg/s (lb/hr),

A,B = constants.

13.2.1. CAHE Shell Side

Shell-side heat transfer correlation for the helically wound CAHE tube bundle is based on the Grimison correlation (Ref. 13-4):

$$N_u = \frac{h_H D_o}{K} = A_1 \quad Re^B \left(\frac{Pr}{0.69}\right)^{0.33} ,$$

where Re is the Reynolds number based on the flow at the minimum free flow area. The geometrical data of the revised CAHE are

D_o = 0.0318 m (1.25 in.) for the tube o.d.,

X_T = 0.0508 m (2 in.) for transverse tube pitch,

X_L = 0.0508 m (2 in.) for longitudinal tube pitch,

A_F = 3.08 m^2 (33.18 ft^2) for the bundle fronted area,

A_1 = 0.195,

B = 0.642 is a constant for $X_T = X_L$ = 0.0508 (2 in.).

Assuming constant physical properties at the expected helium average temperature of 427°C (800°F),

K = 0.277 W/m-°C (0.16 Btu/hr-ft-°F) for helium thermal conductivity,

Pr = 0.67 for helium Prandtl number,

μ = 3.507 x 10^{-4} N/m-s (0.0865 lb/ft-hr) for helium viscosity.

The above correlation is transformed into

$$h_H = \frac{K}{D_o} \; (0.194) \left[\frac{D_o \, \dot{m}_H}{\mu \, A_F \left(\frac{X_T - D_o}{X_T}\right)}\right]^{0.642} \left(\frac{Pr}{0.69}\right)^{0.33} ,$$

which is reduced to

$$h_H = 0.06624\ \dot{m}_H^{0.642}.$$

The subscripts H, w, a, and p are used to signify helium, water, air, and the interconnecting pipe, respectively.

13.2.2. CAHE Tube Side

The tube-side heat transfer coefficient for pressurized water flow is based on the Dittus-Boelter correlation given as

$$N_u = \frac{h_w D_i}{K_w} = 0.023\ (Re_w)^{0.8}\ (Pr_w)^{0.4}.$$

Assuming constant water properties at the expected water average temperature of 149°C (300°F), the tube-side heat transfer coefficient, h_w, for the tube inside diameter of D_i = 0.0249 m (0.98 in.) is given by

$$h_w = 0.09\ m_w^{0.8}.$$

13.2.3. ACL Shell Side and Interconnecting Pipe

The ALC and the interconnecting pipes are not updated. For completeness, the heat transfer coefficients for these components, which were derived similarly as above in Ref. 13-5, are given as follows:

ALC Shell Side

$$h_a = 0.00111\ m_a^{0.8}\quad ,$$

where m_a = air flow rate in kg/s (lb/hr).

ALC Tube Side

$$h_w = 0.061\ (m_w)^{0.8} .$$

Interconnecting Pipe (Hot and Cold Legs) (Ref. 13-5)

$$h_p = 0.1036\ m_w^{0.8} .$$

The input data used to mock up CACS loop components, including the interconnecting pipes and ALC, are listed in Table 13-1.

13.3. PRESSURE DROP CORRELATION FOR CAHE

The pressure drop across the helically wound tube bundle is given in Ref. 13-2 as

$$\Delta p = \frac{4fNG^2}{2g} ,$$

where f = friction coefficient,

$\cong$ 0.07 for the pitch to diameter ratio of 1.6 in both the longitudinal and transverse directions and for the expected Reynolds number range of CAHE operation,

N = number of flow constrictions by the tubes,

= 37 for the bundle height of 1.871 m (6.14 ft) and X_L = 0.508 m (2 in.),

G = mass velocity at the minimum free flow area, kg/m^2-s (lb/ft^2-sec),

ρ = fluid density, kg/m^3 (lb/ft^3),

TABLE 13-1
DATA FOR MOCKUP OF 300-MW(e) CACS

	Core Auxiliary Heat Exchanger Parameters	Auxiliary Loop Cooler Parameters	Each Leg of Interconnecting Pipe
Type	Helically wound cross flow heat exchanger	Finned tube bank	
Material	Stainless steel tubes	Stainless steel tubes	Carbon steel
Tube or pipe outside diameter, m (in.)	0.3175 (1.25)	0.0254 (1)	0.168 (6.625)[a]
Tube or pipe inside diameter, m (in.)	0.249 (0.98)	0.205 (0.81)[a]	0.132 (5.189)[a]
Tube or pipe length, m (ft)	44.71 (146.7)	59.13 (194)[a]	84.28 (276.5)
Number of tubes	50	48[a]	
Tube or pipe thermal conductivity, W/m·K (Btu/hr-ft-°F)	262.7×10^3 (12.85)[a]	204.4×10^3 (10)[a]	500.6×10^3 (24.49)[a]
Tube or pipe specific heat, J/kg·K (Btu/hr-ft-°F)	502.4 (0.12)[a]	544.3 (0.13)[a]	544.3 (0.13)[a]
Design gas flow rate, kg/s (lbm/hr)	9.1 (72,360)	345.0 (2,737,800)	
Design water flow rate, kg/s (lbm/hr)	75.9 (602,300)	75.9 (602,300)	75.9 (602,300)
Design inlet gas temperature to heat exchanger, °C (°F)	832 (1530)	37.2 (99)	
Gas pressure, MPa (psia)	0.179 (26.0)	0.101 (14.7)	

[a] An assumed value.

g = conversion constant.

This correlation was transformed into a pressure loss coefficient, C(4), which is defined in GAFTRAN as

$$C(4) = \frac{\Delta p \; P}{RT \; \dot{m}^2 (12)} \quad ,$$

where Δp = CAHE pressure drop, Pa (psi),

P = helium pressure, Pa (psi),

R = gas constant, 2077.22 J/kg-°K (386 ft-lbf/lbm-°F) for helium,

T = gas absolute temperature, °K (°R).

Using the design conditions given in Table 8-1, the pressure loss coefficient, C(4), is evaluated and implemented in subroutine DPLOOP in GAFTRAN. The revised value is

$$C(4) = 4.18 \times 10^{-9} \; \frac{\text{lbf-sec}^2}{\text{lbm-in.}^4\text{-ft}} \approx 0.3231 \; \frac{1}{\text{m}^4} \quad .$$

It is noted that the pressure loss coefficient of the revised CAHE is about one-half of the previous design value. It is a design improvement which reduces the auxiliary circulator power requirement under DBDA conditions.

13.4. AUXILIARY CIRCULATOR PERFORMANCE CHARACTERISTICS

The auxiliary circulator is a centrifugal compressor design and is driven by a squirrel-cage induction motor which derives variable frequency power from separate essential buses.

An idealized rectangular motor torque-speed performance curve which has both a maximum torque limit and a maximum speed limit has been assumed in these analyses, as shown in Fig. 13-1. The torque required of the circulator drive motor is directly related to the system pressure drop. The circulators are nearly constant volume flow machines, implying that the core mass flow is nearly proportional to the product of the motor speed, the number of operating loops, and the coolant density. Since the system pressure drop varies with the mass flow rate squared, the system pressure drop versus speed curves can be drawn for a given coolant density as shown in Fig. 13-1. The normalized motor torque-speed curve and representative normalized system pressure drop curves are combined in Fig. 13-1 for illustrative purposes only. For a low system pressure drop characteristic, as would be expected for full depressurization with pure helium as the reactor coolant, the maximum speed limit would be encountered and an operating point such as point A might be expected. If significant air ingress occurs in a depressurized reactor, the system density increases and the motor torque limit may be reached at, say, point B and the motor speed would be reduced. Also, since the core represents the major flow resistance in the cooling loop, operating with fewer CACS loops tends to reduce the pressure drop characteristic on a per loop basis. Thus, if air ingress has occurred and three loops are operating, the condition would be at, say, point B. If one loop fails, the remaining two loops would speed up and operate at point C.

This performance characteristic was assumed for the present analysis as well as for the PSID, Amendment 7 analyses.

13.5. CACS INITIAL CONDITIONS

The inactive CACS conditions, while the main loops are operating, constitute the initial conditions. The initial water temperature conditions depend on the helium leak flow through the isolation valve, the water flow rate in the inactive CACS, and the natural convection heat transfer in the ALC. The design data related to the inactive CACS conditions are not finalized and can be controlled to suit the system requirement. Initial hot and

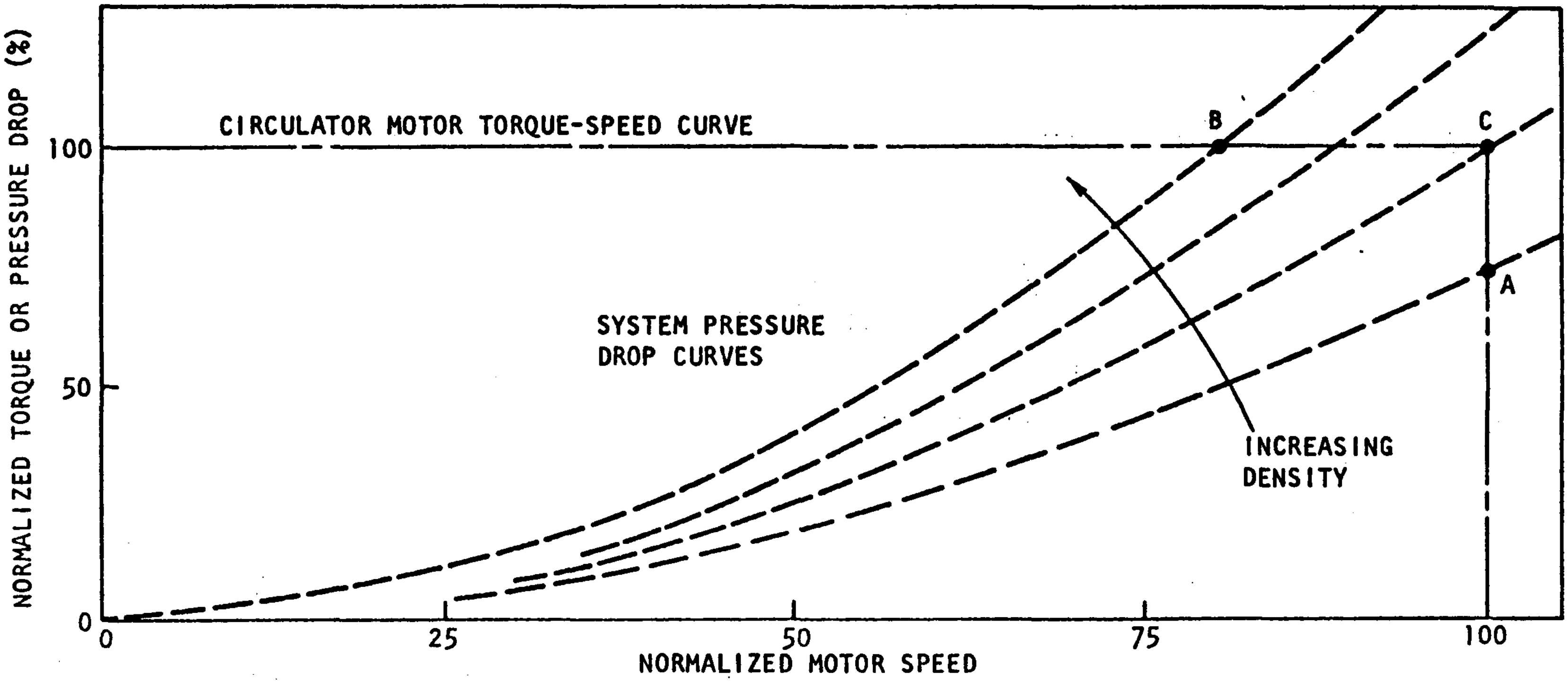

Fig. 13-1. Assumed CACS motor characteristics

cold leg water temperatures of 223°C (433°F) and 151°C (304°F) are assumed, based on 0.26% parasitic thermal loss and 3% [2.34 kg/s (18,000 lb/hr)] water flow rate.

It was known (Section 5) that if the CACS transfer occurs at around 30 s after the reactor trip, some variation of the main loop core cooling action prior to the transfer has no significant effect on the maximum cladding temperature that develops under the CACS operation. Therefore, CACS transfer at 30 s was assumed for all the transient cases examined. During the 30 s prior to the transfer, it was assumed that two main loops perform the shutdown core cooling and that the ALC water pumps and the air fans are turned on at the full rates. To simulate the check valve actuation at the time of loop transfer following a DBDA, it was assumed that the auxiliary circulator attains 50% of the design speed behind the closed check valve. This assumption is consistent with that used in the PSID, Amendment 7 analysis (Ref. 13-1). For the pressurized cooldown cases, nearly zero initial speed (1.4%) was assumed.

13.6. RESULTS

13.6.1. DBDA Transient

The DBDA analysis presented here is based on core cooling using two main or CACS loops following a depressurization accident with a 0.048 m^2 (75-in.^{2}) leak area. A conservative analysis model which accounts for several uncertainty margins, as defined in Section 6, is used for the present analysis. The results of the DBDA analysis using the revised CACS data are shown in Figs. 13-2 and 13-3. The curve in Fig. 13-2 represents the hot spot cladding temperature of the fuel assembly interior rods. The cladding temperature of the edge fuel rods, which are adjacent to the duct wall, is expected to be about 66°C (150°F) higher than the interior rod value due to the edge channel effect (Section 5). Even allowing for the edge cladding temperature defect, Fig. 13-2 shows that the maximum cladding temperature is maintained below 1249°C (2280°F). This temperature indicates an adequate margin to the cladding melting temperature of 1371°C (2500°F) and is lower than a tentative design limit of 1260°C (2300°F).

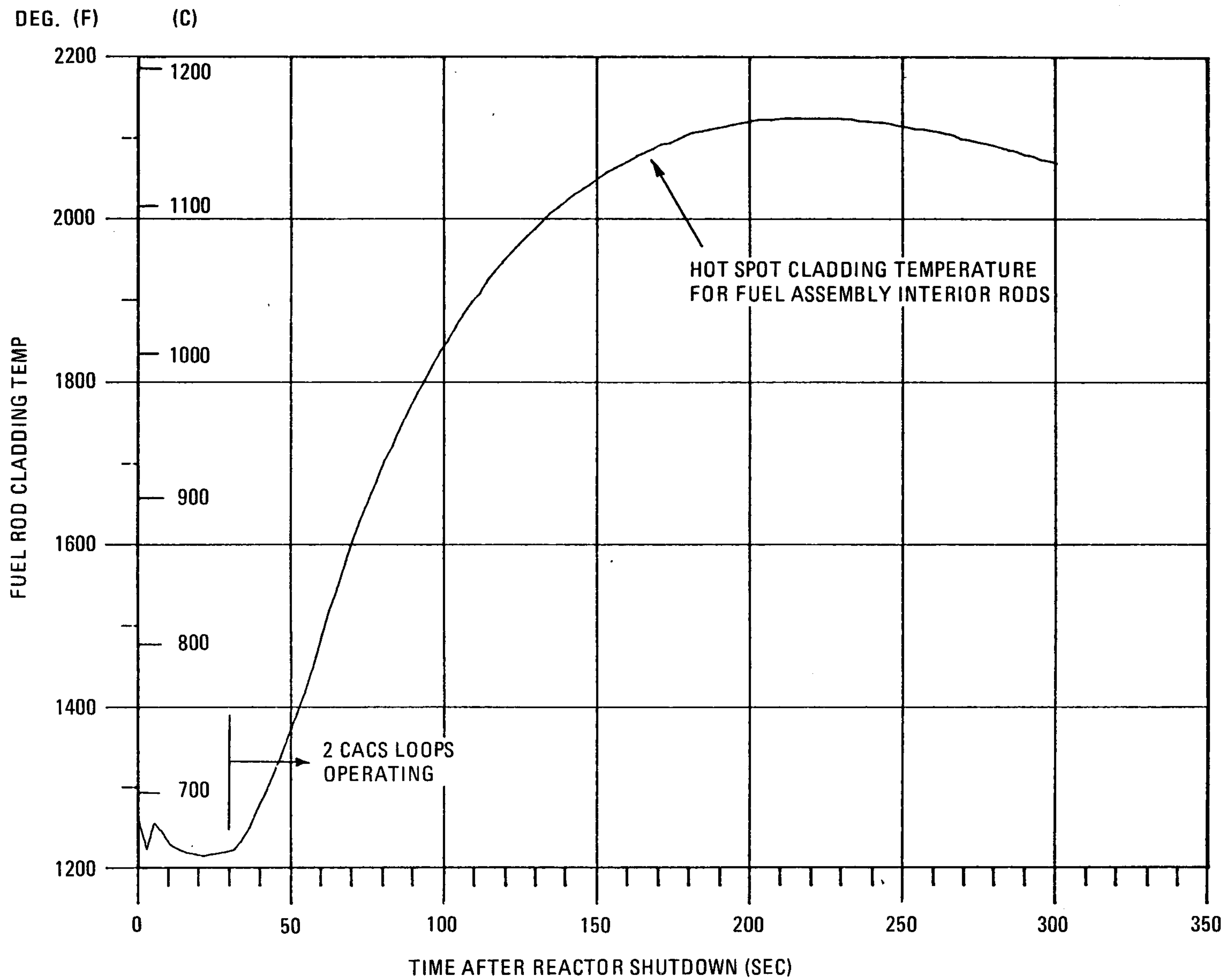

Fig. 13-2. Cladding temperature response during DBDA core cooling with revised CACS

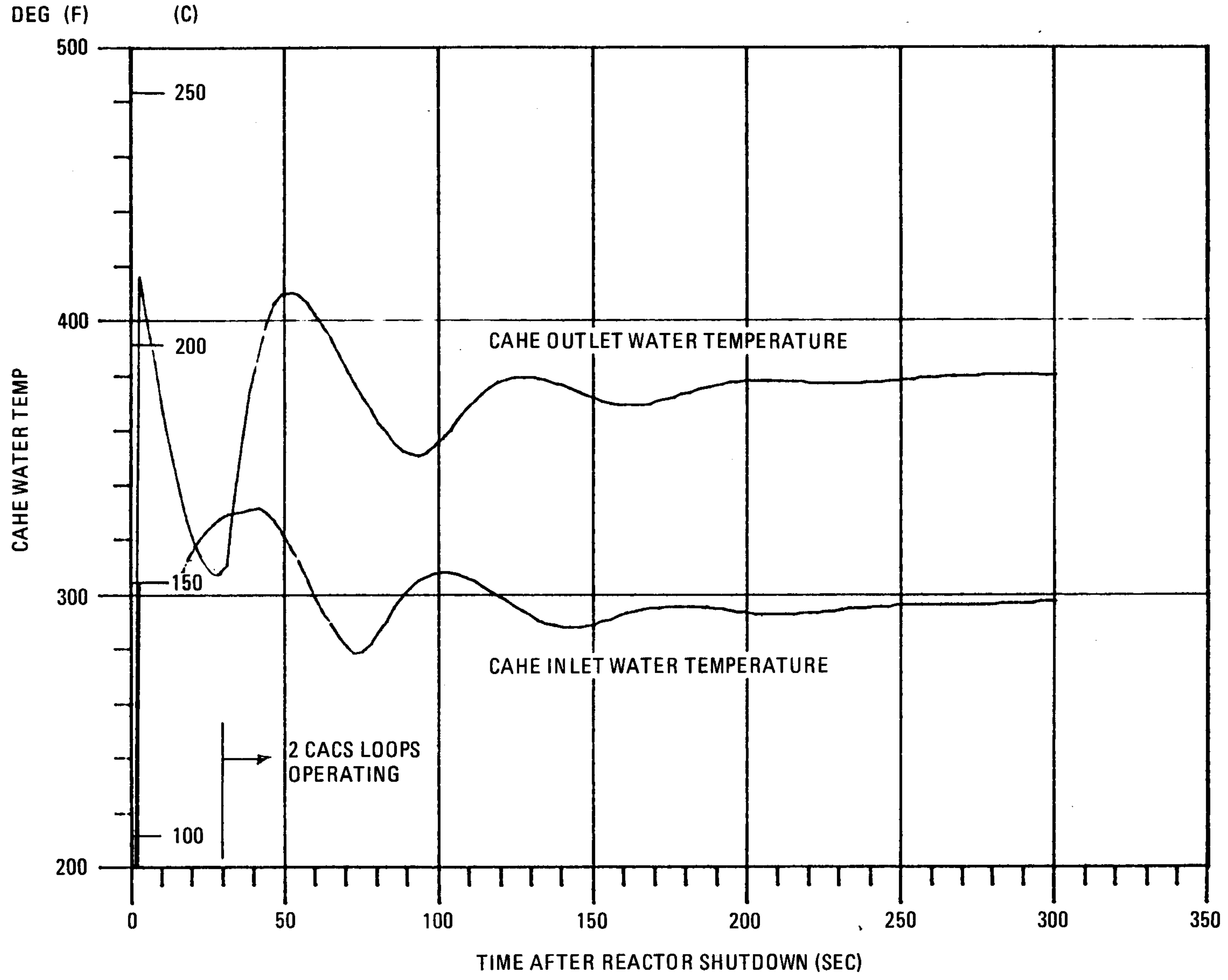

Fig. 13-3. CAHE inlet and outlet water temperature responses during DBDA core cooling with revised CACS

The auxiliary circulator power in this case is 606 hp, which is lower than the 641 kW (860 hp) required for a similar condition using the previous CACS design. The reduced power requirement is due to (1) a lower CAHE pressure drop and (2) lower CAHE water temperature due to a quadrupled water flow rate.

The transient temperature response of the cooling water at the inlet and outlet of the CAHE is shown in Fig. 13-3. The maximum water temperature is 210°C (410°F), which is substantially lower than the boiling temperature of 8.96-MPa (1300-psia) water, which is 303°C (577°F).

13.6.2. Pressurized Cooldown with CACS

Owing to the effective heat transfer of pressurized helium, the CACS capacity is abundant for the pressurized cooldown application. The critical aspects in this case are the maximum CAHE water temperature and the minimum operable speed of the auxiliary circulator motor.

CACS operation under the pressurized conditions calls for greatly different speed and power requirements from those under depressurized conditions. Unless a dual-motor system is employed for the auxiliary circulator drive to suit both sets of requirements, the minimum speed may be limited to 600 rpm (Sections 9, 10, and 11). In order to attain this speed under the pressurized conditions, about twice the motor torque of the DBDA cases is required.

Figure 13-4 shows the core thermal response (the hot spot cladding temperature of the assembly interior rods) during the pressurized cooldown in which the auxiliary circulator torque of 2712 Nm (2000 ft-lb) is used to develop about 790 rpm and 280 kW (375 hp). It is indicated that the core is unnecessarily overcooled in this case. Figure 13-5 shows the CAHE inlet and outlet water temperature transients for the same case. The maximum water temperature is 274°C (525°F), which indicates an adequate boiling margin even if the water pressure is reduced to the 8.96-MPa (1300-psia), 303°C (577°F) boiling point.

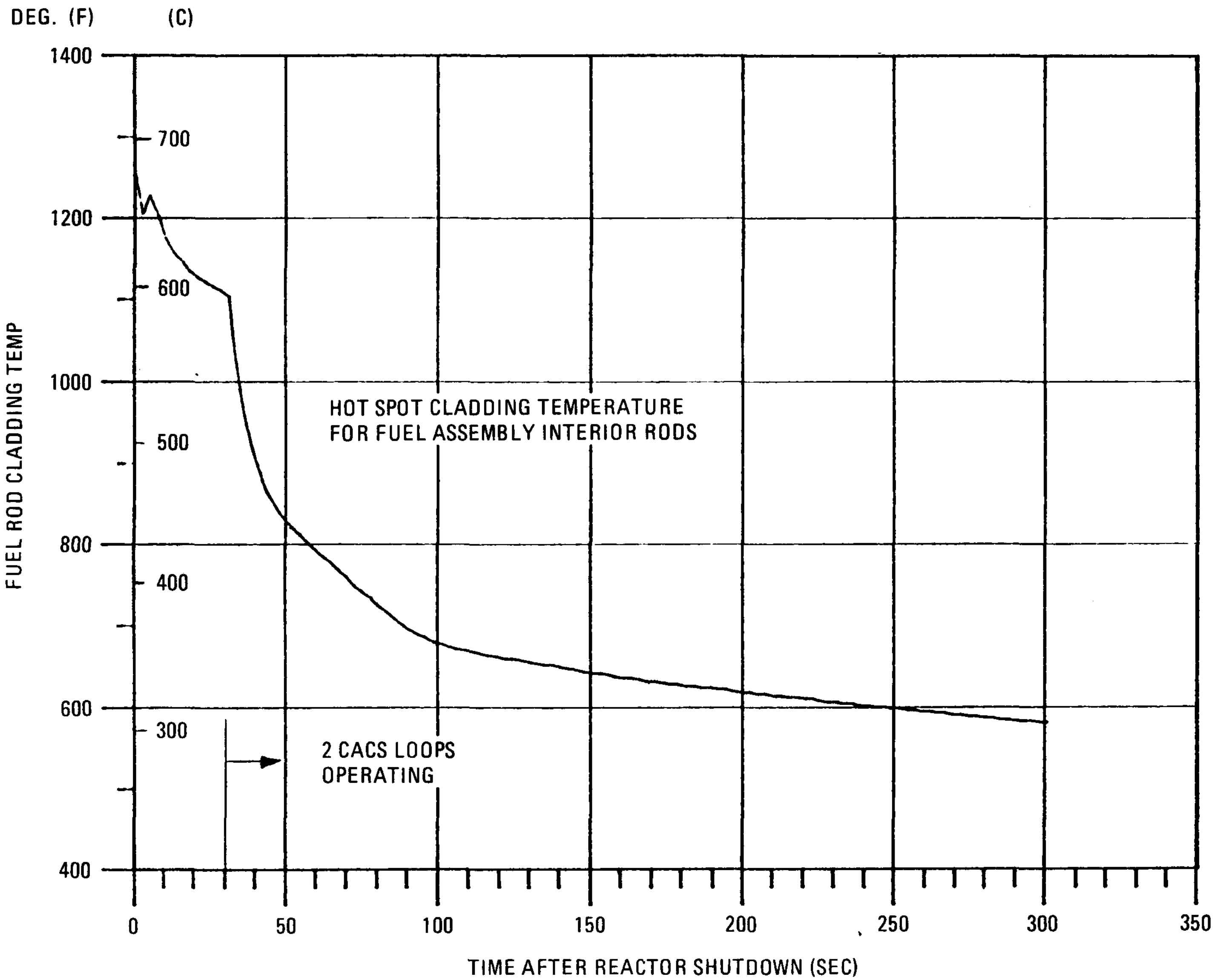

Fig. 13-4. Cladding temperature response during pressurized cooldown with revised CACS: case of high minimum auxiliary circulator speed; 22% of design

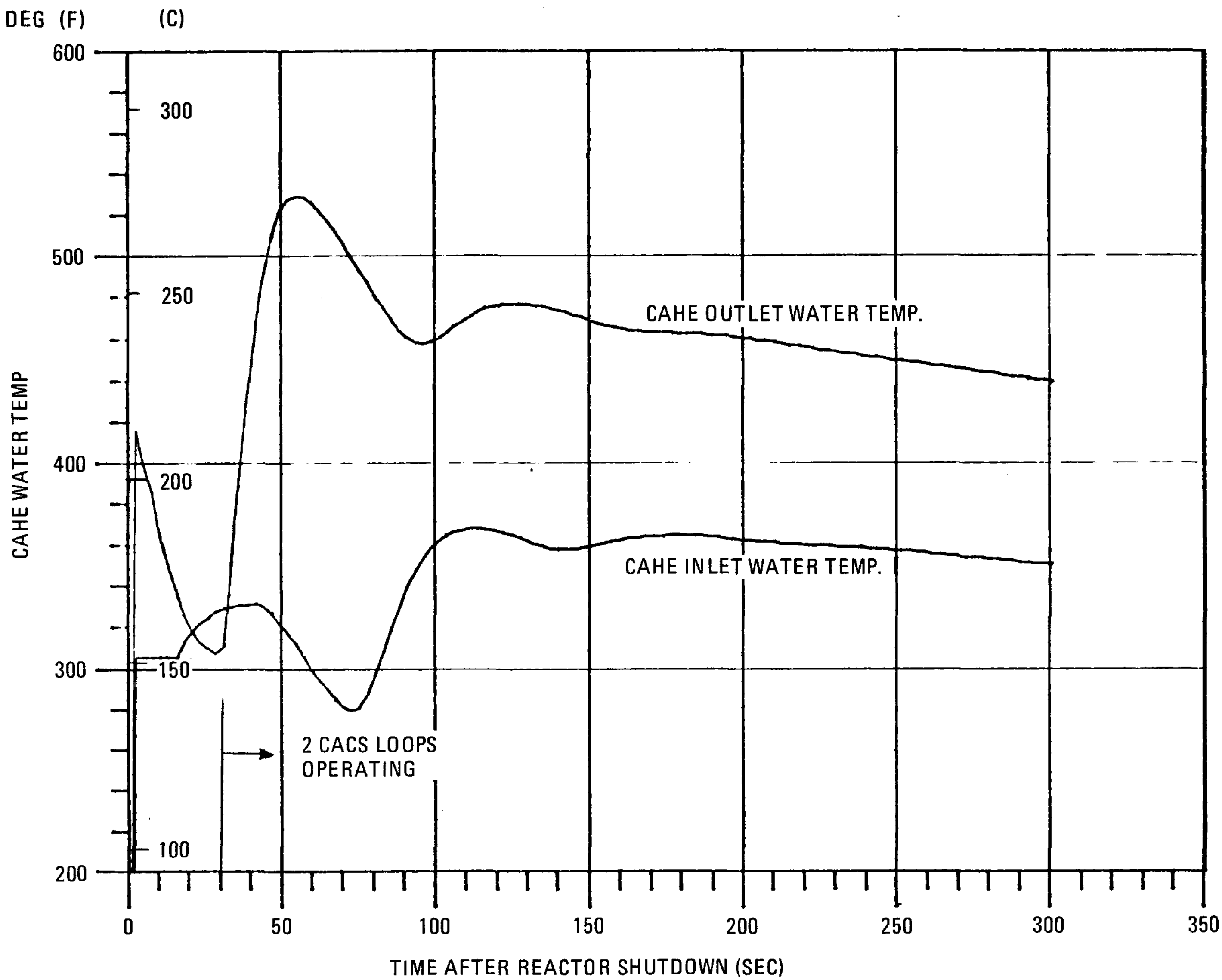

Fig. 13-5. CAHE inlet and outlet water temperature responses during pressurized cooldown with revised CACS: case of high minimum auxiliary circulator speed; 22% of design

Alternatively, if the dual-motor system is available, a low-torque, low-speed operation is also possible. Figures 13-6 and 13-7 show transient thermal responses during such an operation. Figure 13-6 shows the typical cladding temperature response during the pressurized cooldown with two auxiliary circulators which operate at a torque of 54.2 Nm (40 ft-lb), a speed of 90 rpm, and a power of 0.60 kW (0.8 hp). It is indicated in Fig. 13-6 that the core cooling is still adequate at such low-power conditions. The CAHE water temperature response shown in Fig. 13-7 for this case indicates a greater boiling margin than for the previous case shown in Fig. 13-5.

13.6.3. Comparison with Previous CACS Design

In order to identify specific differences between the revised CACS and the previous CACS, the changed input data and the key results of the transient analyses are compared in Tables 13-2 and 13-3, respectively. The major revision is in the CAHE size: the heat transfer area is doubled, the tube flow area is more than doubled, the water flow rate is quadrupled, and the helium flow resistance is halved.

As a result, the auxiliary circulator power for the DBDA core cooling is reduced by 30% and the maximum water temperature is reduced significantly. The reduced maximum water temperature allows an adequate boiling margin even if the water pressure is reduced by 60%, which results in pressure equal to the shell-side pressure of 8.96 MPa (1300 psia).

To compare the transient behavior of the revised CACS and the previous CACS on a consistent basis, the results of a transient analysis obtained with the previous CACS for the roughly equivalent cases are shown in Figs. 13-8 through 13-13. Figures 13-2 through 13-7 may be compared with Figs. 13-8 through 13-13, respectively.

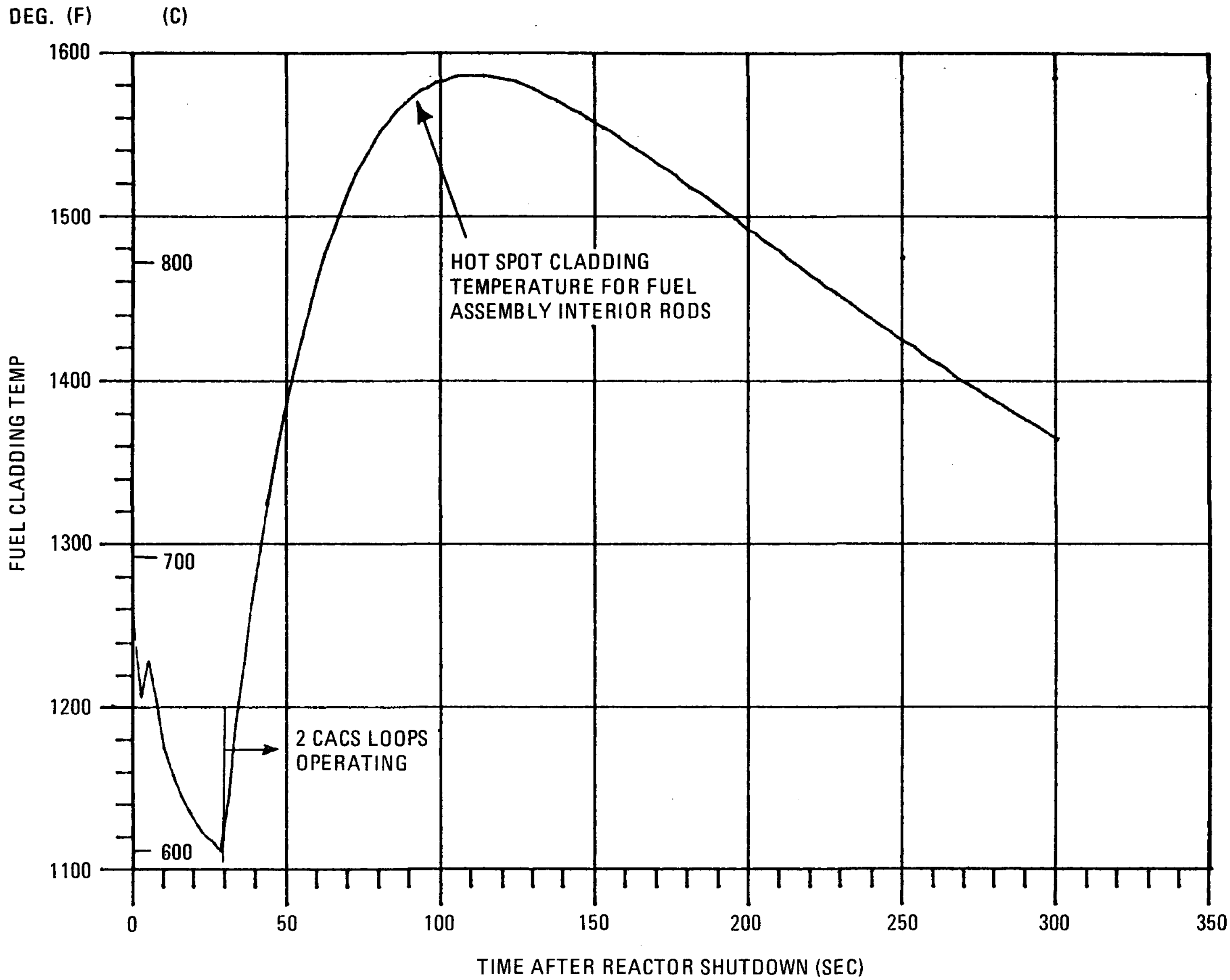

Fig. 13-6. Cladding temperature response during pressurized cooldown with revised CACS: case of low minimum auxiliary circulator speed; 2.5% of design

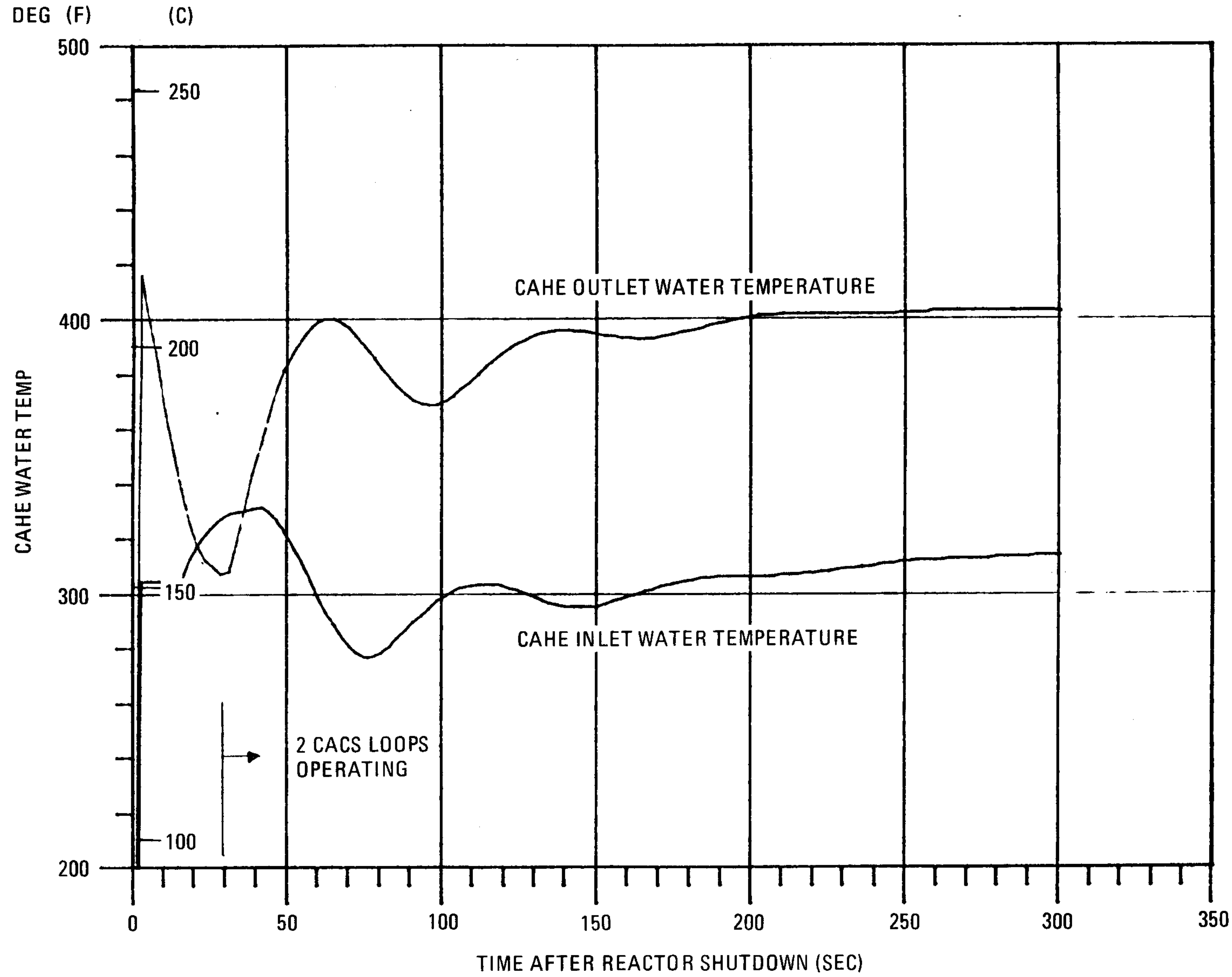

Fig. 13-7. CAHE inlet and outlet water temperature responses during pressurized cooldown with revised CACS: case of low minimum auxiliary circulator speed; 2.5% of design

TABLE 13-2
COMPARISON OF CHANGED INPUT DATA FOR REVISED AND PREVIOUS (PER PSID, AMENDMENT 7) CACS

Changed Input	Revised Design (Sections 9 and 10)	Previous Design (Ref. 13-1)
CAHE		
Bundle frontal area, m^2 (ft^2)	3.08 (33.18)	2.29 (24.7)
Tube diameter, i.d., m (in.)	0.0232 (0.918)	0.148 (0.584)
Tube diameter, o.d., m (in.)	0.0318 (1.25)	0.019 (0.75)
Tube length, m (ft)	44.71 (146.7)	29.50 (96.8)
Number of tubes	50	60
Tube transverse pitch, m (in.)	0.058 (2)	0.287 (1.13)
Tube longitudinal pitch, m (in.)	0.058 (2)	0.254 (1.0)
Bundle height, m (ft)	1.81 (6.14)	0.579 (1.9)
Tube heat transfer area (tube o.d.), m^2 (ft^2)	222.96 (2400)	105.91 (1140)
Tube inside flow area, m^2 (ft^2)	0.024 (0.262)	0.010 (0.1116)
Design water flow rate, kg/s (lb/hr)	75.89 (602,300)	19.40 (154,000)
Design water pressure, MPa (psia)	8.963 (1300)	14.48 (2100)
Tube-side pressure drop, MPa (psi)	0.207 (30)	0.207 (30)
Shell-side pressure loss coefficient, $1/m^4$ [lbf/lbm)($sec^2/in.^5$]	3.877 (4.18×10^{-9})	7.513 (8.1×10^{-9})
Tube-side heat transfer coefficient, $W/m^2 \cdot °K$ ($Btu/hr\text{-}ft^2\text{-}°F$)	$h_w = 673.23\ (0.09) m_w^{0.8}$	$h_w = 1368.9\ (0.183) m_w^{0.8}$
Shell-side heat transfer coefficient, $W/m^2 \cdot °K$ ($Btu/hr\text{-}ft^2\text{-}°F$)	$h_H = 119.92\ (0.06624) m_H^{0.642}$	$h_H = 212.65\ (0.132) m_H^{0.629}$
Auxiliary Circulator		
Moment of inertia, $kg \cdot m \cdot s^2$ ($lb\text{-}ft\text{-}sec^2$)	65.1 (48)	44.7 (33)
Design maximum speed, rpm	3600	4900
Speed at DBDA transfer, % of design speed	50	50
Speed at pressurized cooldown transfer, % of design speed	1.4	1.4
Design helium flow rate, kg/s (lb/hr)	9.1 (72,360)	6.8 (54,250)[a]
Design average pressure, MPa (psia)	0.182 (26.4)	0.178 (25.8)
Design inlet temperature, °C (°F)	221 (430)	204 (400)
DBDA torque limit, Nm (ft-lb)	1356 (1000)	988 (729)[a]
Pressurized cooldown torque limit for high-speed operation, Nm (ft-lb)	2712 (2000)	1977 (1458)[a]
Pressurized cooldown torque limit for low-speed operation, Nm (ft-lb)	54.2 (40)	39.3 (29)[a]

[a] These values are different from those used for PSID Amendment 7 and were used to obtain the results of Figs. 13-9 through 13-14 for a consistent comparison.

TABLE 13-3
COMPARISON OF KEY RESULTS FOR TRANSIENTS USING
REVISED AND PREVIOUS CACS

Changed Output	Revised Design (Sections 9 and 10)	Previous Design (Ref. 13-1)
DBDA Transient		
Maximum cladding temperature, °C (°F)	1249 (2280)	0.265 (2309)
Maximum auxiliary circulator power, MW (hp)	0.4518 (606)	0.6264 (840)
Maximum auxiliary circulator speed, rpm	3600	4900
Maximum water temperature, °C (°F)	210 (410)	283 (542)
Pressurized Cooldown for High Minimum Speed Operation		
Maximum cladding temperature, °C (°F)	732 (1350)	732 (1350)
Maximum auxiliary circulator power, W (hp)	280 (0.375)	416 (0.558)
Maximum auxiliary circulator speed, rpm	790	1624
Maximum water temperature, °C (°F)	274 (525)	398 (749)
Pressurized Cooldown for Low Minimum Speed Operation		
Maximum cladding temperature, °C (°F)	863 (1586)	880 (1616)
Maximum auxiliary circulator power, W (hp)	596 (0.8)	895 (1.2)
Maximum auxiliary circulator speed, rpm	90	177
Maximum water temperature, °C (°F)	206 (403)	301 (573)

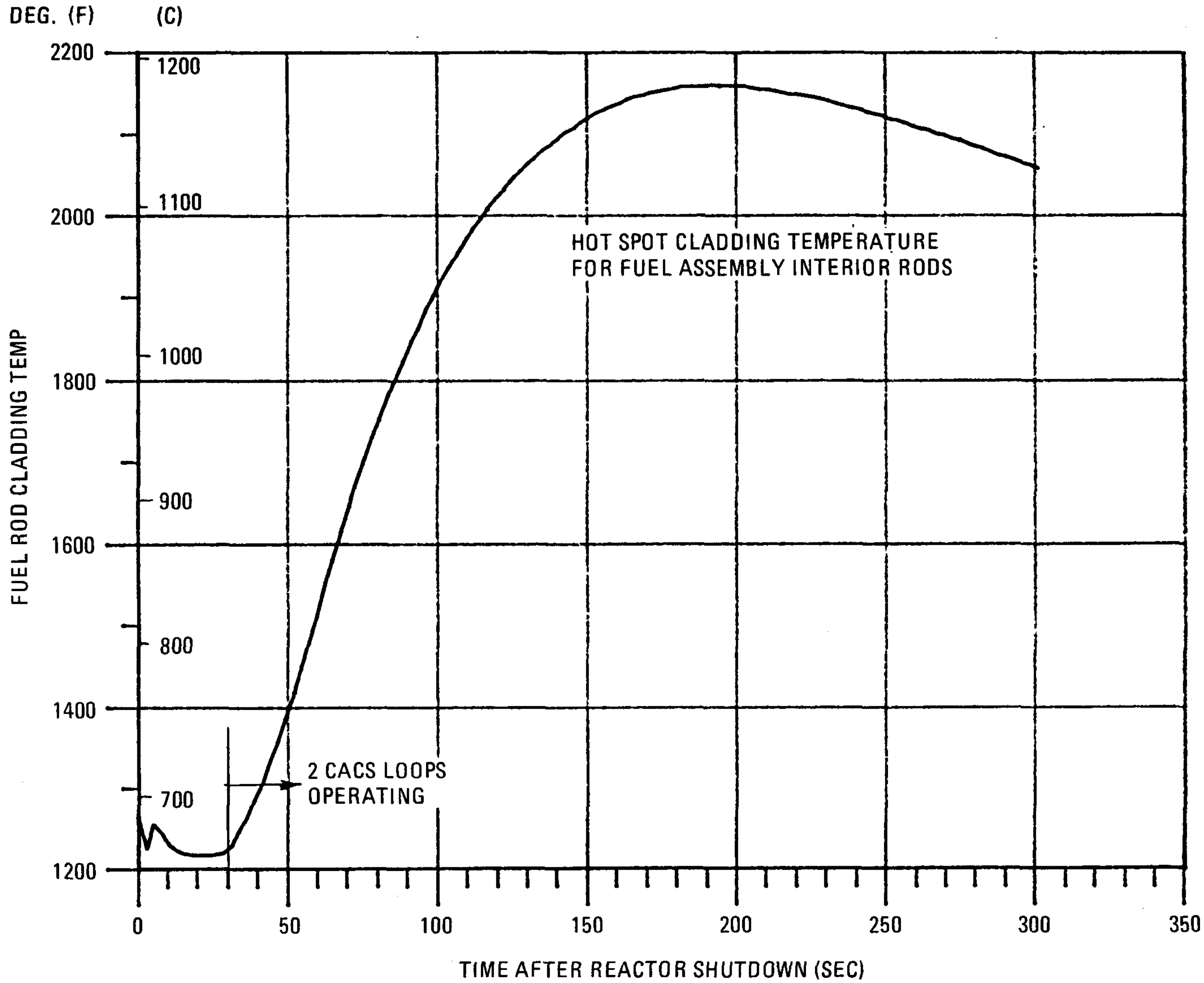

Fig. 13-8. Cladding temperature response during DBDA core cooling with previous CACS

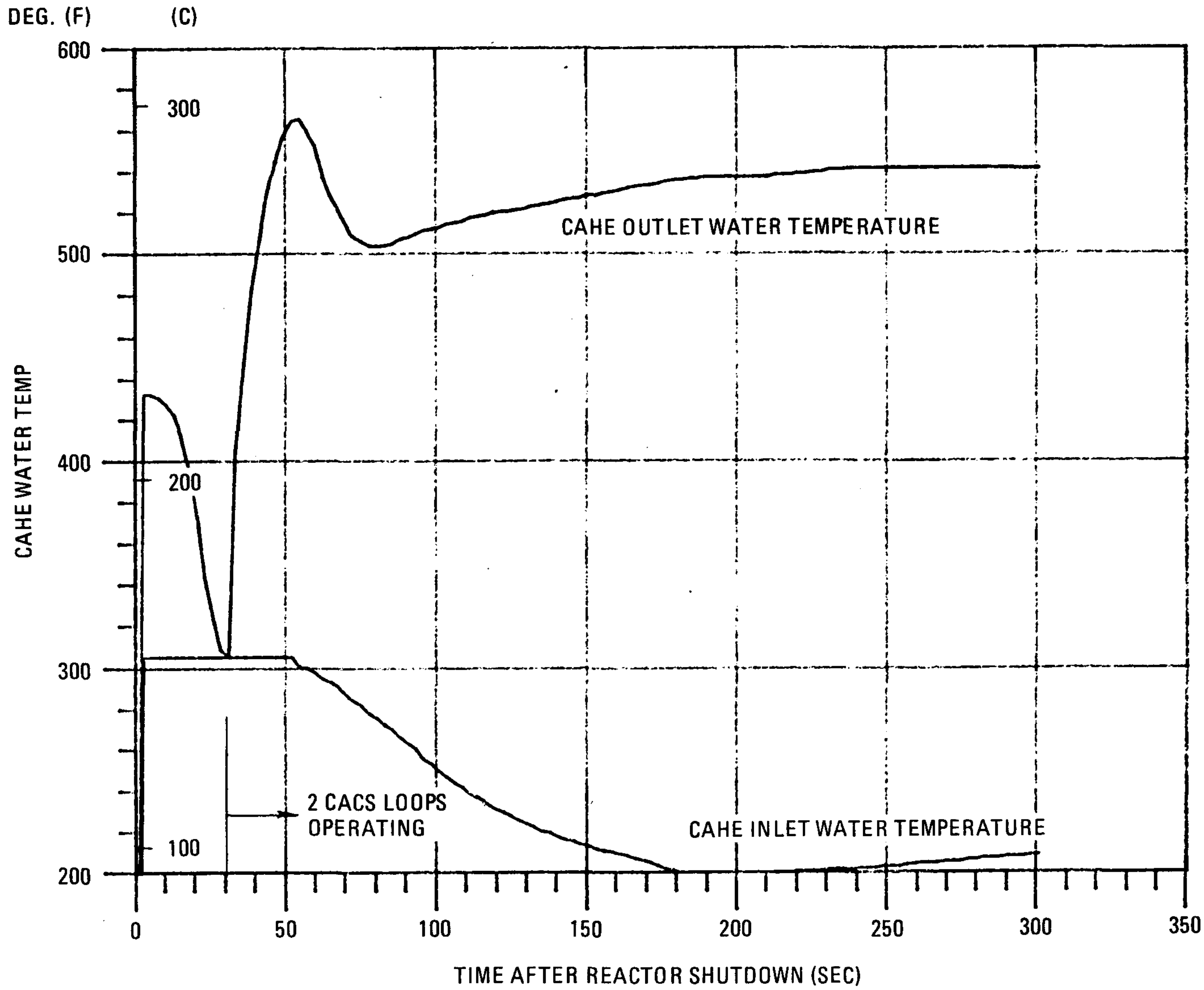

Fig. 13-9. CAHE inlet and outlet water temperature responses during DBDA core cooling with previous CACS

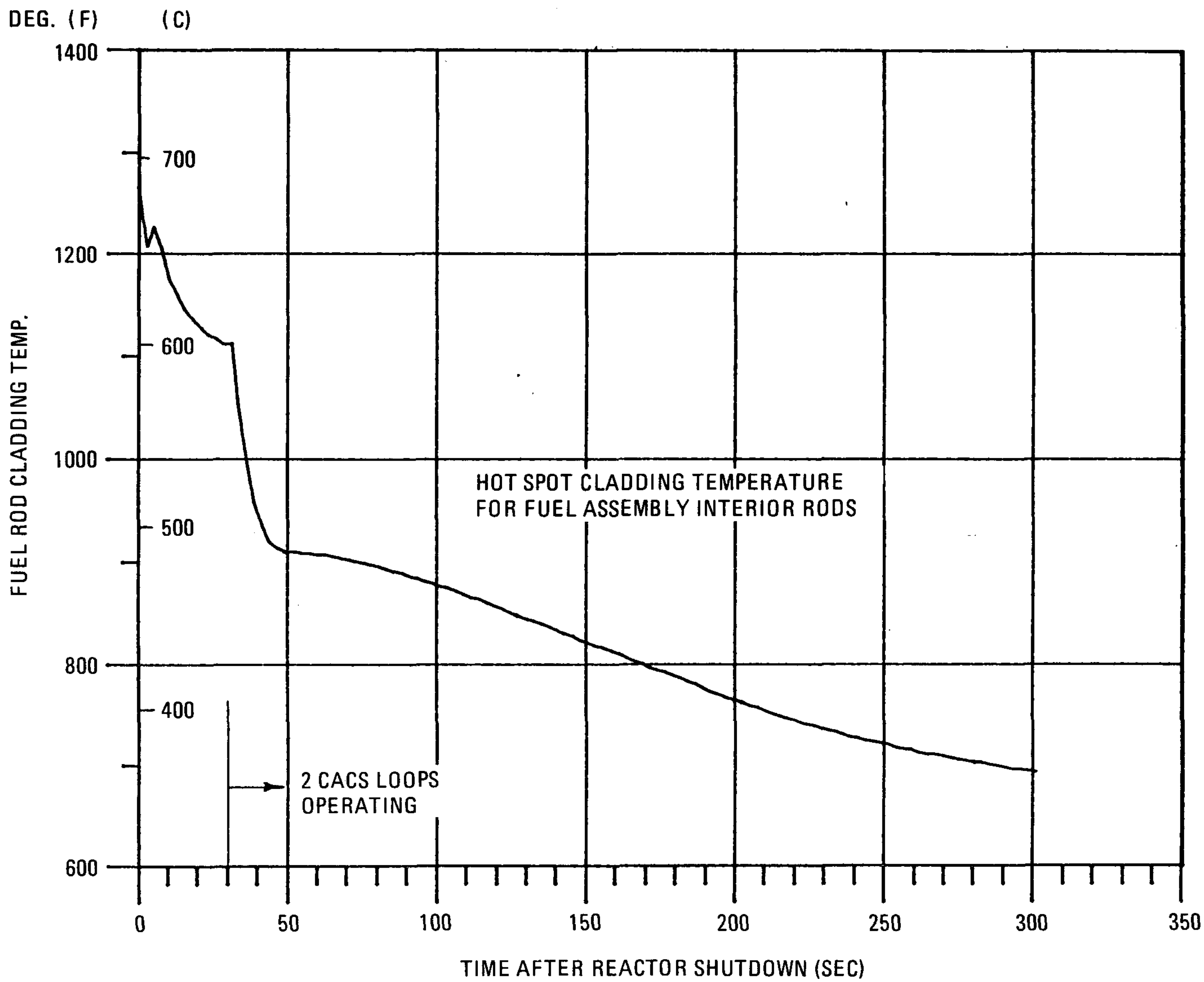

Fig. 13-10. Cladding temperature response during pressurized cooldown with previous CACS: case of high minimum auxiliary circulator speed; 33% of design

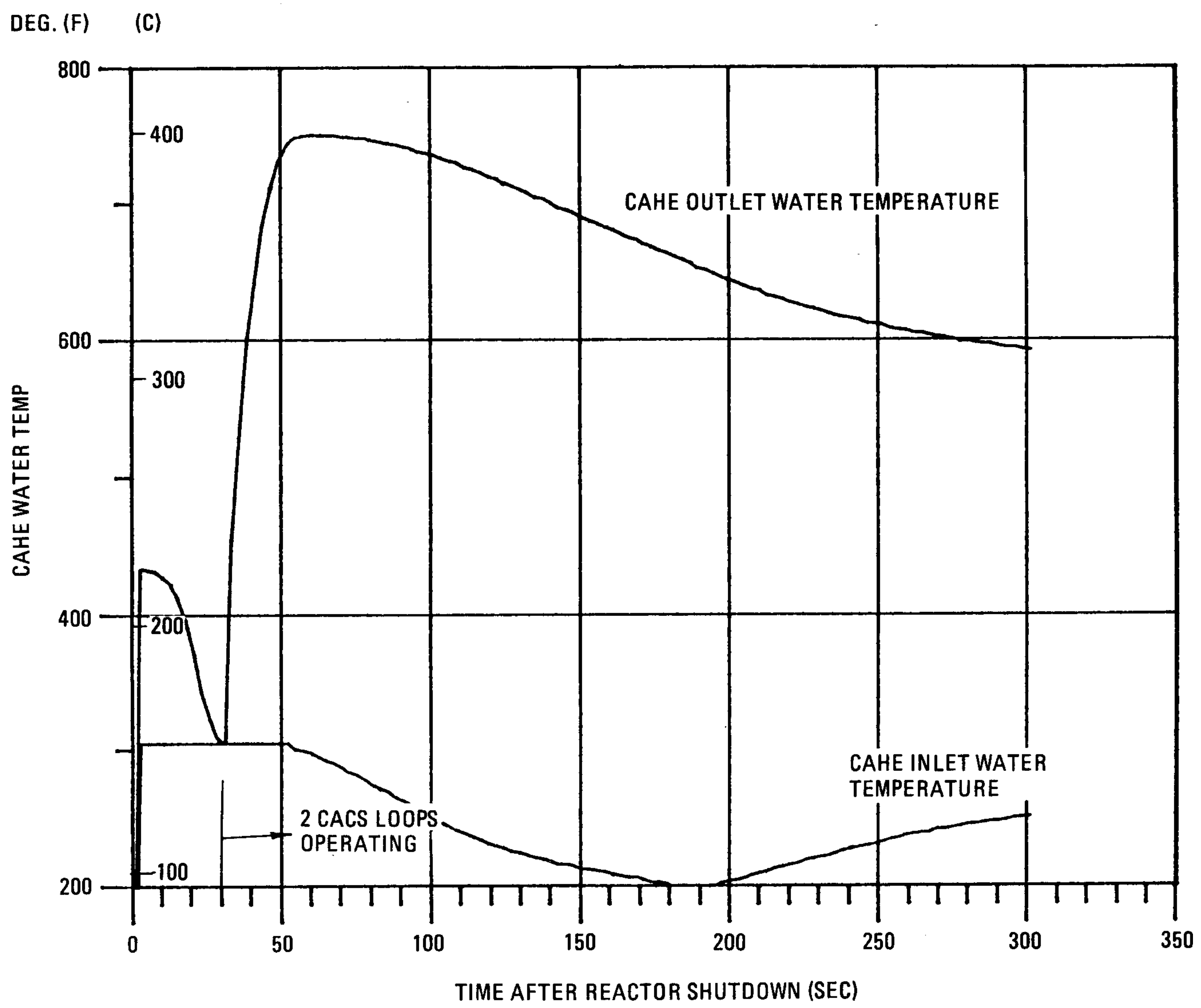

Fig. 13-11. CAHE inlet and outlet water temperature responses during pressurized cooldown with previous CACS: case of high minimum auxiliary circulator speed: 33% of design

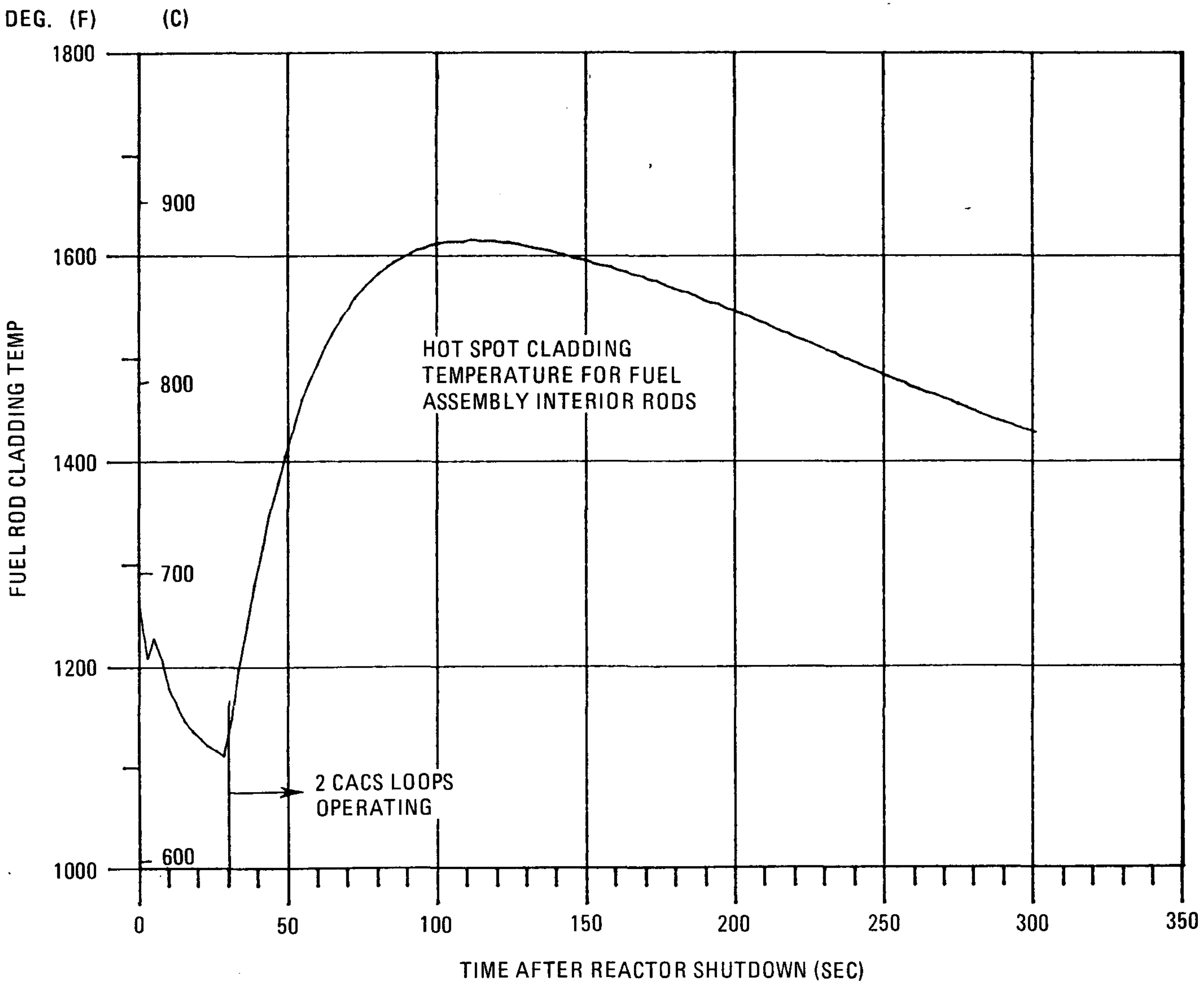

Fig. 13-12. Cladding temperature response during pressurized cooldown with previous CACS: case of low auxiliary circulator speed; 3.6% of design

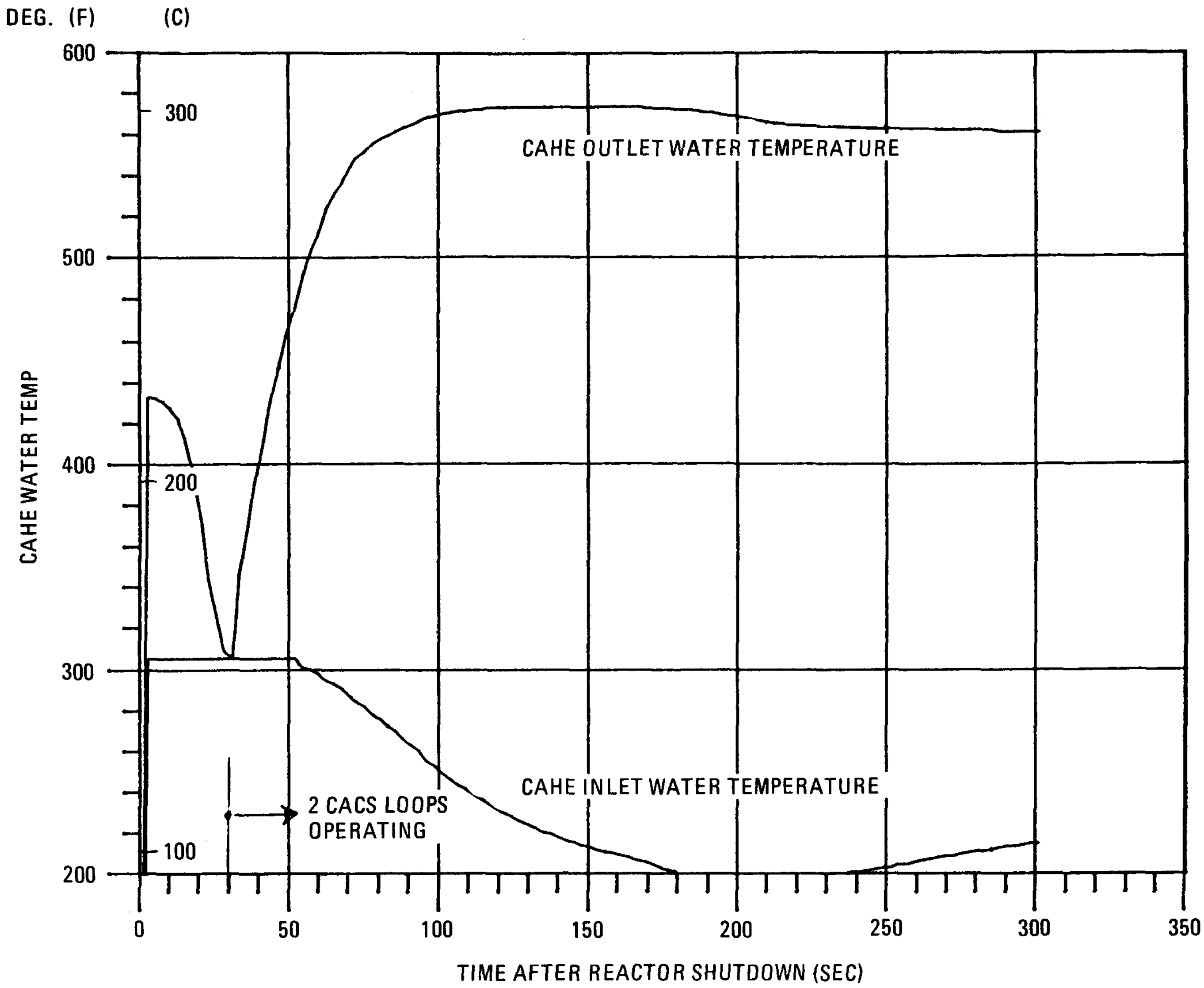

Fig. 13-13. CAHE inlet and outlet water temperature responses during pressurized cooldown with previous CACS: low minimum auxiliary circulator speed; 3.6% of design

13.6.4. Conclusions

Preliminary examination of the revised CAHE design indicates:

1. Adequate core cooling can be achieved with two CACS loops under DBDA conditions using a lower auxiliary circulator power than that indicated by the previous design.

2. An adequate boiling margin for the pressurized water system is indicated during the shutdown cooling of the pressurized core even if the water pressure is reduced as low as the primary coolant pressure 8.96 MPa (1300 psia).

3. The ALC design is not optimized in this study. However, ALC design options may need to be studied with respect to trade-off between the ALC size (cost), the water pressure, the CACS transfer scenario, and the minimum auxiliary circulator speed.

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14. CACS OPEN ISSUES AND FUTURE WORK

The study described herein represents an evolutionary step in CACS development but does not result in a cost or performance optimized system. Considerable potential for improvement remains and can be realized following CACS overall system parametric and functional evaluation studies.

Numerous open issues were identified during the course of the study. Resolution of these issues is expected to have a major impact on future CACS design. These issues include regulatory criteria definitions on diversity and reliability requirements. A list summarizing the more specific issues is given below:

- Cladding damage limits verification.
- Failure criteria and sequences.
- Main loop "coastdown" capability.
- Reliability requirements.
- Main and CACS loop isolation valve design and logic.
- Diversity and redundancy. (Are two forced convection systems sufficiently diverse?)
- DBDA flow area.
- RHR event spectrum (pressurized and DBDA conditions).

- Main loop cooling and CACS functional interfaces (e.g., main loop overspeed and CACS startup time requirements).

- CACS startup time capability.

- In-service inspection affecting component design (e.g., CAHE tube inspection and loop isolation valve actuating devices).

- Establishment of system design parameters.

- Single failure point elimination in MLCS and CACS.

- Containment back-pressure following a DBDA.

14.1. CACS TRADE-OFF STUDY

Work performed under this study provides a basis for refining CACS design requirements. Future work will address these requirements, particularly the short startup time, and the possibility of normally operating or normally idling CACS circulators.

A parametric and functional trade-off study should be performed on the entire system, including the CAHE, auxiliary circulator, circulator drive and control, CACWS, ultimate heat sink, and power supply systems. Methods of rating and criteria should be established and used to perform a relative ranking of alternate concepts. The CACS for GCFR Demonstration and Commercial Plants will be recommended on the basis of the evaluation.