MASTER

Attachment to Letter
No. XL-898-10480
September 1981

DESIGN CRITERIA FOR A SELF-ACTUATED SHUTDOWN SYSTEM TO ENSURE LIMITATION OF CORE DAMAGE

DOE/SF/71032--T45

DE82 011823

N. A. Deane

D. B. Atcheson

GENERAL ELECTRIC COMPANY
ADAVNACED REACTOR SYSTEMS DEPARTMENT
Sunnyvale, California

DISCLAIMER

CONTENTS

		Page
	ABSTRACT	
1.0	**INTRODUCTION**	1-1
2.0	**FUNCTIONAL REQUIREMENTS FOR SASS DERIVED FROM LOA-2 SUCCESS CRITERIA**	2-1
	2.1 Definitiion of "LOA-2 Success" and SASS Top Level Function	2-2
	2.2 Role of SASS in Assuring LOA-2 Success	2-6
	2.3 SASS Functional Requirements	2-8
3.0	**SASS Design Criteria (Damage Severity Limits)**	3-1
	3.1 Primary and Secondary Shutdown System Criteria	3-1
	3.2 SASS Criteria	3-1
4.0	**PRELIMINARY DESIGN OF THE SASS ASSEMBLIES AND CONTROL WORTH ESTIMATES**	4-1
	4.1 Overall SASS Design	4-1
	4.2 The "Three-Assembly-SASS" Configuration	4-3
5.0	**ACCIDENT SCENARIOS**	5-1
	5.1 Introduction	5-1
	5.2 Control Assembly Withdrawal at Full Power With and	5-3
	Without Pump Trip - Maximum Design Rod Withdrawal Speed	5-4
	5.3 Loss of Off-Site Electric Power Triggered Flow Coastdown	5-4
	5.4 Control Assembly Withdrawal at Full Power - Maximum Mechanical Speed	5-4
	5.5 Safe Shutdown Earthquake (SSE)	5-4
6.0	**CDS PHASE II RESPONSE TO SELECTED TRANSIENTS AND SCRAM PARAMETERS**	6-1
	6.1 Transient Event Descriptions	6-1
	6.2 Transient Responses Without Scram	6-6
	6.3 Scram Parameters	6-15
	6.4 Normalized Sodium Outlet Temperatures	6-22
	6.5 SASS Response Time Requirements for CDS Phase II Core	6-41
7.0	**CONCLUSION**	7-1
	REFERENCES	
	MAJOR CONTRIBUTORS	
	APPENDIX - PRELIMINARY DEFINITION OF LOA-2 GOALS	A-1

DESIGN CRITERIA FOR A SELF-ACTUATED SHUTDOWN SYSTEM

ABSTRACT

Safety-based functional requirements and design criteria for a self-actuated shutdown system (SASS) are derived in accordance with LOA-2 success criteria and reliability goals. The design basis transients have been defined and evaluated for the CDS Phase II design, which is a 2550 MWt mixed oxide heterogeneous core reactor. A partial set of reactor responses for selected transients is provided as a function of SASS characteristics such as reactivity worth, trip points, and insertion times.

1.0 INTRODUCTION

The objective of this document is to identify design criteria for a Self-Actuated Shutdown System (SASS) using a systems engineering approach. The first step in the criteria evaluation process was to define the role of the SASS system within the overall Plant Protection System. In this document, it was assumed that the function of the SASS system is to assure limitation of core damage consistent in the requirements of Line-of-Assurance-2 (LOA-2).[1.1-1] The Safety Program Plan definition of LOA-2 (see 1.1-1) was used to define generic, core-design-independent, SASS-design-independent safety functional requirements which are believed to be applicable to any self-actuated shutdown system with a function to limit core damage (LOA-2). If the same system is also required to perform a second function, such as to ensure the accommodation of design basis events (LOA-1), additional, more restrictive requirements would be applicable.

Functional requirements are described in Section 2 of this document. Generic design criteria that are necessary and sufficient to meet these functional requirements are defined in Section 3. These design criteria depend upon plant and core design but they do not imply a specific SASS design. To some extent, the design criteria are influenced by the choice of design-basis normal and off-normal operating conditions. The plant design chosen as the basis for this document is the CDS Phase II design, which is a loop-type, 1000 MWe LMFBR with a heterogeneous, mixed-oxide core. The design-basis transients considered in this study are defined in Section 5, and the core thermal response to these events is described in Section 6.

Several related documents have been issued jointly by AI, GE, and W-ARD during the past few years.[1.1-2] The present document represents a refinement of the earlier reports in two areas:

a. The current document attempts to clarify the relationship between safety-based SASS functional requirements and the Line-of-Assurance approach to LMFBR safety.

b. Design criteria are based upon the CDS Phase II heterogeneous core instead of a homogeneous core design.

In addition, more specific guidelines concerning the treatment of uncertainties in design calculations are defined than were provided in previous documents.

Once design criteria are developed in terms of upper limit values for core conditions, such as fuel and coolant temperatures, fuel pin failures, and core component deformation, performance requirements for the SASS system can be defined. Typically, performance requirements specify values for the scram parameters, such as the delay time between a change in core temperatures, flows or fluxes, the time of control rod insertion, and scram worth of the SASS system that must be achieved to assure that core conditions will be limited as specified in the design criteria. While the primary objective of this document is to establish design criteria, a preliminary specification of SASS performance requirements is presented in Section 6.5 to aid the designer in selecting among conceptual SASS designs.

2.0 FUNCTIONAL REQUIREMENTS FOR SASS DERIVED FROM LOA-2 SUCCESS CRITERIA

As an initial step in defining performance requirements, design requirements, and reliability requirements for a self-actuated shutdown system (SASS), it is necessary to define the top-level function of the system. Once this is done, it is possible to derive a set of requirements to be imposed on the system that will assure the function is achieved. In this section, the top-level function of a SASS is defined, and the functional requirements are derived. The top-level funcion is summarized in Table 2.2-1. Necessary and sufficient SASS functional requirements are summarized in Tables 2.2-1 and 2.2-2, while Table 2.2-3 lists detailed requirements derived from Tables 2.2-1 and 2.2-2.

It is essential to note that the functional requirements derived here apply only to the self-actuated mode of any shutdown system. As a result, the functional requirements presented in this document do not include requirements derived from non-safety considerations (e.g., reactor availability requirements, post-actuation, reactor operability, etc.). Functional requirements derived from these non-safety considerations would have to be added to the list presented in this document provided they are consistent with safety-related functional requirements.

Before proceeding to a discussion of the function and functional requirements for a SASS, it seems desirable to place the current document in perspective relative to prior work and to activities planned for the near future. Functional requirements and design criteria for SASS systems have previously been issued jointly by AI, GE, and WARD. This earlier work established requirements based on a SASS function definition that was intended to assure inherently actuated shutdown with core damage essentially within Line of Assurance 1 (LOA-1) limits. In addition, design requirements were based on a homogeneous core design. The present document is based on the CDS Phase II heterogeneous core design, and the SASS function is to meet LOA-2 goals. LOA-2 goals, rather than LOA-1 goals, were adopted as a basis for defining SASS requirements because the less restrictive LOA-2 goals should provide greater latitude for the SASS designer to add diversity to to the system. This reflects the desire to protect against common-mode failures of both the primary shutdown system and its backup systems. It is recognized that increased diversity may be obtained at the expense of reliability. It is not the purpose of this document to determine the compatibility of functional requirements based on LOA-2 protection and other functional requirements.

2.1 Definition of "LOA-2 Success" and SASS Top-Level Function

As noted above, the primary objective of this document is to identify functional requirements that are necessary to meet the objective of protecting LOA-2 integrity. Therefore, the top-level function considered here may be stated as:

> "Given that the primary shutdown system(s) have failed to terminate an accident sequence (so that LOA-1 has been penetrated), the SASS must assure LOA-2 success with reliability $\geq$ X."

This statement of the SASS function is useful in developing functional requirements only if "LOA-2 success" is defined in terms that can be expressed and evaluated quantitatively. The definition adopted for the present study is discussed in the remainder of this subsection and in Appendix A.

LOA-2 success is most commonly defined as limited core damage. While the concept of limiting core component damage to a small portion of the core (e.g., a few subassemblies) is straightforward, its usefulness depends on one's ability to define damage in clear and quantifiable terms. Only after this definition is established is it possible to establish an upper limit on damage that is clearly consistent with LOA-2 success.

Definition of Limited Core Damage

The approach used in this study to define "limited core damage" was to focus on the intent of LOA-2, and to derive from that intent a working definition of LOA-2 success. The working definition is intended to be entirely consistent with other definitions of LOA-2 success and limited core damage, while providing clearer guidelines to be used in the design process.

The key step in developing an adequate working definition of the phrase, "limited core damage", is to perceive correctly the intention behind this phrase. We believe the intention is to define a set of reactor states within which there is very high confidence that the energy content of the core (and the rate of increase in core energy content) is much lower than that required to challenge the capability of the reactor pressure vessel and containment building. This is similar to the LOA-3 goal. The difference between the LOA-2 goal and the LOA-3 goal is the desired level of confidence. Very high confidence that the core energy level will remain acceptably low is achieved in LOA-2 by assuring that the accident sequence will not propagate from an event involving loss of component structural integrity, material phase changes, or abnormal material motion in a few assemblies to involvement of a significant fraction of the core in such phenomena. This confines potentially autocatalytic or energetic phenomena to a small fraction of the core mass, such that the maximum theoretical thermal-to-mechanical energy conversion will not challenge the reactor containment.

In order to confine potentially autocatalytic or energetic phenomena to a small fraction of the core mass with the required level of confidence, it is necessary to avoid two situations:

1. Significant insertion of positive reactivity via material motion or phase change, and

2. Core component geometries, or rates of change in geometry, that are so different from the normal envelope of conditions that subsequent changes cannot be described with confidence.

Item 1 must be avoided because positive reactivity insertion can lead to large increases in core-wide energy content. Item 2 must be avoided because significant departures from normal geometry imply reactivity changes, a potential for energetic events, and the loss of assured coolable geometry. In addition, both items lead to increased uncertainty in the outcome of the accident sequence.

Items 1 and 2 provide a working definition of "Limited Core Damage". Item 2 limits the extent of disruption in the worst few assemblies in the core, while Item 1 limits the amount of disruption in the whole core. While Item 1 can be interpreted clearly enough to be useful in the design process, Item 2 is too ambiguous to be useful to the designer. Therefore, the following guidelines are provided to aid in interpreting Item 2:

2a. Expulsion of molten fuel into voided or unvoided coolant channels is to be avoided but molten fuel motion within the original envelope of the fuel pin cladding is allowable.

2b. Cladding melting of the entire circumference of any fuel pin is to be avoided at all axial locations. This does not preclude cladding melting of a small fraction of the pin circumference at a local hot spot.

2c. Stable coolant boiling is allowable, but coolant voiding and cladding dryout are to be avoided.

2d. Small-area cladding failures are allowable, but large-area breaches that could lead to coolant voiding or molten fuel expulsion from the pin must be avoided.

Items 1 and 2, supplemented by guidelines 2a through 2d, form the definition of "Limited Core Damage" that was adopted in this study as a basis for defining SASS functional requirements and design criteria.

Item 2, and Items 2a through 2d, are believed to be sufficient to assure coolable geometry throughout the accident sequence. However, these conditions are more restrictive than are required to produce a reasonable expectation of coolable geometry. The more restrictive conditions listed above are necessary to preclude the localized occurrence of potentially autocatalytic or energetic events that could propagate into core-wide phenomena. By prohibiting localized occurrences of these events, one eliminates the need to consider a number of mechanisms (e.g., coolant flow redistribution between assemblies, duct melting and distortion, etc.) by which localized events might propagate throughout the core. The analyses presented in Sections 5 and 6 of this document suggest that the more restrictive requirements should not penalize the SASS design unduly, so that relaxation of requirements to assure coolable geometry alone is unnecessary.

Required LOA-2 Success Probability

Quantitative determination of a required value for the probability of LOA-2 success is beyond the scope of this document. For design purposes, the high degree of confidence required that Items 1 and 2 (defined previously in this section) are satisfied, combined with the conservative nature of these items, is believed to be adequate. For the present study, it has been assumed that a target value for the probability of LOA-2 success may be imposed on the designer at some point in time, so that design requirements defined during the current study might have required probabilities associated with them at some future time. To allow for this, the requirements described in Section 2.2 have been arranged in a logical structure designed to facilitate a probabilistic risk analysis, and probabilities (values to be determined) have been included in each statement of requirements. Some initial thoughts describing one approach that might be used to establish probability and reliability goals for individual engineered safety systems based on a target value for LOA-2 success probability are presented in Appendix A.

Although a firm value of LOA-2 success probability has not been derived for use in this study, and the analysis required to assign probability goals to each requirement in Section 2.2 has not been performed, it is important to note that reliability goals are iimplicit in all requirements. Therefore, the design criteria defined in Section 3 of this document are to be regarded as initial estimates of deterministic (i.e., non-probabilistic) design criteria that are believed to assure satisfaction of the rigorously derived probabilistic criteria that assure LOA-2 success. For example, one design criterion in Section 3 specifies a deterministic limit on the amount of fuel melting that can occur in the fuel pin with highest fuel temperature in the core. This limit is defined deterministically for one fuel pin in order to avoid imposing on the SASS designer a requirement for core-wide, probabilistic evaluations of transient fuel temperature. However, this limit is established to satisfy the core-wide probabilistic criterion of real interest.

Simplification of design criteria from core-wide probabilistic criteria to single-pin deterministic criteria helps the designer, but penalties are also incurred. First, the simplified criteria are valid only for a given core design (the "CDS Phase II" core in this study). Second, the deterministic criteria must be more restrictive to account for the simplifying assumptions used to replace the probabilisitc analysis. An example of this latter effect is the conservatism introduced into engineering hot-channel factors to simplify temperature calculations during the fuel pin design process.

2.2 Role of SASS in Assuring LOA-2 Success

The purpose of Section 2.2 is to provide perspective regarding the role of SASS, and the contents of this document, in assuring LOA-2 success. As indicated in Table 2.2-1, SASS is one element of a system of engineered safety systems and procedures that affects LOA-2 integrity. SASS has primary responsibility for protecting LOA-2 integrity against some intitating events, and only secondary responsibility for other initiators. The primary focus of this document is on events for which SASS has a major protective role.

While this document is intended primarily to establish SASS design requirements that will assure adequate response of the system when called upon, it is important to recognize that LOA-2 may also be violated if SASS does not respond at all when called upon, if SASS is not called upon, or if it is called upon too late to protect LOA-2. Consideration of these possibilities leads directly to SASS requirements that are unrelated to response time and sensor capability requirements, provides a convenient framework for identifying the roles of other safety systems in protecting LOA-2, and provides a framework for identifying the initiating events that SASS protects against.

As noted above, there are just four ways that LOA-2 integrity can be lost, given that a SASS system is present, an initiating event has occurred, and LOA-1 integrity has been violated. These are:

I SASS Responds Inadequately When Called Upon
II SASS Is Not Called Upon
III SASS Does Not Respond When Called Upon
IV SASS Is Called Upon, But Too Late

Table 2.2-1 identifies possible causes for each of these possibilities, and identifies the causes that must be eliminated by SASS design. The causes that are outside the control of the SASS designer are of interest, because they indicate areas that must be confronted in the overall LMFBR Safety Program in order for the SASS effort to be effective in protecting LOA-2 (i.e., areas that could lead to violation of LOA-2 integrity, event if SASS operates perfectly). However, the requirements identified in this document are those derived from the parts of Table 2.2-1 for which the SASS designer provides the principal protective function.

As shown in Table 2.2-1, the SASS designer can play an important role in protecting against all four possible LOA-2 failure paths. Requirements presented in this document reflect this fact. Although analytical results focus primarily on areas I and IV of the table, requirements are also presented in Section 2.3 that are derived solely from the reliability considerations noted in areas II and III of Table 2.2-1. For example, some requirements stated in Section 2.3 are based on judgment concerning design features that are needed to avoid common-mode or common-cause failures. In this area, and in other areas related to SASS reliability, the requirements presented here represent a starting point. A more complete list of reliability-related requirements can be derived when specific SASS designs are considered. The present document is intended to define requirements that are independent of the SASS design concept.

Although it is not explicitly mentioned in Table 2.2-1, the definition of "limited core damage" is central to Items I and IV, because these items refer to the amount of core disruption that occurs prior to the time that SASS responds (Item I) or is called upon (Item IV). The definition of "limited core damage" is used in Section 2.3 to define SASS functional requirements that block failure path I. Functional requirements derived from the need to block failure paths II and III are stated in Table 2.2.3 without further discussion. Failure path IV is important only for initiating events that have very low probabilities of occurrence, and the primary sources of protection are the FEDAL system and inherent core phenomena. Therefore, no SASS functional requirements are defined to block this failure path. Similarly, failure path II.D leads to no SASS functional requirements, because SASS has no protective function during RBCB operation.

2.3 SASS Functional Requirements

The purpose of this section is to define SASS functional requirements such that failure of LOA-2 by any of the failure paths affected by SASS action is a low-probability event. These functional requirements are intended to be independent of both reactor design and the design of SASS.

Table 2.2-3 lists the SASS functional requirements needed to prevent LOA-2 failure by the paths identified in Table 2.2-1. To show that each of the possible failure paths is covered by at least one SASS requirement, each item in Table 2.2-3 is referenced to a failure path from Table 2.2-1. In addition, each requirement in Table 2.2-3 is arranged in order according to the failure path confronted by that requirement. Thus, requirements 1 through 8 in Table 2.2-3 refer to failure path I, requirements 9 through 18 are intended to block failure path II, and requirements 19 through 23 are needed to prevent LOA-2 failure by failure path III. As noted above, no SASS requirements are derived from failure path IV.

Table 2.2-2 is included in this section in order to show explicitly how the section 2.1 definition of limited core damage influences SASS functional requirements. The two-part working definition of limited core damage is expanded in Table 2.2-2, and detailed limits on specific aspects of core damage are defined. Since Table 2.2-2 is an expanded version of failure path I, requirements in Table 2.2-3 that are based on path I are referenced to items in Table 2.2-2 rather than to items I.A and I.B in Table 2.2-1.

Consistent with the Section 2.1 definition of limited core damage, Table 2.2-2 shows that three classes of phenomena must be limited or prevented in order to assure accident termination with limited core damage. First, positive reactivity insertion must be limited so that core-wide energy content is too low to challenge containment integrity. Limiting this type of core damage establishes bounds on integral core-wide conditions, but does not explicitly limit the extent of damage in the worst few assemblies. Second, damage in the worst few assemblies must be limited to maintain high confidence in the progression of the accident sequence. The third category of core damage considered in Table 2.2-2 is damage to engineered safety systems with some responsibility for preserving the integrity of LOA-2, LOA-3, or LOA-4.

Given Tables 2.2-1 through 2.2-3 and the preceeding discussion of the relationships between these tables, the considerations leading to each of the SASS functional requirements in Table 2.2-3 should be reasonably clear. Therefore, the remainder of this section is devoted to discussion of nomenclature and items that require clarification.

The phrase "called upon" in Table 2.2-1 must be defined carefully in order understand the table. This phrase refers to a change in core conditions (such as power or temperature) to which SASS is expected to respond. If SASS is provided with sensors that are theoretically able to sense a core operating parameter, and that operating parameter changes, the SASS is regarded as having been called upon. For example, if an earthquake occurs and SASS is not equipped with accelerometers as part of its sensor system, SASS is not regarded as "called upon" unless other core parameters change. If core parameters change enough to challenge LOA-2 integrity, and sensors designed to respond to those core parameters are present, SASS is regarded as being called upon, whether or not the sensors cause SASS action. A related item is the distinction between failure paths I.B, III.A and IV.A in Table 2.2-1. Failure paths I.B and III.A include the situation in which SASS responds too slowly to a design-basis event to protect LOA-2 integrity. Path IV.A includes the situation where the design basis event progresses too rapidly for SASS to respond. Clearly, the distinction is a matter of definition of the events used as a basis for SASS design. In this study, it was assumed that SASS design basis events would be defined by those responsible for funding SASS development. Presumably, SASS must be capable of protecting the reactor against some minimum set of initiating events in order to make SASS development cost effective.

In Table 2.2-2, the phrase "structural failures" in item 1.3 refers to pin failures in which the pin breaks into two or more unconnected pieces, pin failures in which a substantial fuel area is exposed to the coolant, and failures of the upper and lower support structure. These failures are to be prevented because they could lead to motion of solid fuel that is sufficient to produce positive changes in reactivity. The phrase "pin structural integrity" in item 2.2 refers to the ability of the cladding to restrict movement of solid fuel and to maintain fuel pins in one piece.

TABLE 2.2-1
POSSIBLE LOA-2 FAILURE PATHS AND THE ROLE OF SASS IN BLOCKING THESE

		Source of Protective Function
I.	SASS RESPONDS INADEQUATELY WHEN CALLED UPON	
	A. Insufficient Reactivity Insertion	SASS Designer
	B. SASS Response Too Slow	SASS Designer
II.	SASS IS NOT CALLED UPON	
	A. Human Error (Sensors Disconnected or SASS Bypassed)	Computer-aided Operation and Maintenance
	B. Accident Initiated After Shutdown (SASS Affects Decay Heat Level and Degree of Subcriticality)	SHRS
	C. SASS Malfunctions and Acts As Accident Iniator	SASS Designer
	D. Excessive Radioactivity Due to Fuel Failure and RBCB Operation	Reactor Operator and Containment
III.	SASS DOES NOT RESPOND WHEN CALLED UPON	
	A. Human Error (Mechanical Design, Maintenance, Sensor Design)	SASS Designer, Computer-aided Operation and Maintenance
	B. Common-Mode Failure of All Shutdown Systems	SASS Designer
IV	SASS IS CALLED UPON TOO LATE	
	A. Beyond-Design-Basis Initiating Event	Inherent Core Phenomena SASS Designer or FEDAL
	B. Sensor Placement Too Localized in Core	SASS Designer

TABLE 2.2-2

CONDITIONS THAT MUST BE SATISFIED TO ASSURE ACCIDENT TERMINATION WITH LIMITED CORE DAMAGE

1.0 LIMIT CORE ENERGY CONTENT BY LIMITING POSITIVE REACTIVITY INSERTION

1.1 Limit fuel melting to less than 2% of the fuel mass in the core with $\geq$ 95% probability

1.2 Limit amount of coolant in core with < 95% quality to < 10% of total core inventory with $\geq$ 95% probability.

1.3 Prevent structural failures of reactor components that could lead to positive reactivity changes with probability [TBD]. (Prevent material motion without phase change).

2. MAINTAIN HIGH CONFIDENCE THAT LOCALIZED DAMAGE WILL NOT PROPAGATE BEYOND A FEW SUBASSEMBLIES

2.1 Prevent expulsion of molten fuel from any pin with probability [TBD].

2.2 Limit cladding melting such that pin structural integrity is preserved and molten cladding movement is neglible with probability [TBD].

2.3 Limit coolant voiding in any coolant channel to be consistent with Item 2.2 with probability [TBD].

2.4 Limit solid fuel and fission product release from failed pins to < 2% of subassembly contents (by volume)

3.0 MAINTAIN FUNCTIONAL INTEGRITY OF ENGINEERED SAFETY SYSTEMS THAT INFLUENCE INTEGRITY OF LOA-2, LOA-3, OR LOA-4

3.1 Avoid SASS environmental conditions that could prevent SASS action

3.2 Prevent damage to SHRS

3.3 Maintain conditions at pressure vessel within appropriate ASME limits

TABLE 2.2-3

LIST OF SASS FUNCTIONAL REQUIREMENTS DERIVED FROM CONDITIONS NEEDED TO ASSURE LOA-2 INTEGRITY (see Tables 2.2-1 and 2.2-2)

Item No.	Functional Requirements to be Imposed on SASS Design	Source of Requirements in Tables 2.2-1 and 2.2-2 (Item No)
1	The SASS system must limit fuel melting to < 2% of fuel mass in the core with probability TBD (see Table 2.2-2).	1.1
2	SASS must limit the extent of coolant vaporization in the primary system such that pressure acting upon the pressure vessel remains within ASME limits in the absence of rapid pressure transients, and such that positive reactivity insertion is counteracted by inherent mechanisms. Suggested limit is that less than 10% of the coolant in the core should have < 95% quality with probability TBD (Table 2.2-2).	1.2, 2.3
3	The SASS system must limit the number of fuel and blanket pins in the core with gross (non-pinhole) breaches to < 15% of the pins in the core with probability TBD (see Table 2.2-2).	1.3
4	The SASS system must limit maximum core power to maintain the rate of core material vaporization at rates low enough to preclude missile generation, pressure wave phenomena, or other pressure transient events when the reactor is not prompt critical. SASS must accomplish this with probability TBD (see Table 2.2-2).	1.3, 3.1, 3.2, 3.3
5	The SASS system must prevent cladding melting of the entire pin circumference in any pin. Cladding melting over an area greater than 20% of the outer surface area of a single fuel pellet shall be limited to less than 10% of the pins in any subassembly (see Table 2.2-2).	1.3, 2.2, 2.4
6	The SASS system must prevent gross (non-pinhole) breaches in pins with > 20% axial peak molten fuel area, or must limit all pins to less than this amount of axial peak fuel melting. (see Table 2.2-2).	2.1
7	The SASS system must limit fuel pin failures such that the amount of fuel and fuel-coolant chemical interaction product expelled into the coolant in any subassembly is < 2% of the contents of the assembly (by volume) with probability TBD (see Table 2.2-2).	2.2, 2.3, 2.4, 3.1, 3.2

TABLE 2.2-3 (Cont)

Item No.	Functional Requirements to be Imposed on SASS Design	Source of Requirements in Tables 2.2-1 and 2.2-2 (Item No)
8	The SASS system must insert sufficient reactivity soon enough to maintain pressure vessel wall and seal temperatures below the ASME limiting values with probability TBD. (see Table 2.2-3).	3.3
9	The SASS must be available to operate during the approach to critical and during all critical operation including 0 to 100 percent of full power. (see Table 2.2-1).	II.A
10	The SASS shall provide an actuator to detect ground accelerations greater than or equal to those defined for the SSE. (see Table 2.2-1).	II.A, III.A
11	The SASS system must insert enough negative reactivity when actuated to maintain the total energy in the core and primary heat removal system to a value consistent with the design of the Shutdown Heat Removal System (SHRS) with probability TBD. (see Table 2.2-1).	II.B
12	The SASS system must insert the reactivity defined in Item 11 early enough to be consistent with the design basis and functional requirements of the SHRS with probability determined as in Item 11.	II.B
13	The SASS system as a minimum should provide limit location indication (i.e., full-in - full-out) to the reactor operator in the control room to allow verification that decay heat levels will be obtained that are consistent with SHRS capabilities. (see Table 2.2-1).	II.B
14	The SASS control assembly shall be designed so that unplanned control removal from the core region connot occur during shutdown, including maximum achievable primary heat transport system pump coolant flow. A mechanical orifice zone discriminator shall be provided. (see Table 2.2-1).	II.C
15	The SASS shall be designed to fail safe (i.e., with the absorber in the full-in position) for failure modes such as electrical supply failure, component failures, etc. (see Table 2.2-1).	II.C

TABLE 2.2-3 (Cont)

Item No.	Functional Requirements to be Imposed on SASS Design	Source of Requirements in Tables 2.2-1 and 2.2-2 (Item No)
16	The absorber material shall be chemically compatible with the coolant to preclude unacceptable absorber loss. (see Table 2.2-1).	II.C
17	The SASS shall not produce material from structural failure of its components that could cause flow blockages or primary heat transport system damage within or outside of the control assembly. (see Table 2.2-1).	II.C
18	The SASS system must be maintainable and testable in situ, in order to demonstrate reliability throughout its life. In-situ testing of parts of the system based on natural or inherent phenomena such as melting point or magnetic saturation may not be necessary provided adequate testing has been performed to confirm that performance is as designed in a reactor environment. (see Table 2.2-1).	III.A, II.C
19	Each individual SASS control assembly shall be capable of independent operation.	III.A
20	The SASS shall accommodate top head rotation of (TBD) degrees and severe core distortions such as might be caused by a seismic event or any Class A, B or C event as defined by the plant Overall Plant Design Specification (OPDS). (see Table 2.2-1).	III.B
21	The SASS shall provide an actuator to detect ground accelerations greater than or equal to those defined for the SSE. (see Table 2.2-1).	II.A, III.A
22	The self actuating mode of operation of SASS must be independent from, and different from, that of the PPS in order to minimize the probability of common-cause or common-mode failures between the two systems. (see Table 2.2-1).	III.B
23	The SASS should trigger scram with components located in the following regions which are listed in the order of their priority. (see Table 2.2-1): 1. Within the SASS control assembly duct envelope, 2. in and/or around the SASS control driveline envelope, 3. in and/or around the SASS control rod drive mechanism envelope, 4. exterior to the reactor vessel.	III.B

3. SASS DESIGN CRITERIA (DAMAGE SEVERITY LIMITS)

3.1 Primary and Secondary Shutdown System Criteria

Before proceeding with the specification of the SASS criteria, it is of interest to review the design criteria (damage severity limits) to be met by the primary and secondary shutdown systems. These damage limits are given in Table 3.1-1. It should be noted that the next higher level of damage is allowed for the secondary control system. As stated in the CRBRP PSAR, this hierarchy reflects the rationale that the damage limit can be increased with decreased probability of occurrence. The above rationale has been coupled with the LOA-2 safety objectives to arrive at a set of preliminary damage limits for SASS.

3.2 SASS Criteria

The severity limits to be accommodated by SASS are established in accordance with the LOA-2 objectives as stated in Section 2. Because of the limited understanding of reactor events associated with fuel-coolant interactions, gross fuel pin failures, and boiling, the criteria for preliminary evaluation of LOA-2 events have been selected to restrict these phenomena to isolated localized events within subassembly boundaries similar to the "major incident" severity level. However, consistent with the philosophy established for the primary and secondary shutdown systems, the damage severity limits are relaxed by using nominal, rather than 3σ hot-channel, temperatures in the analysis. In addition, nominal values are used for the Doppler and other reactivity feedback rod worths, drop times, detection times and delay times. These assumptions lead to higher failure probabilities than the secondary shutdown system limits; this is consistent with the less restrictive LOA-2 success criteria. Specific accident scenarios are discussed in Section 4. If the specified guidelines outlined in this section are exceeded, additional more detailed evaluations would be required to determine if the SASS design and functional requirements adequately meet the LOA-2 functional requirements discussed in Section 2.

TABLE 3.1-1

PRIMARY AND SECONDARY SHUTDOWN SYSTEM DAMAGE SEVERITY LIMITS+

	Damage Severtiy Limit			
	Primary System Only Functioning		Secondary System Only Functioning	
	Without Stuck Rod	With Stuck Rod	Without Stuck Rod	With Stuck Rod
Normal: Operational (2)	Not Applicable	Not Applicable	Not Applicable	Not Applicable
Upset: Anticipated Faults	Operational Incident	Operational Incident	Minor Incident (1)	Minor Incident (1)
Emergency: Unlikely Faults	Minor Incident	Minor Incident	Major Incident	Major Incident
Faulted: Extremely Unlikely Faults	Major Incident	Major Incident	Not a Design Basis 93)	Not a Design Basis (3)

(1) Failure of the primary system to scram when required for an anticipated fault is defined as an extremely unlikely event (faulted condition). However, the damage severity limit for the secondary shutdown system is conservatively specified to assure fuel pin integrity even for the concurrent anticipated fault and failure of the primary shutdown system.

(2) No action required by Plant Protection System during Normal Operation.

(3) Combined probability of two independent failures (extremely unlikely fault and failure of primary control rod system) is exceedingly low and not appropriate as a design basis. However, as an exception, upon concurrent loss of off-site power a safe shutdown earthquake with a consequent step reactivity insertion and failure of the primary control rod system, the secondary shutdown system shall be capable of shutting down the reactor with exceeding major incident limits.

Since the power level following scram is initially determined by the amount and rate of the reactivity insertion and power then decays relatively slowly, it is important to ensure that enough negative reactivity is provided that the generated power including the decay heat is adequately removed by the flow coastdown and long-term natural circulation. The worst combination of heat generation and coolant flow may occur relatively late in the transient. The present SASS criteria are being derived for the "CDS Phase II" core with the CRBR flow coastdown to a minimum flow of 3% of full flow.

The reliability requirements for SASS are determined consistent with the LOA-2 criteria. Acting in the self-actuated mode, SASS should meet a goal unreliability or failure rate of 10^{-2} per event, considering only those events included within the SASS design basis. This requirement impacts on the number of required SASS assemblies (see Section 4).

A summary of the preliminary core design limits for SASS to meet the top-level LOA-2 requirements as specified in Section 2 is presented in Table 3.2-1. These limits are: no sodium boiling, no cladding melting, no fuel melting and approximately $3 negative reactivity worth. These local point limits applied to nominal conditions are considerably removed from the general LOA-2 requirements presented in Table 2.2-3. The reason for this point limit approach is to simplify design analyses and parametric studies so that multiple SASS concepts can be investigated. Table 3.2-2 describes how each of the requirements of Table 2.2-3 are met by the more simplified point limits.

The no nominal sodium boiling limit provides assurance that voiding of the core has been precluded and cladding melting is unlikely. Voiding of the core usually results in a positive net reactivity addition of $2 to $5, which can melt potentially large portions of the driver fuel and release potentially large amounts of energy. The no-nominal-boiling limit helps to meet requirements 2, 4, 5, and 8 of Table 2.2-3.

The no-nominal-fuel-melting limit was selected because if no fuel melting occurs, reactivity insertions from fuel movement should not occur and energetic molten fuel-coolant interactions (MFCI) will be precluded.

TABLE 3.2-1

SUMMARY OF PRELIMINARY SASS DESIGN CRITERIA AND DAMAGE SEVERITY LIMITS

Event Classification	Damage Severity Limits	Preliminary Design Criteria+
Hypothetical Event (failure to scram)	LOA-2*	No sodium boiling No cladding melting No fuel melting** $3 scram worth

*The LOA-2 damage severity limit (limited core damage) is defined in Section 2. As specified in the above table, it resembles a major incident except for the reduced reliability and the use of nominal values in the design criteria. In the CRBRP, a major incident is defined as an occurrence which results in 1) substantial fuel and/or cladding melting or distortion in individual fuel rods, but the configuration remains coolable; 2) plant damage that may preclude resumption of plant operation, but no loss of safety functions necessary to cope with the occurrence; and/or 3) radioactivity release that may exceed the 10CFR20 guidelines but are well within the 10CFR100 guidelines.

+These limits apply to the nominal values.

**In nominal peak-power pin at beginning of equilibrium cycle.

TABLE 3.2-2

RELATIONSHIP OF SASS OVERALL REQUIREMENTS TO POINT-LIMIT TYPE REQUIREMENTS

Table 2.2-3 Requirement	Requirement	Simplified Requirement
1	Limit Fuel melting to < 2% of mass in core.	No fuel melting in nominal peak pin.
2	Limit vaporization such that < 10% of the Na has a quality of $\leq$ 95% with a TBD probability.	No boiling prevents vaporization.
3	Limit the number of fuel and blanket pins in the core with non-pinhole breaches with a probability of TBD.	No boiling prevents clad dry out type failure. No fuel melting should reduce probability of crack type failure due to FCMI caused by volume expansion upon melting.
4	Limit core power to limit rate of material vaporization to preclude missile generation which could fail the vessel with a TBD probability.	No sodium boiling and no fuel melting preclude vaporization.
5	Limit cladding melting.	No cladding melting.
6	Prevent failures in pins with > 20% fuel melt, or limit fuel melt in worst pins to < 20% of area.	No fuel melt.
7	Limit the amount of fuel/coolant chemical interaction product to be $\leq$ 2% of the volume of the fuel assembly with a probability TBD	No sodium boiling should prevent clad dry-out type failures and no fuel melting should prevent clad failure due to FCMI caused by volume expansion of fuel upon melting.
8	Timing of reactivity insertion must be rapid enough to ensure that vessel temperature limit is met with TBD probability.	No boiling limit should be more constraining since core ΔT is $\sim$15.% higher than the reactor bulk ΔT.
9	Operation at all power levels	Addressed by design.
10	Provide ground acceleration actuator.	Addressed by design.

TABLE 3.2-2 (Cont)

Table 2.2-3 Requirement	Requirement	Simplified Requirement
11	Total worth must be sufficient so that decay heat can be removed.	Since the hot-operating-to-cold (400°F) power coefficient is between \$2.48 and \$3.29, the \$4.2 system (i.e., 4 out of 4) will shut off fission power very rapidly so that only decay power levels will be seen. \$3.15 system (i.e., 3 out of 4) also should provide adequate shutdown. However, the shutdown temperatures may be somewhat higher (~700°F).
12	Timing of reactivity insertion must be rapid enough to insure requirement 11.	Boiling and melt limits are more constraining, therefore this item should automatically be met provided SHRS works as designed.
13	Limit location indication.	Addressed by design, 3 out of 4 requirement verification.
14	No hydraulic control rod ejection.	Addressed by design.
15	Fail safe	Addressed by design.
16	Absorber/coolant compatability	Addressed by design.
17	No particle/object generation	Addressed by design.
18	The SASS system must be maintainable, testable, and replaceable during refueling shutdown.	Addressed by design.
19	Independent operation	Addressed by design.
20	Accommodation of head rotation and core distortion.	Addressed by design.
21	Maximize use of inherent mechanisms.	Addressed by design.
22	The SASS must be independent and different from the PPS to establish the probability of common cause/mode failures to be ≤TBD.	Addressed by design selection and failure mode/cause analysis.
23	Trigger component locations	Addressed by design.

The no-nominal-fuel-melting limit helps to meet requirements 1, 3, 4, 6, and 7 of Table 2.2-3.

A no-nominal-clad-melting limit is imposed. However, since the boiling temperature of sodium is approximately 300°C below the melting temperature of D9 cladding (approximately 2400°F), the boiling limit is more constraining than the clad melt limit.

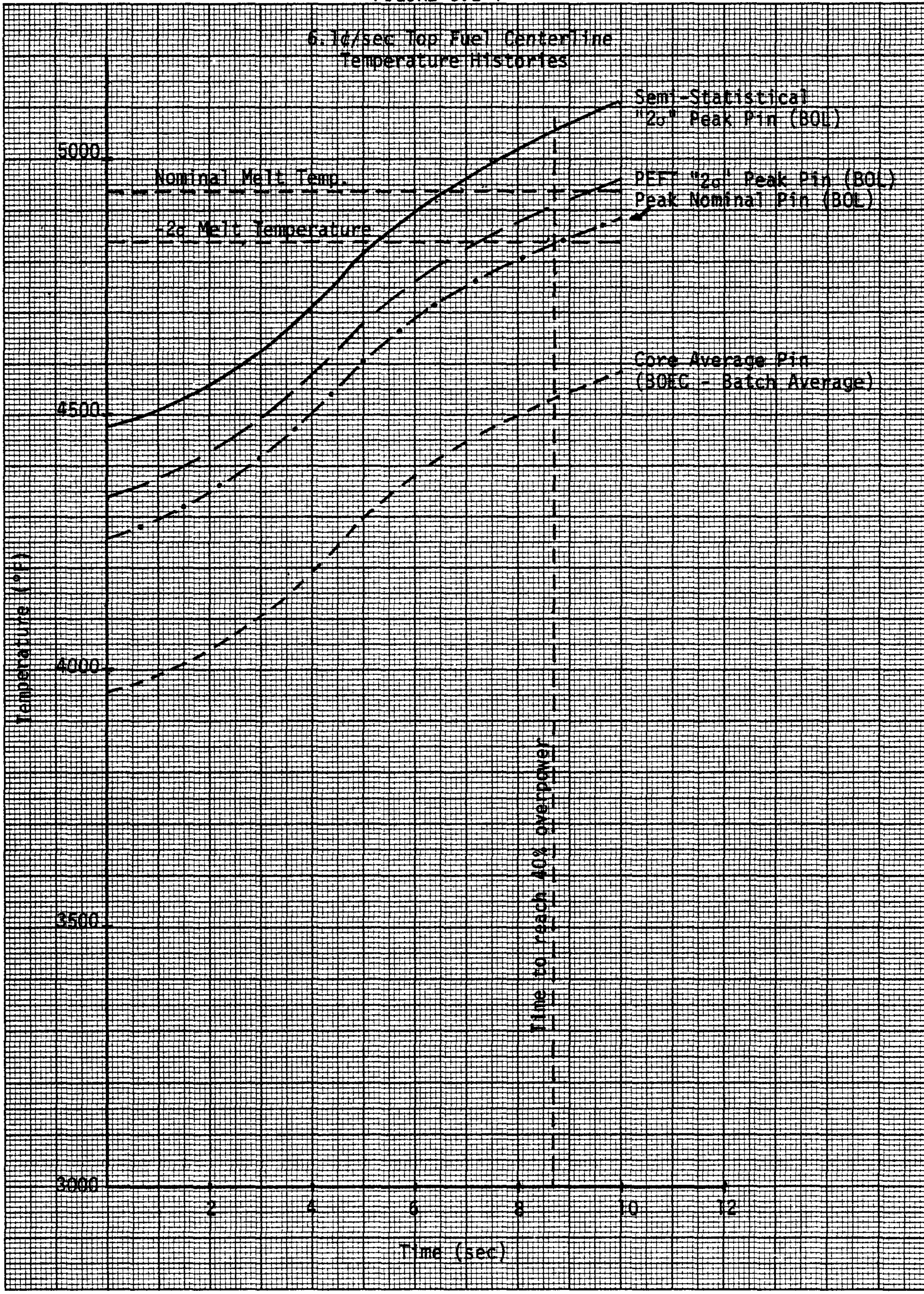
The $3 scram worth lower limit ensures that the temperature reactivity defect can be overridden to guarantee power reduction to decay heat levels which are small enough to be removable by the shutdown heat removal system.

All of the above limits have been imposed on the nominal or best-estimate temperatures and core design conditions. The reason for selecting nominal conditions is that SASS is a device to ensure LOA-2 termination of the transient rather than LOA-1 termination. Since LOA-2 allows a limited amount of core damage to occur, using a nominal limit implies that there will be some probability that the limit will be some probability that the limit will be exceeded in some instances for the hot channel. the magnitude of this probability has been investigated for the boiling limit and fuel melt limit to demonstrate that the hot channel also has a fairly low probability of exceeding the point limits and to estimate the magnitude of potential core envolvement and damage.

Assuming that the SASS system allows temperatures to approach the boiling limit, then the nominal peak sodium temperature is 1800°F. Based on the CDS semi-statistical hot channel factor, the standard deviation is 41°F based on the steady state ΔT, and 113°F based on the transient ΔT. The statistical steady state standard deviation has been estimated to be 20°F using the PACT code. The boiling temperature mean value is estimated to be approximately 1900°F for CDS with a standard deviation of approximately 30°F. Assuming that the peak temperatures and the boiling temperature are normally distributed gives a probability of hot channel boiling of .198 for the standard deviation of 113°F on the peak sodium temperature. For peak sodium temperature standard deviations of 41°F and 20°F, this probability reduces to .025 and .0027 respectively. Thus the chance of hot channel boiling is between 0.20% and 20%. This means that 80% of the time no sodium boiling in the hot channel would be expected. Local boiling of hot channels is acceptable with respect to the overall LOA-2 objective. The potential for the average core fuel assembly to boil can be estimated for a mean fuel assembly sodium outlet temperature of 992°F at beginning of equilibrium cycle. The standard deviation estimate varies, depending on the stitistical model. The standard deviation could have a value of 32°F, 88°F, or 20°F. The probabilities of core wide boiling are estimated to be 3.60×10^{-7}, 1.078×10^{-4} and 3.5×10^{-7} for each of the sodium temperature standard deviations. Thus, there is little likelihood of the average assembly boiling.

For the fuel melting limit a 40% overpower criteria was set (see section 6.5) to ensure that no nominal peak pin melting would occur. At 40% overpower the peak pin nominal centerline temperature is 4830°F. The semi-statistical standard deviation is estimated to be 110°F and the Monte Carlo standard deviation is 40°F based on the PEFT code. The mean fuel melting temperature is estimated to be 4937°F with a standard deviation of 50°F. Again, assuming a normal distribution the probability of the peak pin fuel melting is .19 to .05 for the semi-statistical and Monte Carlo approach, respectively. Thus approximately 80% of the time that SASS responds there will be no peak pin fuel melting. For the average fuel pin the peak center-line temperature is approximately 4530°F at 40% overpower with a standard deviation of between 110° and 40°F. The melt probability for the average pin is between 3.70×10^{-4} and 3.6×10^{-7}, which means that there is little likelihood that the average pin will get involved in fuel melting if the core relative power is constrained to be less than or equal to 140% of nominal. Figure 3.2-1 shows the time dependent nature of the fuel centerline temperature for the 6.1¢/sec TOP event to a total of 60¢ for the CDS Phase II core. The 2σ values and the nominal values are plotted to show the amount of overlap of the fuel temperature probability distribution with the distribution of the melt temperature. At 40% overpower the nominal peak temperature is just below the -2σ melting temperature. This provides some conservatism to cover potential heterogeneous core modeling inadequacies related to power shape changes for control rod withdrawal events.

FIGURE 3.2-1


6.1¢/sec Top Fuel Centerline
Temperature Histories
Semi-Statistical
"2σ" Peak Pin (BOL)
PEFT "2σ" Peak Pin (BOL)
Peak Nominal Pin (BOL)
Nominal Melt Temp.
-2σ Melt Temperature
Core Average Pin
(BOEC - Batch Average)
Time to reach 40% overpower
Temperature (°F)
5000
4500
4000
3500
3000
2
4
6
8
10
12
Time (sec)

Based on the relatively low probabilities of sodium boiling in an average assembly and average pin fuel melting, it is concluded that the nominal temperature point limits of Table 3.2-1 should be adequate to ensure that the LOA-2 goals of Section 2 are met.

4.0 PRELIMINARY DESIGN OF THE SASS ASSEMBLIES AND CONTROL WORTH ESTIMATES

4.1 SASS System Design

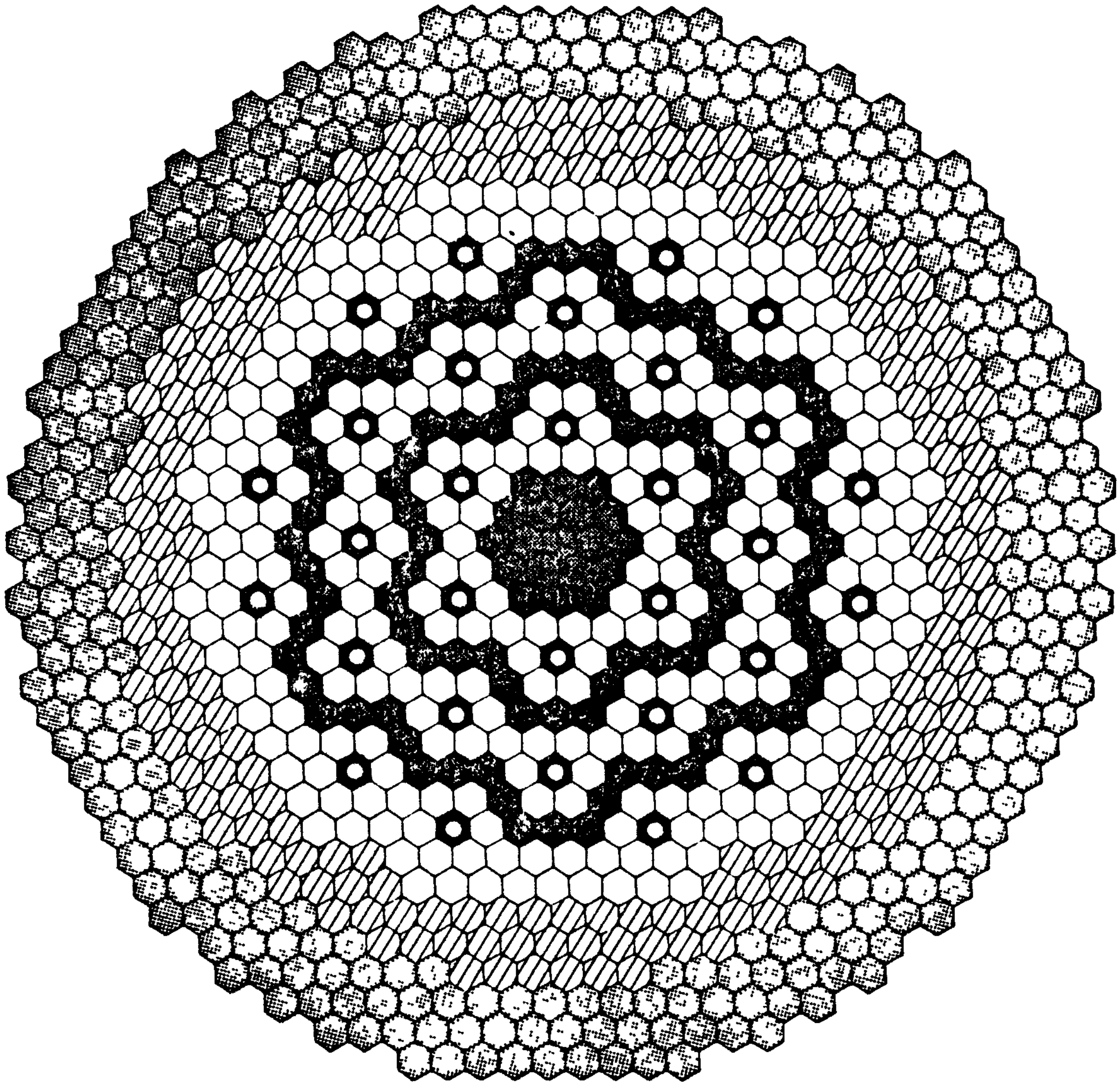
The design of SASS is guided by the following criteria:

1. Provide the capability to limit the consequences of selected hypothetical events such that the LOA-2 success criteria are satisfied;
2. Provide for adequate long-term shutdown;
3. Improve the licensability of LMFBR's;
4. Minimize impact on plant performance;
5. Justify in terms of risk-benefit considerations.

Given an assembly design and criteria, a shutdown system (number of assemblies and locations) can be determined. The following considerations pertain specifically to the "CDS Phase II" core. The core layout is shown in Figure 4.1-1. It contains a total of 30 primary and secondary control assemblies. Such a core can readily accommodate a self-actuated shutdown system with negligible impact on reactor performance.

Preliminary SASS assembly designs have been developed for the one-piece and articulated-absorber concepts. The present analysis applies to the one-piece absorber design. The SASS assembly design is more conservative than that of the secondary control assembly; it allows for a larger radial gap between the outer duct and the guide tube. This design is capable of accommodating relatively large duct bowing and distortions. The effective absorber volume fraction is approximately 34%.

A number of different approaches have been considered for the self-actuated shutdown system:



ASSEMBLY PITCH = 5 93 in.

DRIVER FUEL	300
INTERNAL BLANKET	115
RADIAL BLANKET	204
CONTROL	30
RADIAL SHIELD	306
TOTAL	955

CDS PHASE II OXIDE CORE LAYOUT

Figure 4.1-1

1. Three fully enriched (92% ^{10}B) SASS assemblies are substituted for three of the middle-row primary control assemblies;
2. Four fully enriched SASS assemblies are substituted for four of the middle-row primary control assemblies;
3. Four fully enriched SASS assemblies are judiciously inserted in the outer fuel rows, leaving the primary and secondary shutdown systems intact;
4. SASS is combined with the secondary system.

The "three-assembly-SASS" configuration has been analyzed in detail. The results reported below indicate that it does not meet the design criteria. It is concluded that a minimum of four SASS assemblies are required. The operating limits can be met with three SASS assemblies, but a (3/4) system is required to meet the reliability goals. Because of the strong control rod interaction effects and the sensitivity of the power distribution, detailed analyses need to be carried out in support of the "four-assembly-SASS" configurations.

4.2 The "Three-Assembly-SASS" Configuration

4.2.1 Control Worth

Detailed 2-D (X,Y) diffusion calculations have been performed for the "three-assembly-SASS" design. The control worths are as follows:

a) end-of-equilibrium cycle (EOEC)
   - 3 fully inserted SASS assemblies, 3.15$;
   - 2 fully inserted SASS assemblies, 2.02$;

b) beginning-of-equilibrium cycle (BOEC)
   - 2 fully inserted SASS assemblies with 12 outer primaries inserted to criticality, 1.64$;
   - 3 fully inserted SASS assemblies with one of the outer primary assemblies assumed stuck in the withdrawn position, 3.11$

- 2 fully inserted SASS assemblies with the outer primary assembly adjacent to the stuck SASS assembly assumed stuck in the withdrawn position, 1.15$.

From the results reported in Section 6, it is apparent that two SASS assemblies do not adequately shut down the reactor for an unprotected SSE. A minimum of approximately 3$ is required to prevent boiling given the CRBRP flow coastdown.

4.2.2 Reliability Considerations

The probability of failure of a single CRBRP primary or secondary shutdown assembly in case of an SSE is estimated to be of the order of 10^{-2} (typical values are $p \simeq 2\text{-}3 \times 10^{-2}$). This probability increases significantly (to approximately 10^{-1}) for seismic events greater than the SSE. Although design variations can reduce this failure probability, it is likely to require a major undertaking with respect to testing and design innovations. CRBRP values ($p \simeq 10^{-2}$) are therefore assumed for SASS. With respect to the above reliability considerations, it is important to emphasize that SASS can only provide a significant risk reduction if one assumes failure of the primary and secondary systems, which is most likely during highly unlikely or beyond-design-basis events. Although the LOA-1, or operating, envelope is highly reliable, the reliability of the shutdown system decreases with the severity of the event and it is eventually limited by common-mode and beyond-design-basis-event failures.

The probability of failure for a (3/3) system is 3p while for a (3/4) system it is approximately $4p^2$. It is then apparent that if SASS is to have an unreliability of less than 10^{-2} per demand given $p \simeq 10^{-2}$, and (n-1/n) system is required. Given the required reactivity worth and the requirement of minimum impact on plant performance, a (3/4) system for SASS is appropriate.

4.2.3 Long Term Shutdown

The proposed (3/4) SASS layout would provide adequate long-term shutdown in combination with the SHRS. For the "CDS Phase II" core a reactivity insertion of 3$ yields an isothermal temperature of approximately 370°C (700°F). This compares favorably with the "hot-standby" temperature of 340°C (650°F) or the inlet temperature of 335°C (670°F). This temperature reactivity defect is readily accommodated with only three SASS assemblies. Since most SASS concepts have their trigger device located in or around the SASS assembly, this device is usually designed to trigger only this particular assembly. However, a single assembly will not be sufficient to shut the reactor down to the power levels required by the shutdown heat removal system. If the heat removal system cannot remove sufficient heat, then temperatures will rise again until another SASS would be triggered. However, this will require very long-term and expensive transient analysis to demonstrate that eventually at least 3 SASS rods enter this core. Therefore, it should be required that when one SASS assembly is triggered a signal to trigger the release of the rest of the SASS assemblies be provided. Note that this is not a necessary condition to meet the LOA-2 requirements but it is a sufficient condition. If no signal is provided to the other SASS assemblies, then sequential actuation of the SASS rods will be required. In the case of sequential rod drops, higher temperatures will be reached more often. This will probably increase this number of fuel failures relative to the number of failures that would occur with coupled triggering of the SASS assemblies.

5.0 ACCIDENT SCENARIOS

5.1 Introduction

SASS is to be actuated if both the primary and secondary shutdown systems fail. The probability of such an event is extremely low, but within this frame work a wide range of conditions can be postulated for determining the SASS requirements. The list of events considered here is not intended to be exhaustive, but it includes representative reactivity insertion and undercooling events within the classes of anticipated, unlikely, and extremely unlikely events combined with failure of both the primary and secondary shutdown systems. The response characteristics of the reactor to these events needs to be determined to establish design criteria for SASS which are consistent with the functional requirements. Reactor response is also needed to derive SASS response requirements from the design criteria. Selected accidents have been analyzed as a function of SASS characteristics such as reactivity worth, trip points, and insertion times. The results are reported in Section 6.

In generating these hypothetical accidents, it is assumed that the primary and secondary control systems fail completely. This is a highly conservative assumption, since in reality at least partial control insertion is likely to occur. The severity of the event is further compounded by assuming that only (N-1-out-of-N) SASS assemblies scram. Finally, consistent with the LOA-2 criteria, the analysis only is performed using nominal values. This is in sharp contrast with the analysis of the design basis events which are performed at 2σ or 3σ conditions.

The selected SASS design basis transients are summarized in Table 5.1-1. These transients represent the set of bounding or umbrella transients that should provide the designer sufficient detail to provide a

TABLE 5.1-1

SASS Design Basis Transients

Plant Condition	Transient	Transient Features	Flow Conditions
Anticipated event without scram	Control assembly withdrawal at maximum design speed (9 in/min)	Ramp rate of 0.76¢/sec up to 60¢	(i) constant flow (at 100% of nominal) (ii) pump trip at 15% overpower
	Loss of off-site electric power	CRBRP type flow coastdown	no pony motors, 3% natural circulation
Unlikely event without scram	Control assembly withdrawal at maximum mechanical speed (72 in/min)	Ramp rate of 6¢ sec up to 60¢	(i) constant flow (at 100% of nominal) (ii) pump trip at 15% overpower
Extremely unlikely event without scram	Safe Shutdown Earthquake (SSE)	(i) flow coastdown (ii) 20¢ step insertion (iii) oscillatory reactivity insertion ±60¢ at 3.8 Hz for 10 sec	CRBRP type flow coastdown

SASS concept that will respond successfully to a broad range of off-normal events. The SASS concept cannot protect against reactivity events of greater than 4$ which could be caused by a core support failure or a failure of the plant control system causing a banked withdrawal or consecutive element withdrawal of the primary control rods. It is believed that the probability of such events can be controlled by the plant designer to be sufficiently small so that they contribute very little to the overall risks to the plant.

5.2 Control Assembly Withdrawal at Full Power With and Without Pump Trip Maximum Design Rod Withdrawal Speed

For this event, it is assumed that the reactor is at full power at BOEC and that, as a result of a malfunction in the circuit, one of the control rods is withdrawn at the maximum design withdrawal speed. The maximum design rod withdrawal speed is limited to approximately 23 cm/minute (9 in/min).[5.2-1]

For the CDS Phase II core, 2-D (X,Y) diffusion calculations indicate that for a critical reactor at BOEC the rod run-out worth is approximately 35¢. This value is essentially the same as the average worth of the partially inserted control rods. Because of the ambiguities associated with modeling partially inserted control rods, it is recommended that a run-out rod worth of 60¢ be used. This value was obtained by multiplying the average worth of a partially inserted rod in the outer primary ring (approximately 33¢) by a first-out rod interaction factor of 1.785, as suggested in the "CDS Ground Rules Document."[5.2-2] The purpose of this assumption is to provide the highest expected reactivity insertion.

For the above event, the reactivity insertion would have a maximum rate of 0.76¢/sec up to a total of 60¢. Depending on the plant protection system design, pump trip may or may not occur at 15% overpower. Both cases were examined in this study.

5.3 Loss of Offsite Electric Power Triggered Flow Coastdown

The loss of all off-site power trips all primary and intermediate sodium pumps, commencing a flow coastdown. The CDS plant is assumed to be designed with CRBR-type flow coastdown. For the resulting short flow coastdown, this event if left unprotected is a major safety concern with respect to hypothetical core disruptive accident (HCDA) initiation.

5.4 Control Assembly Withdrawal at Full Power-Maximum Mechanical Speed

This event is similar to the continuous rod withdrawal incident described in Section 5.2 with additional failures resulting in a withdrawal rate equal to the maximum mechanical speed capability of the CRDM, which is approximately 183 cm/minute (72 in/min).[5.4-1] In the CRBRP PSAR this event is classified as extremely unlikely. Consistent with the discussion of Section 5.2, this event results in a maximum ramp insertion of approximately 6¢/sec up to a maximum reactivity of 60¢. This event was evaluated with and without pump trip at 15% overpower.

5.5 Safe Shutdown Earthquake (SSE)

For the CDS Phase II core, the SSE is postulated to result in the following severe combinations of conditions:

(i) loss of off-site electrical power resulting in a flow coastdown,

(ii) radial compaction with a step reactivity insertion of approximately 20¢.

(iii) axial acceleration of the core and vessel resulting in an oscillatory reactivity insertion ranging between ± 60¢ with a frequency of approximately 3.8 Hz over an assumed interval of 10 seconds.

The SSE is an extremely unlikely event. Assuming additional failure of the primary and secondary shutdown systems, the SSE is likely to be the bounding event for determining the SASS design criteria and response requirements. This is substantiated by the analyses reported in Section 6.

The basis for the Safe Shutdown Earthquake (SSE) with Flow Coast Down (FCD) event is a 10 second duration earthquake which is postulated to cause vertical oscillation of the core relative to the control rod and a stick-slip core compaction. The oscillations were assumed to be at 3.8 cycles per second based on PLBR plant studies.[5.5-1] The stick-slip positive reactivity step insertion and the oscillatory ramp reactivity insertion due to relative vertical motion of the core with respect to the parked control assemblies were super imposed. A loss of pump power is also assumed causing a flow coast down as in the LOF event.

Figures 5.5-1 and 5.5-2 show the core geometry used in the evaluation of the stick-slip step reactivity insertion. The material properties used for the core former and assembly ducts were those of SS-304 and D-9, respectively. For this analysis the core assemblies and the former pads were allowed to expand from cold geometry to the hot operating conditions using the known assembly average duct wall outlet temperatures for MOEC conditions of each core zone and former temperatures of 955°F for the top load pad (TLP) former and 730°F for the above-core load pad (ACLP) former. The resulting clearances between the outer assembly duct load pad and the core former ring were evaluated. Forcing the closure of this gap by bowing of the assembly ducts as shown in Figure 5.5-3 defines the displacement (ΔR) at the core midplane. ΔR was then used to calculate the stick slip step reactivity insertion as follows:

$$\$ \quad (\beta) = \left(R\,\frac{dk}{dR}\right)\left(\frac{\Delta R}{\beta R}\right) = .93\,\frac{\Delta R}{R}$$

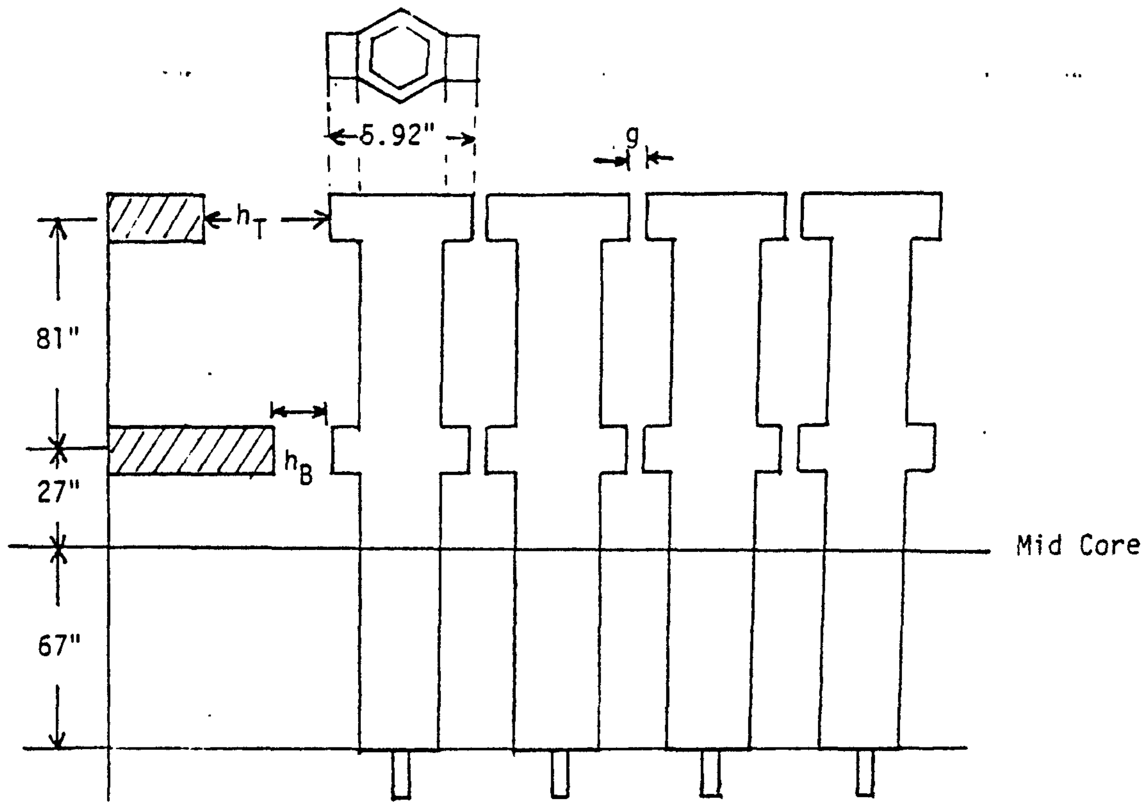
where

$$\frac{Rdk}{dR} = .338$$

$$\beta = .003647$$

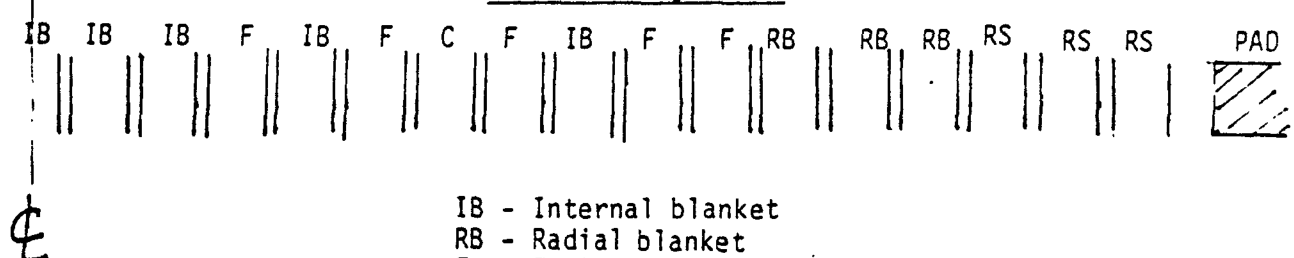
$$R = 80.5 \text{ inches}$$

Figure 5.5-1
Cold Core Geometry -
Edge Assembly - Former Pads Clearance



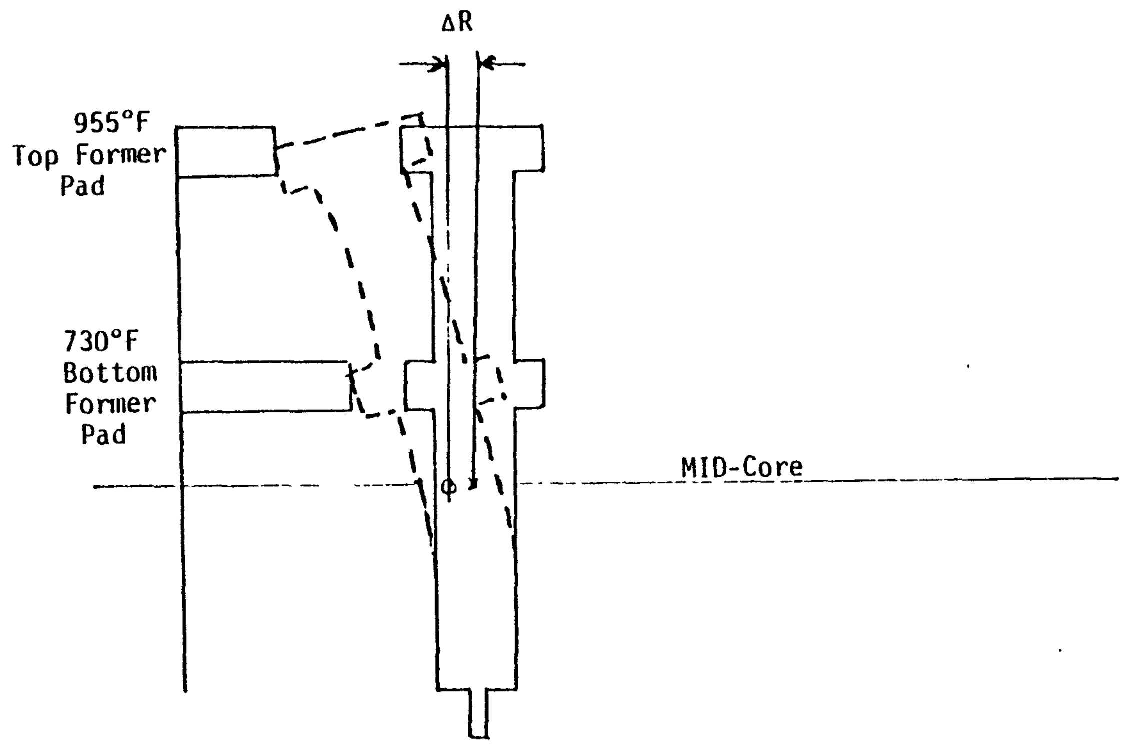
h_T - top former pad clearance
h_B - bottom former pad clearance
g - interassembly gap

Figure 5.5-2
Core Assembly Order



IB - Internal blanket
RB - Radial blanket
F - Fuel
RS - Radial Shield

Figure 5.5-3
Hot Geometry



Uncertainties in dimensions were added to the nominal values for Figures 1 and 2 to obtain the maximum stick-slip ΔR possible under the assumptions of this model.

	Nominal + Uncertainity
Interassembly gap (mils)	10 + 8 = 18
Lower former pad gap (mils)	60 + 10 = 70
Upper former pad gap (mils)	120 + 10 = 130

A stick-slip step reactivity insertion of 12.2¢ was obtained. Accounting for an estimated 50% uncertainty in the Rdk/dR value, the maximum expected stick-slip reactivity is calculated to be 18.3¢. From this, the value of 20¢ was then chosen for the stick-slip positive reactivity step insertion. Several effects have been neglected in this analysis which will require further work and they include 1) clearances at the inlet nozzle which would probably contribute less than 2 to 4 cents, 2) effects of reverse temperature gradients which could increase the core midplane ΔR, 3) effects of above core former removal which could increase the core midplane ΔR and 4) 3-D reactivity effects of the heterogeneous core which can only be investigated using the NUBOW-3D code.

The value of 60¢ for the oscillating reactivity was selected to allow sufficient margin from prompt criticality when combined with the stick-slip step reactivity and analysis uncertainties. The 60¢ requires that the 12 partially inserted outer ring primary control assemblies not move more than 1.69 inches. Due to control worth uncertainties, such as the small worth of the control rod in the upper axial blanket of 1 to 2¢ and uncertainty in the initial insertion distance of 17.2 inches, CDS currently requires the relative motion to be less than 1.5 inches.

It should be pointed out that the reactivity effects and the flow coastdown are taken to represent the upper bound core response to the SSE. It may be possible to have no reactivity insertion and no flow coast down combined with a hypothetical common mode failure of the primary and secondary control rod systems. Although the event would appear to be benign for the short term, long term effects of unknown common cause failures in the SHRS could pose significant problems if the core power is not shut off. It is for this reason that SASS should include a seismic actuator as well as thermal and neutronic actuators, since it is the purpose of the SSE evaluation for SASS to demonstrate safe shutdown for this event. The seismic sensor should probably be mounted on the reactor vessel head and should detect vertical or horizontal accelerations that are greater than or equal to those calculated for this position during the SSE. This will also provide protection in the event of a non-conservative analysis of the amounts of amplification provided by the plant systems to this point during in SSE.

6.0 CDS PHASE II RESPONSE TO SELECTED TRANSIENTS AND SCRAM PARAMETERS

6.1 Transient Event Descriptions

For the SASS scram parametric study, the following four transient events, further described in Section 5, were initially chosen:

1. Transient Undercooling (TUC) Event
   The relative flow coastdown (FCD) versus time is shown in Figure 6.1-1. This curve has the form of F/Fo = 1/(1 + 0.2788t), where t is in seconds, until the time where natural circulation flow of approximately 3% take over at approximately 116 seconds following pump trip.
2. Anticipated Transient Overpower (TOP) Event
   The reactivity for this event was modeled as a ramp as shown in Figure 6.1-2. For the with pump trip case, the flow coastdown of the TVC event was assumed to begin at 29.8 seconds which correspond to 15% overpower plus 0.4 seconds delay time for the pump trip signal to be sent.
3. Unlikely Transient Overpower Event
   The reactivity for this event was modeled as a ramp as shown in Figure 6.1-3. For the with pump trip case, the flow coastdown was assumed to begin at 2.15 seconds which corresponds to 15% overpower plus 0.4 seconds delay time for the pump trip signal to be sent.
4. Safe Shutdown Earthquake (SSE)
   The reactivity and relative flow for this event was modeled as shown in Figure 6.1-4. The relative flow for this event is identical to that of the flow coastdown event.

All analyses were performed at BOEC using nominal values, as discussed in Section 3.

Figure 6.1-1

TUC Relative Flow Versus Time

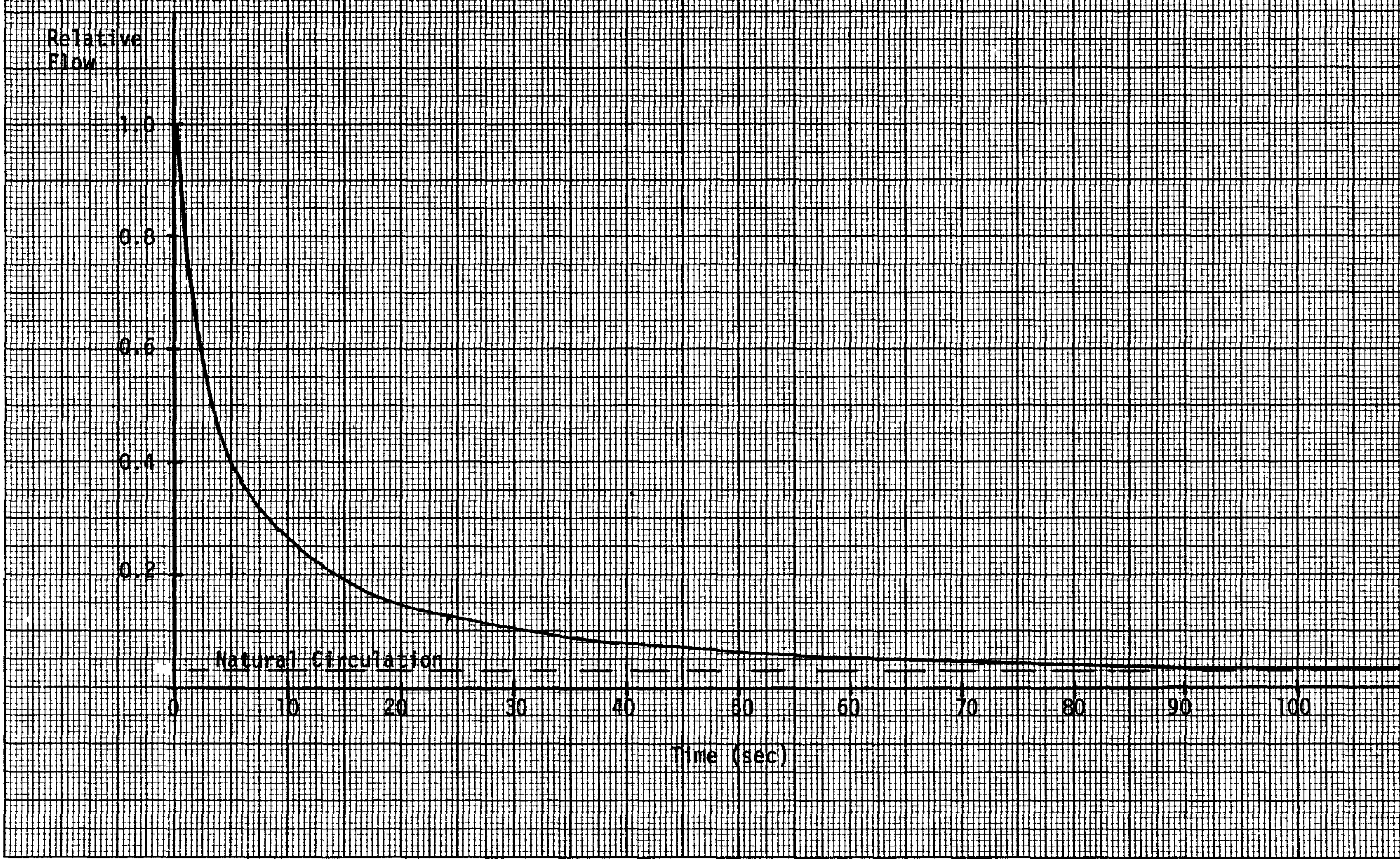


Figure 6.1-2

Nine Inches per Minute Rod Runout Worth Versus Time

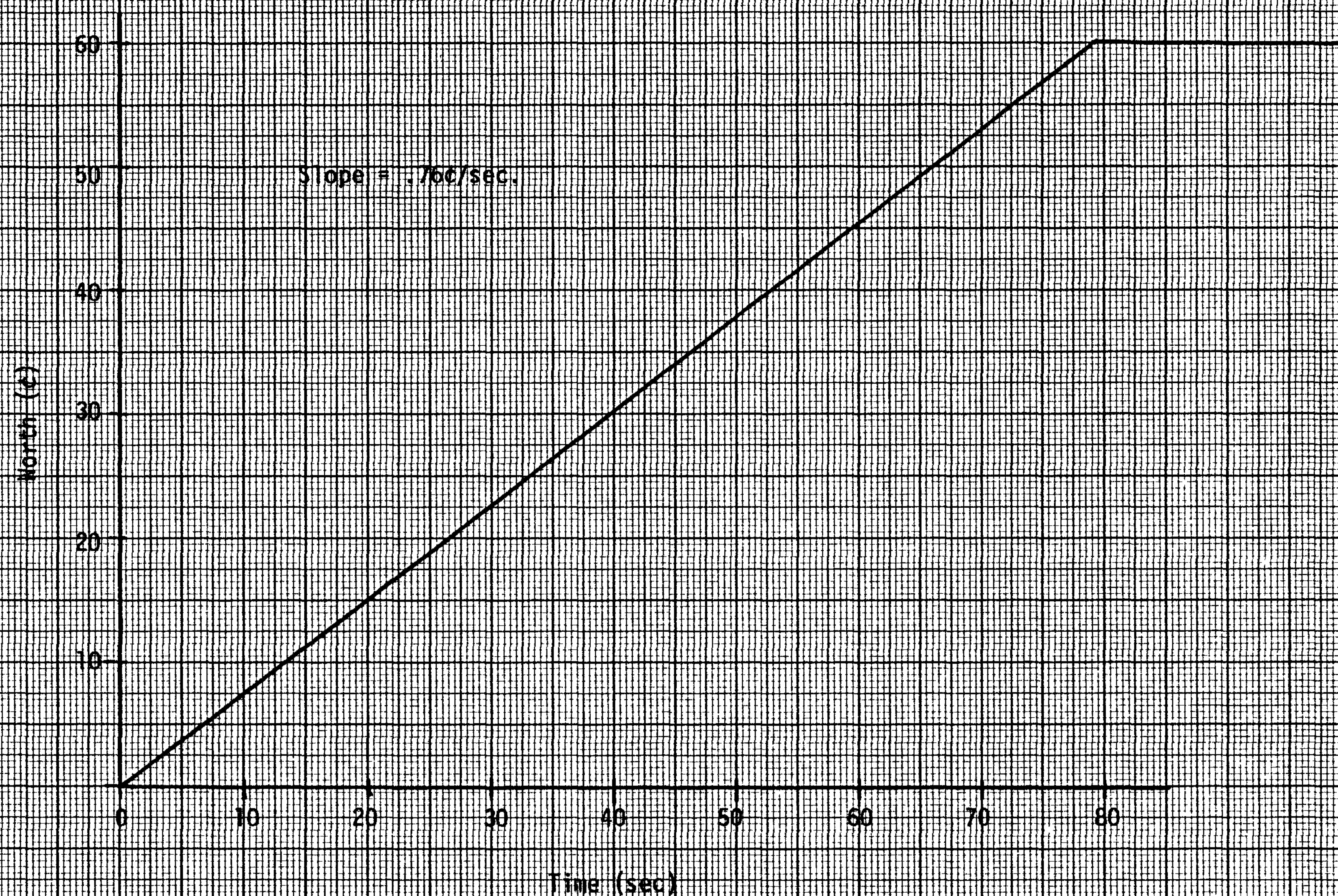


Figure 6.1-3

Seventy-Two Inches per Minute Rod Runout Worth Versus Time

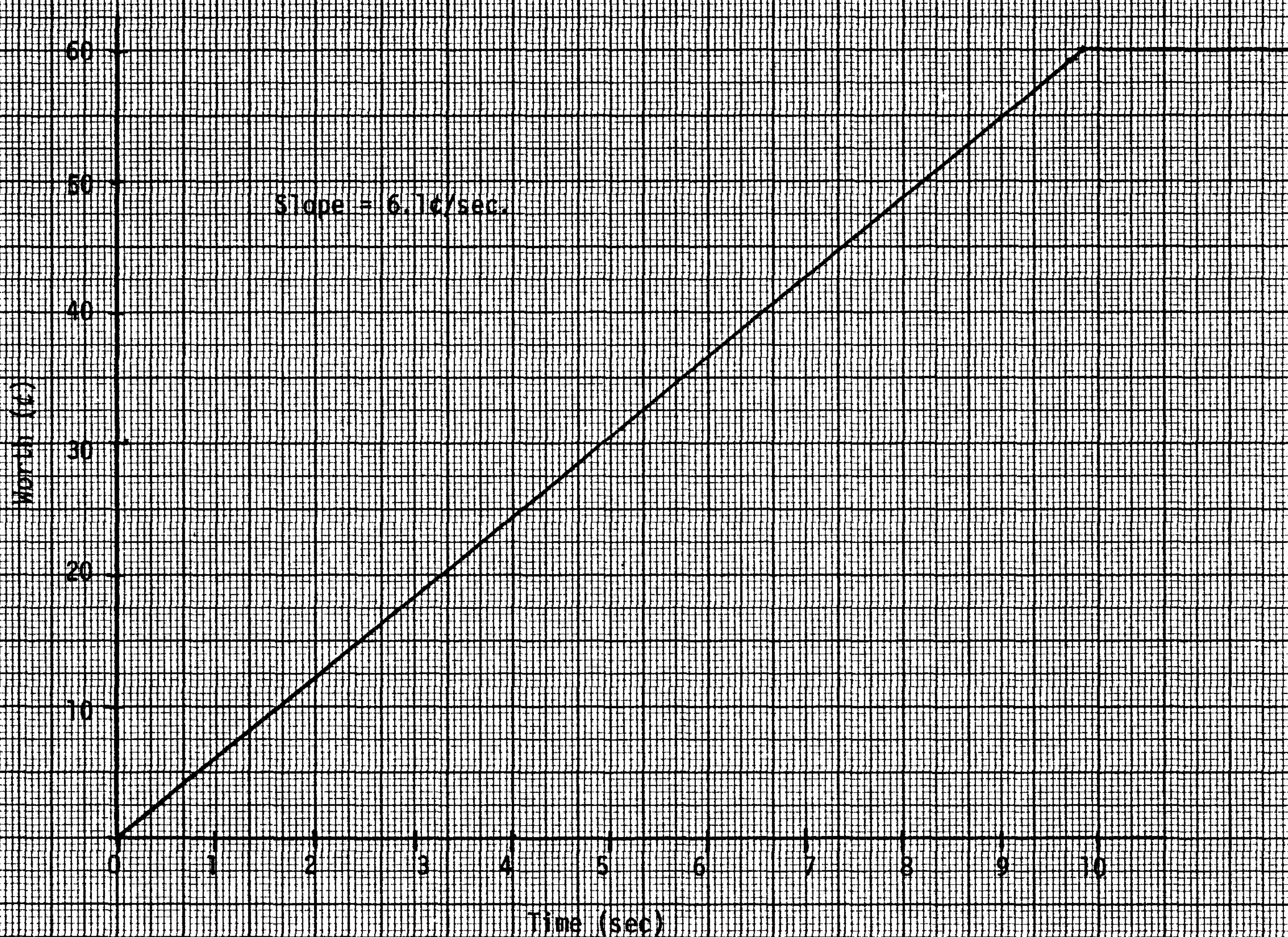
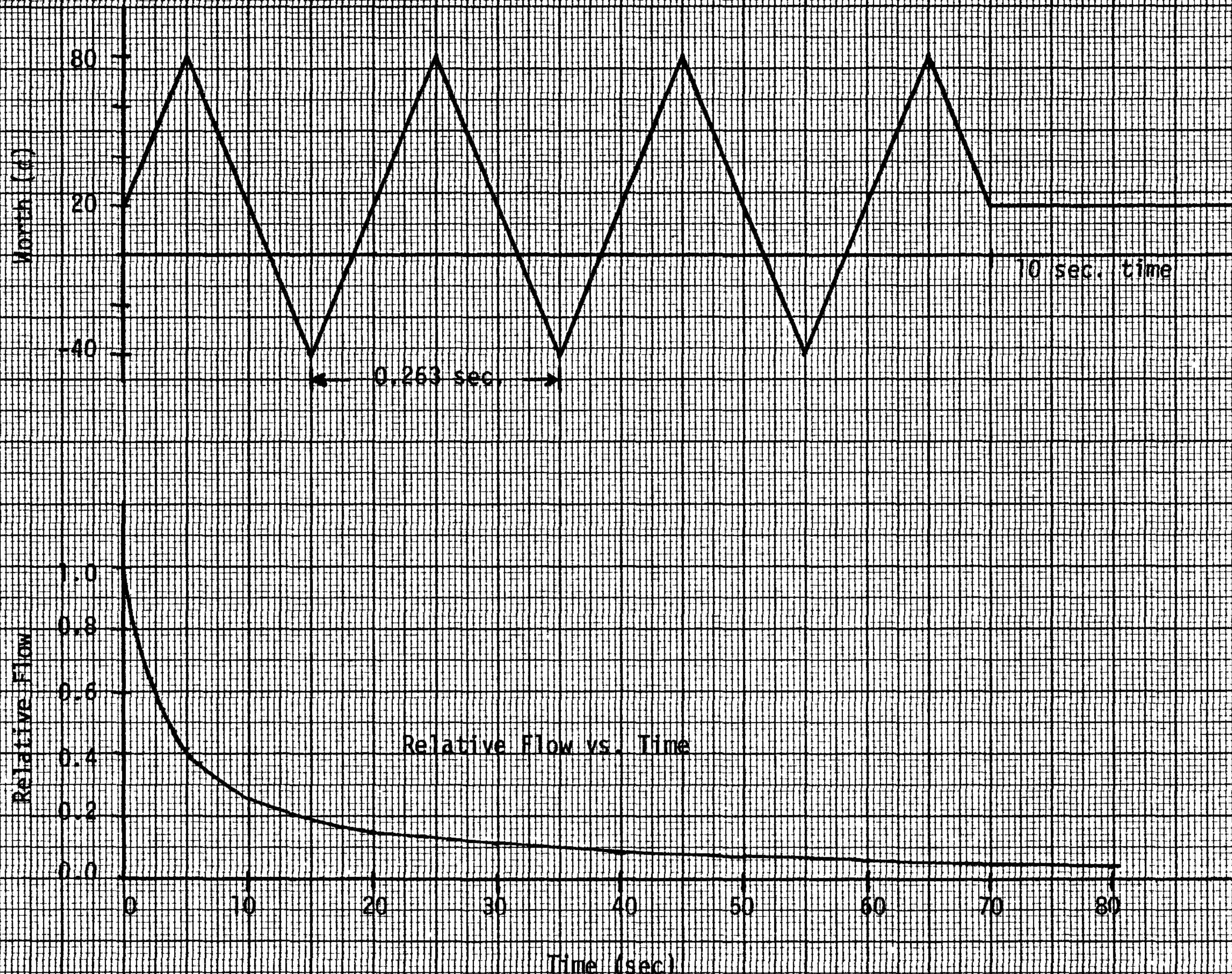


Figure 6.1-4

SSE Reactivity and Flow Driving Functions



6.2 Transient Responses Without Scram

The core responses for the selected transient were analyzed using the heterogeneous core version of CORTAC.[6.2-1] CORTAC is a transient analysis code with a core restraint response capability. The thermal-hydraulic modeling includes interassembly heat transfer. Sodium boiling is not treated. Neglecting the structural response and the differences in the thermal models, CORTAC has been validated by comparison with the accident analysis code SAS-3D [6.2-2] up to the point of sodium boiling for both TOP and TUC events.

The four transient events described above were analyzed first assuming no scram using sodium boiling as the transient time limiting condition. The relative power and flow histories as well as the maximum coolant temperature versus time for each of the events are described below.

Relative power and flow histories

a) TUC - Figure 6.2-1 shows the relative power for this event decreasing as a function of time while the relative flow follows the form described in Section. 6.1.

b) TOP (9 in/min) - Figures 6.2-2 and 6.2-3 provide the relative power and flow histories for this event. The power eventually stablizes at a relative value of approximately 1.4 for the without-pump-trip case.

c) TOP (72 in/min) - Figures 6.2-4 and 6.2-5 provide the relative power and flow histories for this event. For the without-pump-trip case the relative power increases with time until the rod is fully out at 9.8 seconds and then goes to an equilibrium value of approximately 1.36.

d) SSE - Figure 6.2-6 shows that the oscillatory relative power responds with the same frequency of 3.8 cycles/second as the oscillatory reactivity insertion; but it goes down in magnitude inside an envelope which levels off somewhat more slowly than the flow coastdown.

Figure 6.2-1

Relative Power and Flow vs. Time for the TUC Event With No Scram

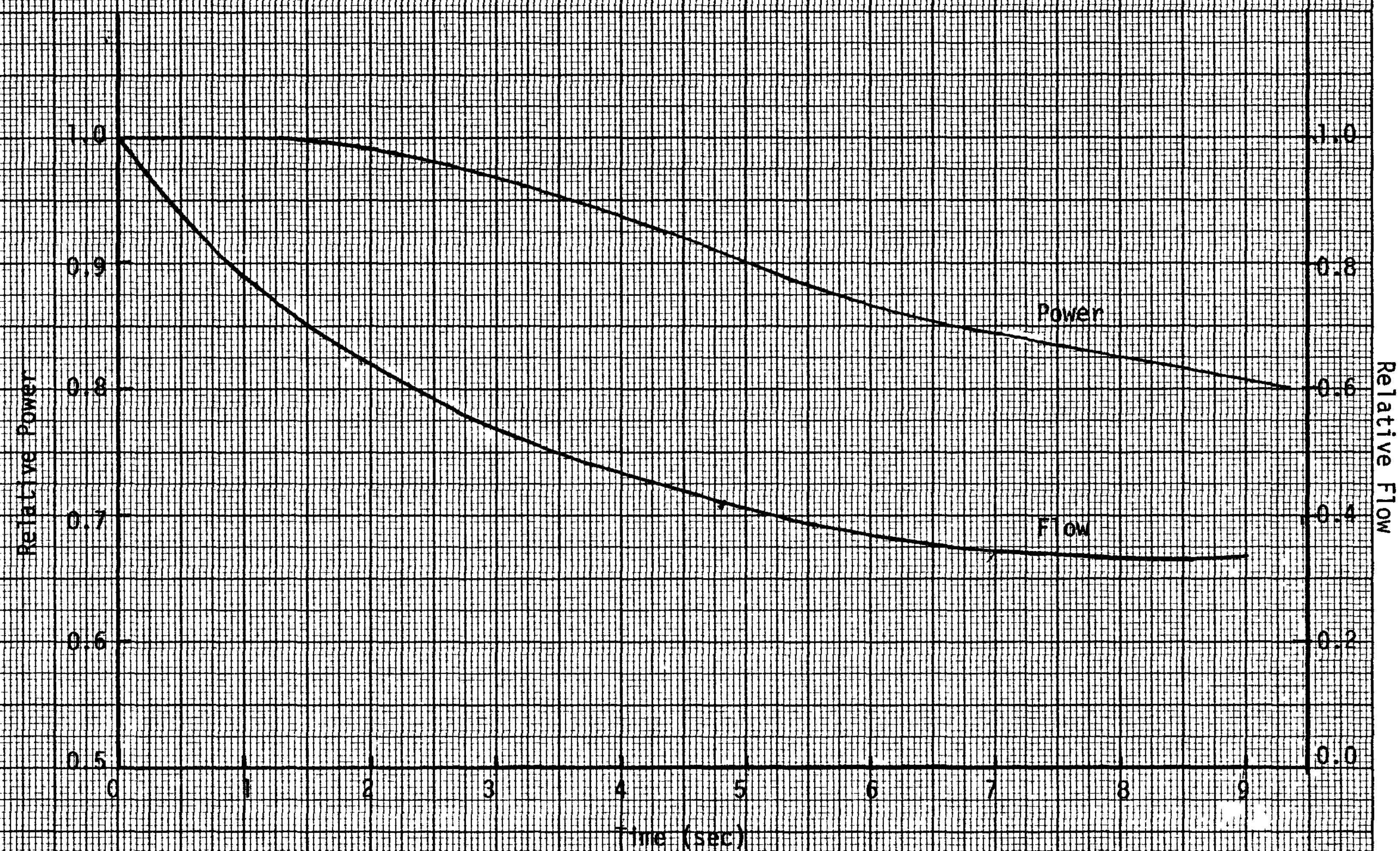


Figure 6.2-2

Relative Power and Flow vs. Time for the TOP (0.76¢/sec) Event With No Scram

(No Pump Trip)

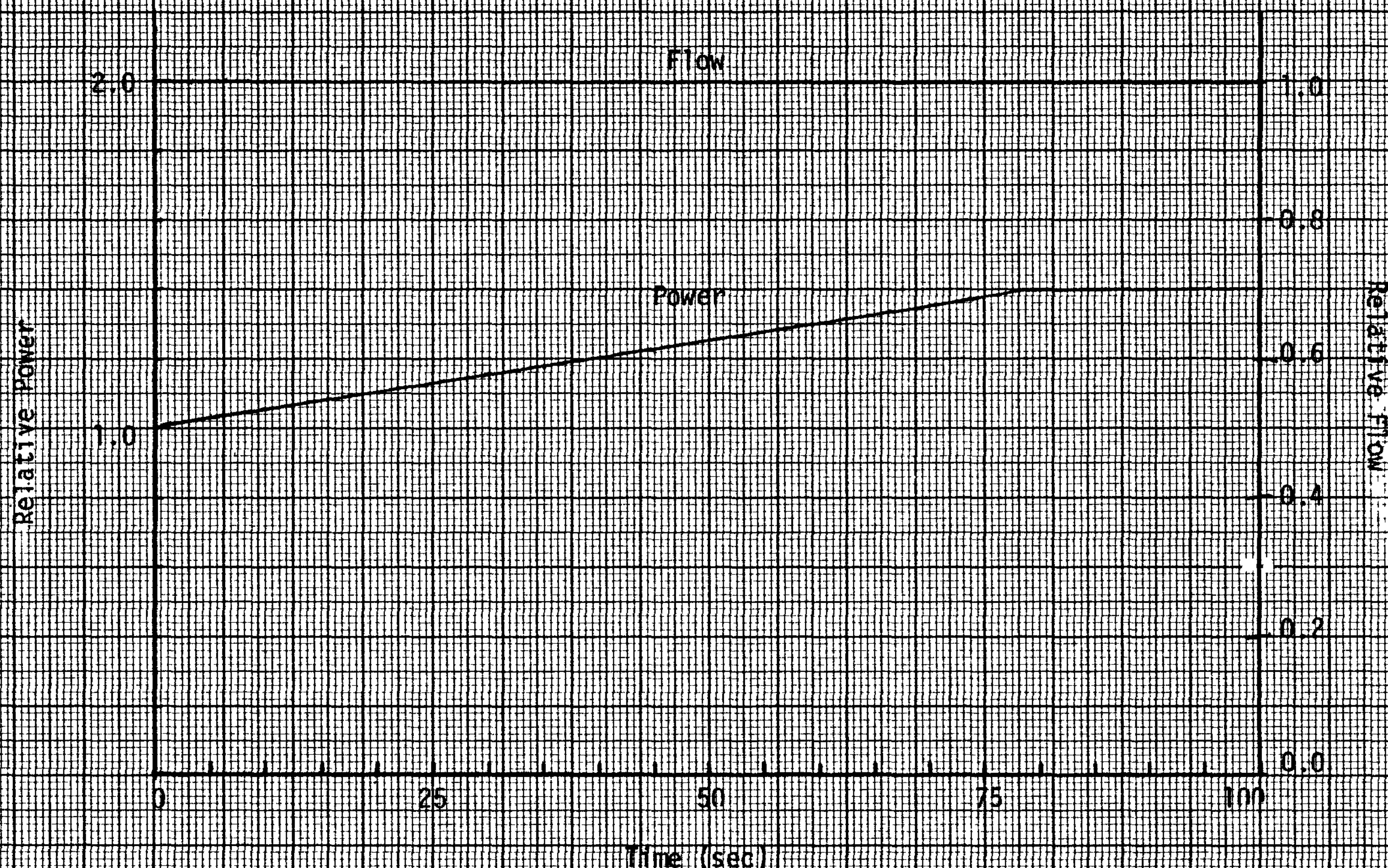


Figure 6.2-3

Relative Power and Flow vs. Time for the TOP (.76¢/sec) Event with no SCRAM (with pump trip)

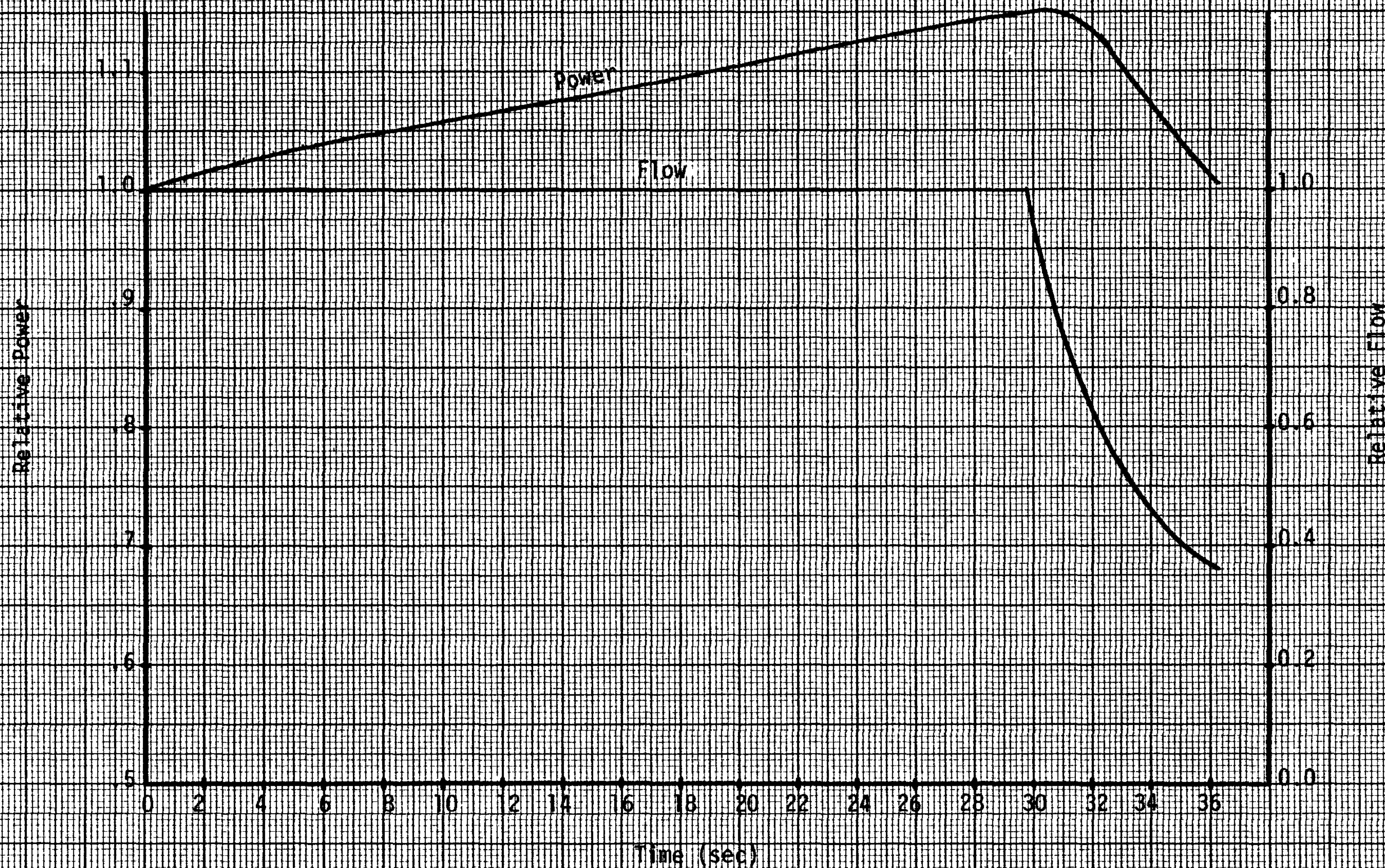


Figure 6.2-4

Relative Power and Flow vs. Time for the TOP (6.1¢/sec) Event With No Scram

(No Pump Trip)

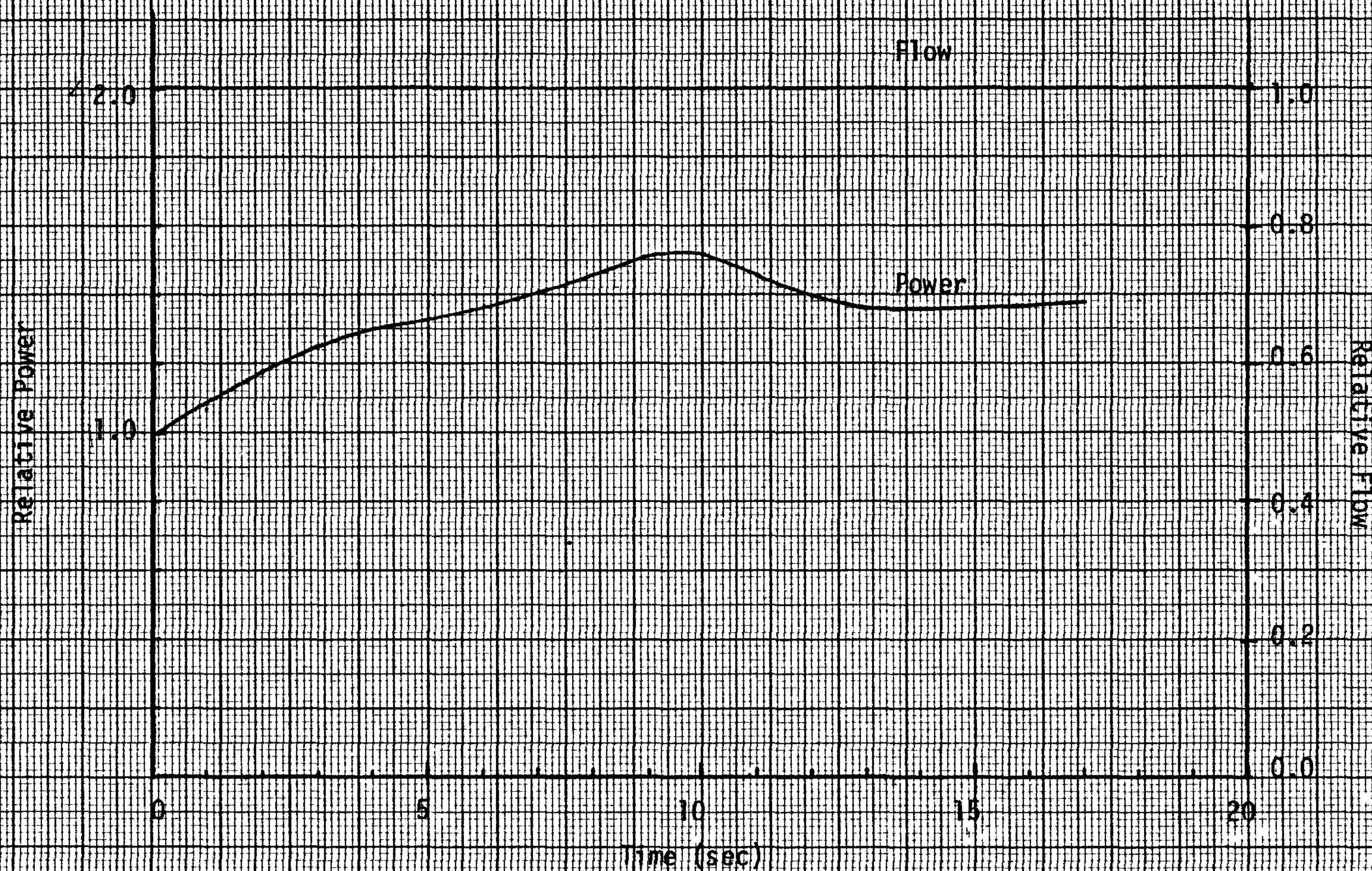


Figure 6.2-5

Relative Power and Flow vs. Time for the TOP (6.1¢/sec) Event
With No Scram
(With Pump Trip)

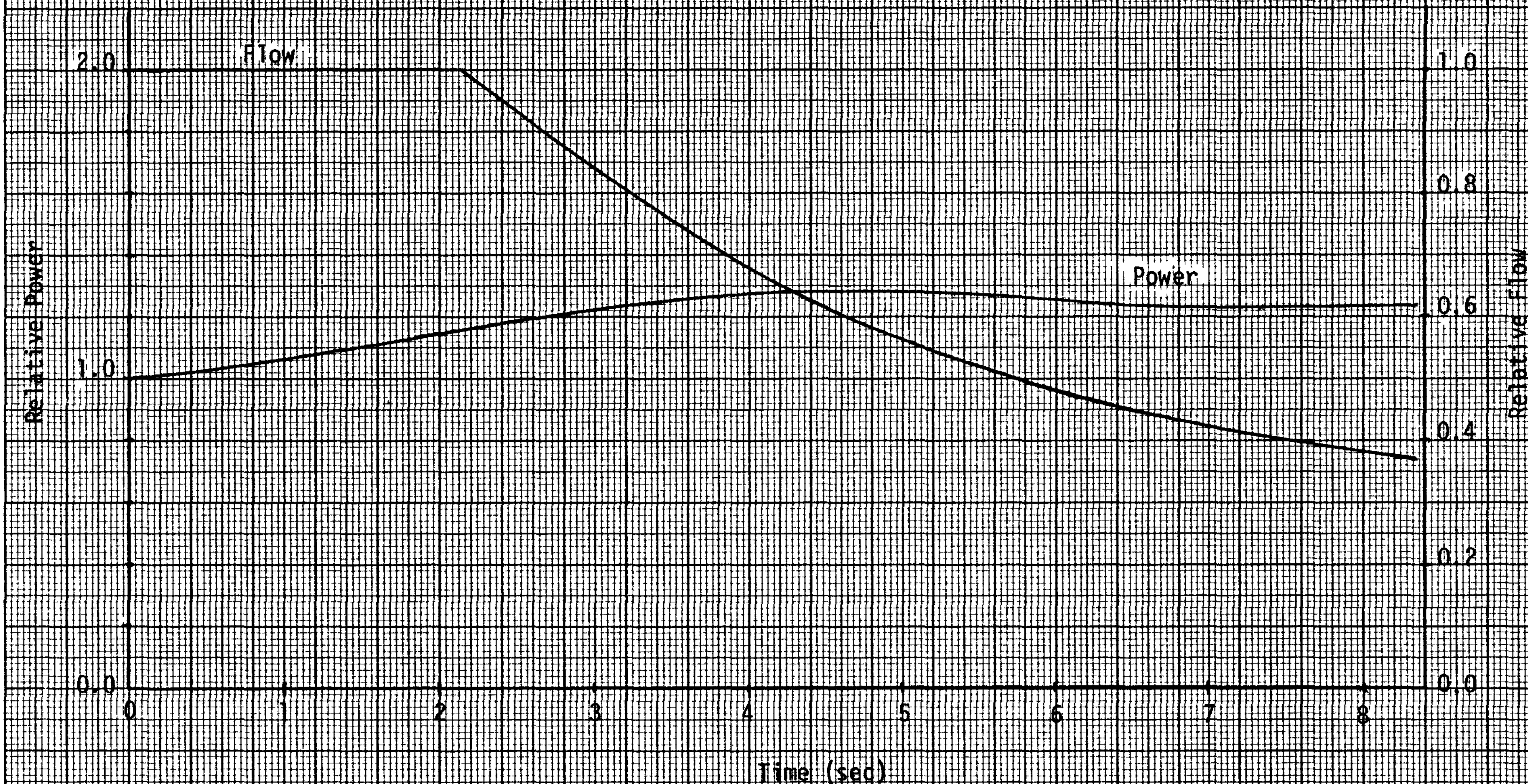
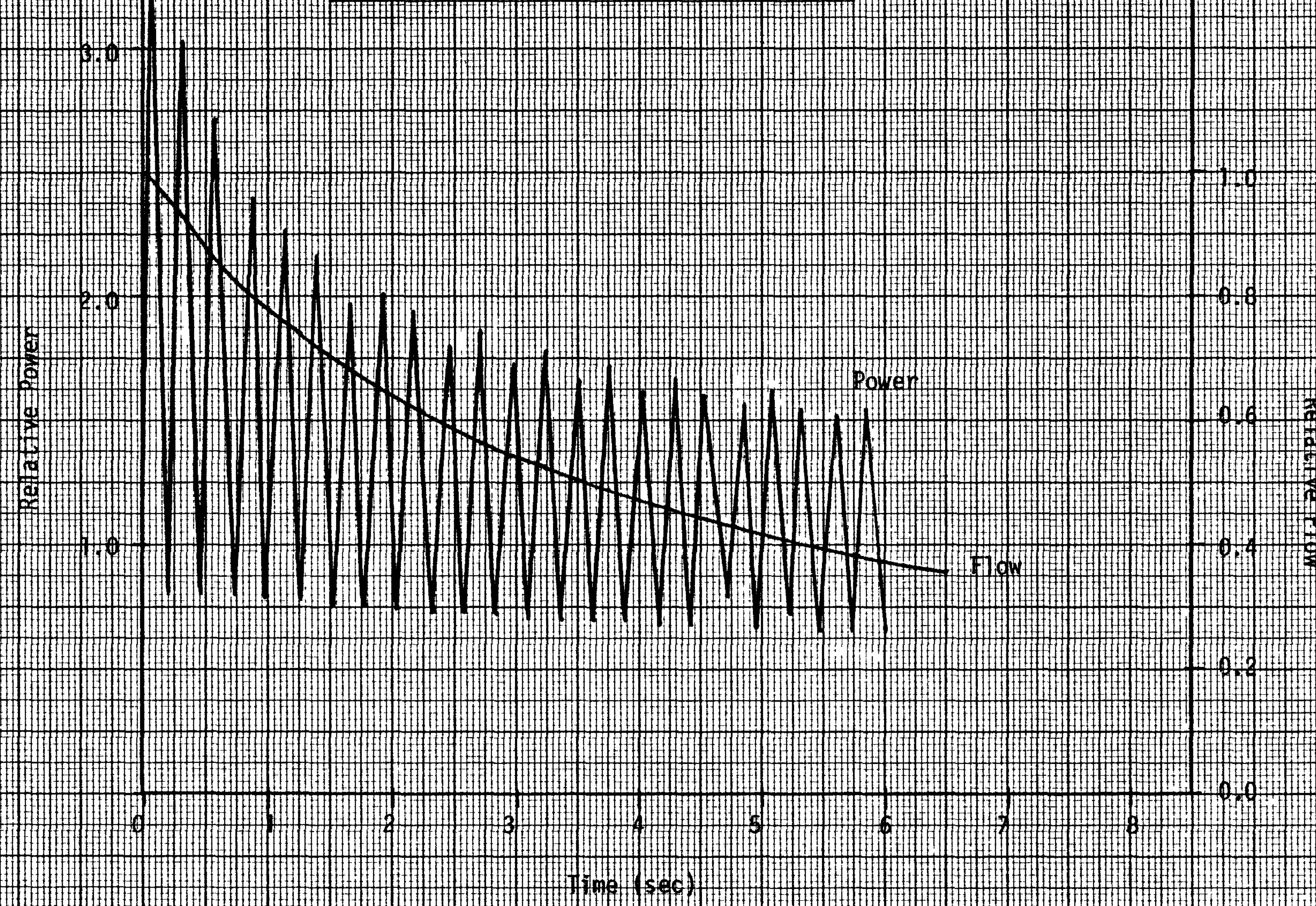


Figure 6.2-6

Relative Power and Flow vs. Time for the SSE
With Flow Coast Down Event With No Scram



GRAPH PAPER GRAPHIC CONTROLS CORPORATION Buffalo New York
Printed in U.S.A.
SQUARE 10 X 10 TO THE CENTIMETER AS 8014-60

Figure 6.2-7

Maximum Coolant Temperature vs. Time for the TOC Event With No Scram

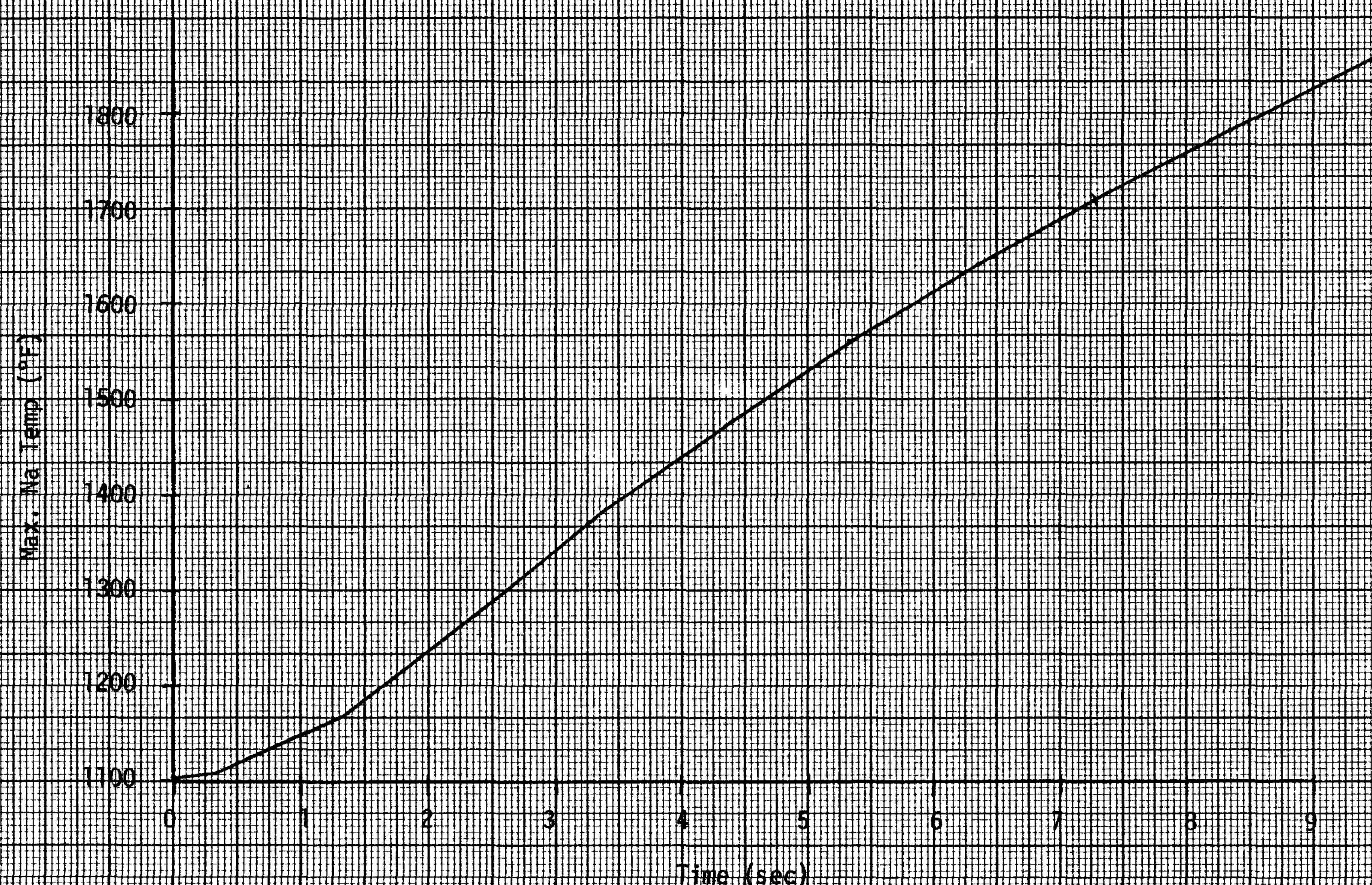
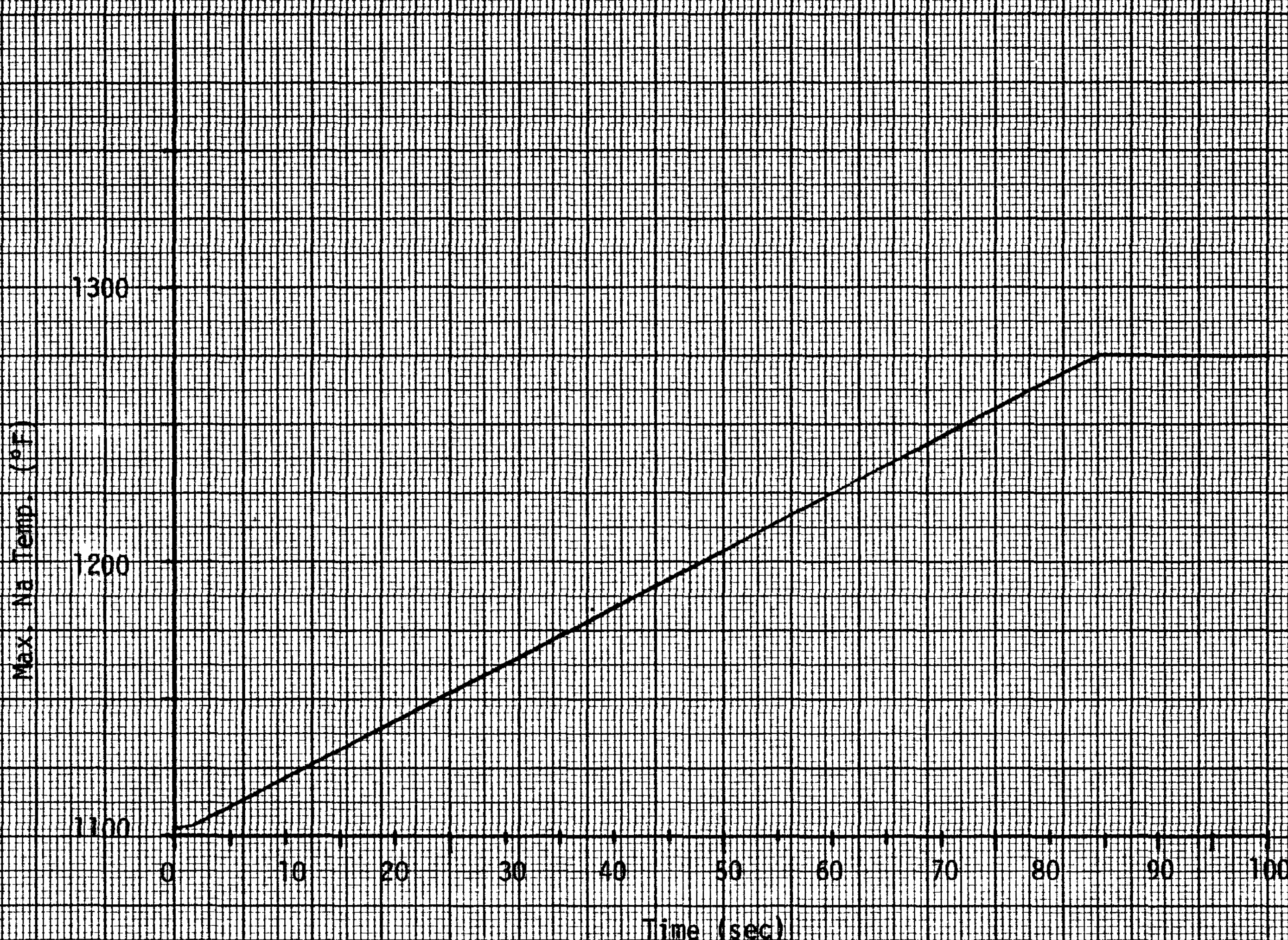


Figure 6.2-8

Maximum Coolant Temperature vs. Time for the TOP (0.76¢/sec) Event With No Scram

(No Pump Trip)



Maximum coolant temperature histories

a) TUC - Figure 6.2-7 shows the maximum sodium temperature going up with time. Sodium boiling occurs at 8.6 seconds.

b) TOP (9 in/min) - Figure 6.2-8 shows the maximum sodium temperature for this event without pump trip going up with time until about 4 seconds past the time when the rod is fully out. The maximum sodium temperature then stablizes at 1275°F, and no sodium boiling is predicted. Figure 6.2-9 shows that the maximum sodium temperature for this event with pump trip will reach boiling in 36.2 seconds.

c) TOP (72 in/min) - Figure 6.2-10 shows the maximum sodium temperature for this event without pump trip going up with time until about 2 seconds past the time when the rod is fully withdrawn. The maximum sodium temperature than stabilizes at 1270°F and no sodium boiling is observed. Figure 6.2-11 shows that the maximum sodium temperature for this event with pump trip will reach boiling in 7.8 seconds.

d) SSE - Figure 6.2-12 shows the maximum sodium temperature for this event will reach boiling in 6.1 seconds.

6.3 Scram Parameters

The parametric cases investigated in this study include two scram worths ($1.60 and $4.00), three SASS insertion times (1, 2, and 4 seconds) and up to four SASS delay times (including detection times) depending on the event. The $1.60 scram corresponds to approximately two SASS rods inserted while the $4.00 scram corrsponds to approximately four or five SASS rods fully inserted.

The peak sodium temperature that is reach for a given transient is plotted to allow this parameter to predicted for various SASS concepts. Figures 6.3-1 and 6.3-2 show the peak sodium temperature for the TUC event as a function of delay time and insertion times for scram worths of $1.60 (initial peak) and $4.00 (absolute peak), respectively. Figure 6.3-1 only provides the initial peak sodium temperature since the $1.60 scram eventually leads to sodium boiling.

Figure 6.2-9

Maximum Coolant Temperature vs. Time for the TOP (0.76¢/sec) Event With No Scram
(With Pump Trip)

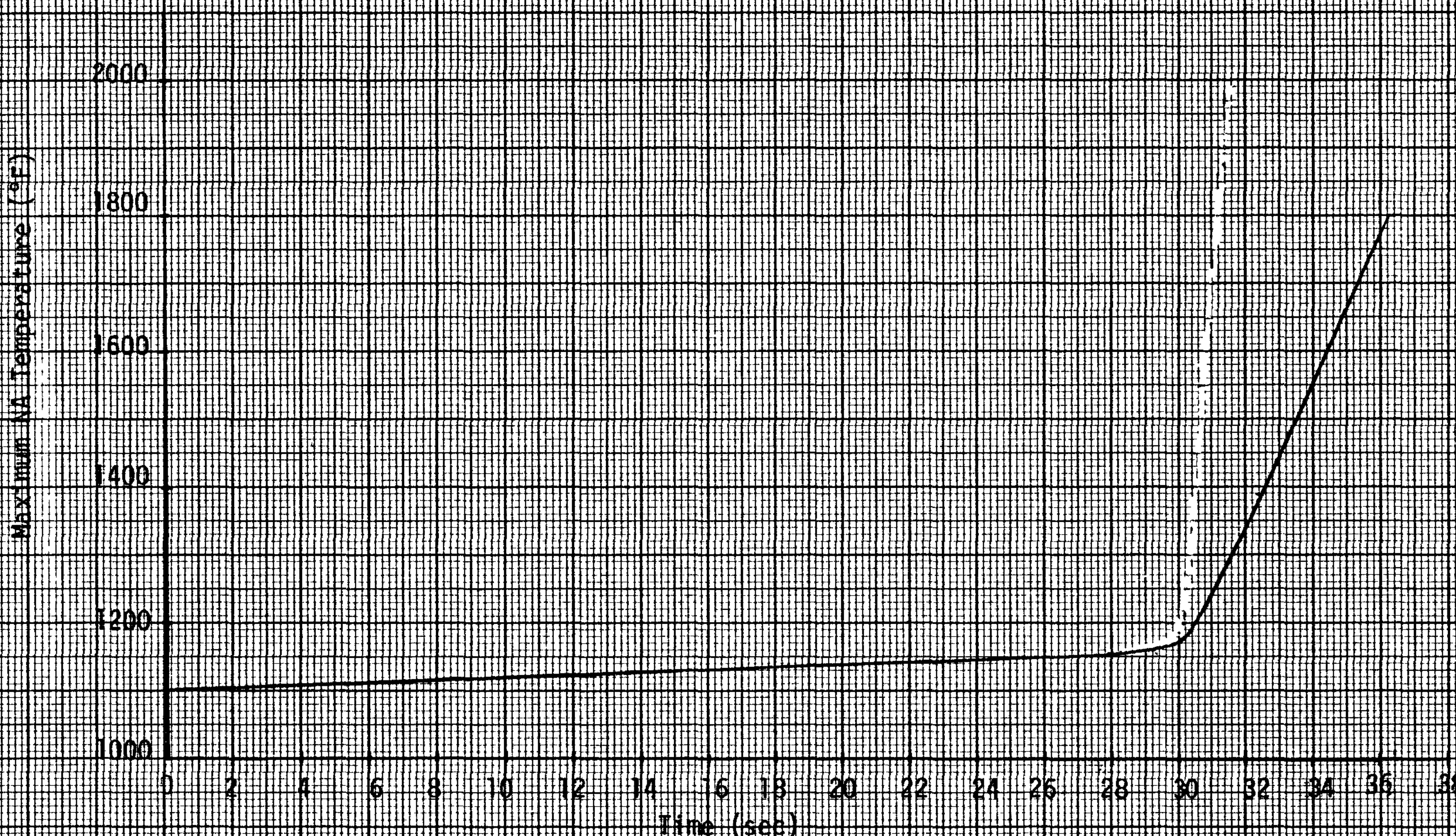


Figure 6.2-10

Maximum Coolant Temperature vs. Time for the TOP (6.1¢/sec) Event With No Scram

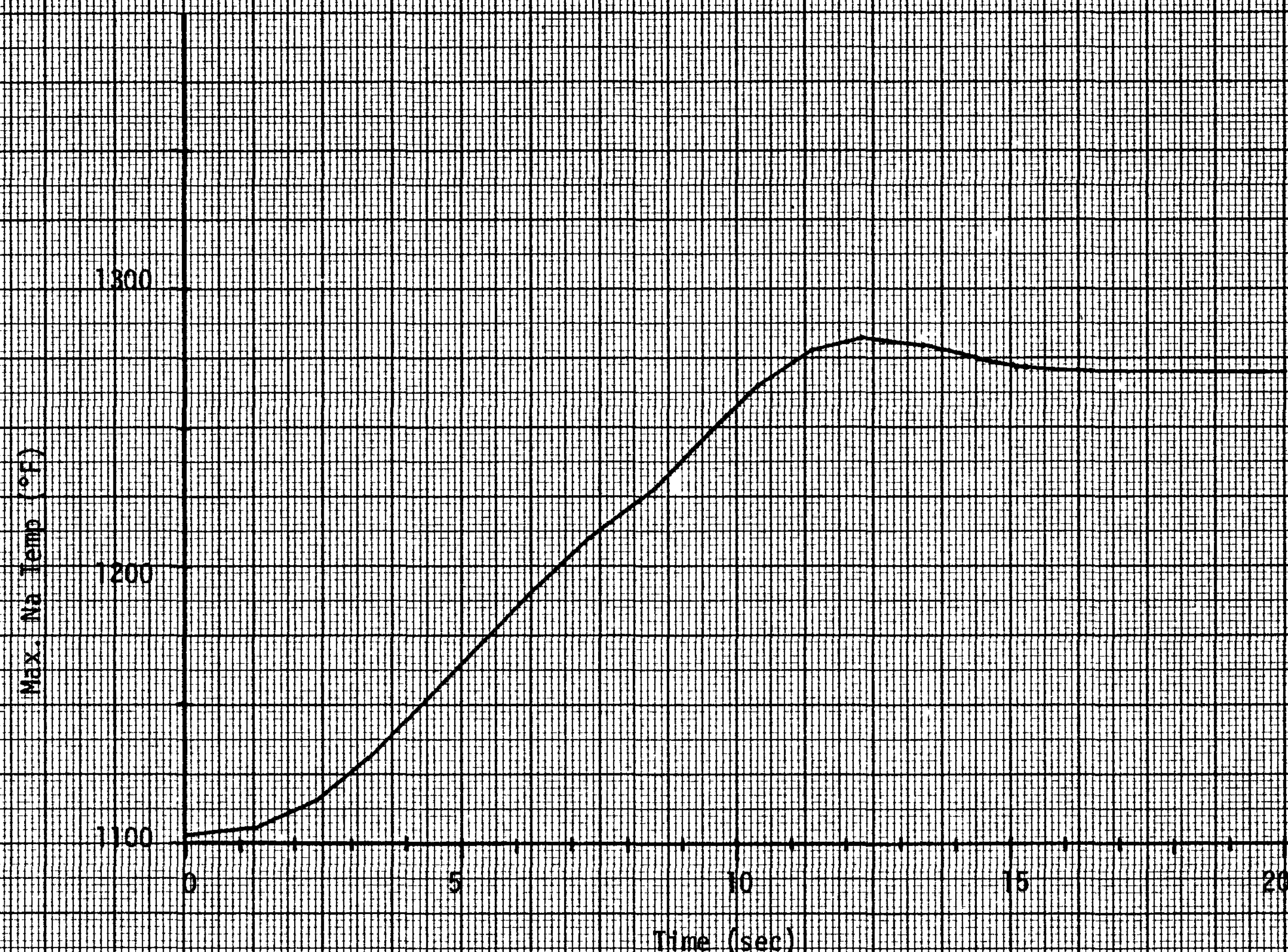


Figure 6.2-11

Maximum Coolant Temperature vs. Time for the TOP (6.1¢/sec) Event With No Scram
(With Pump Trip)

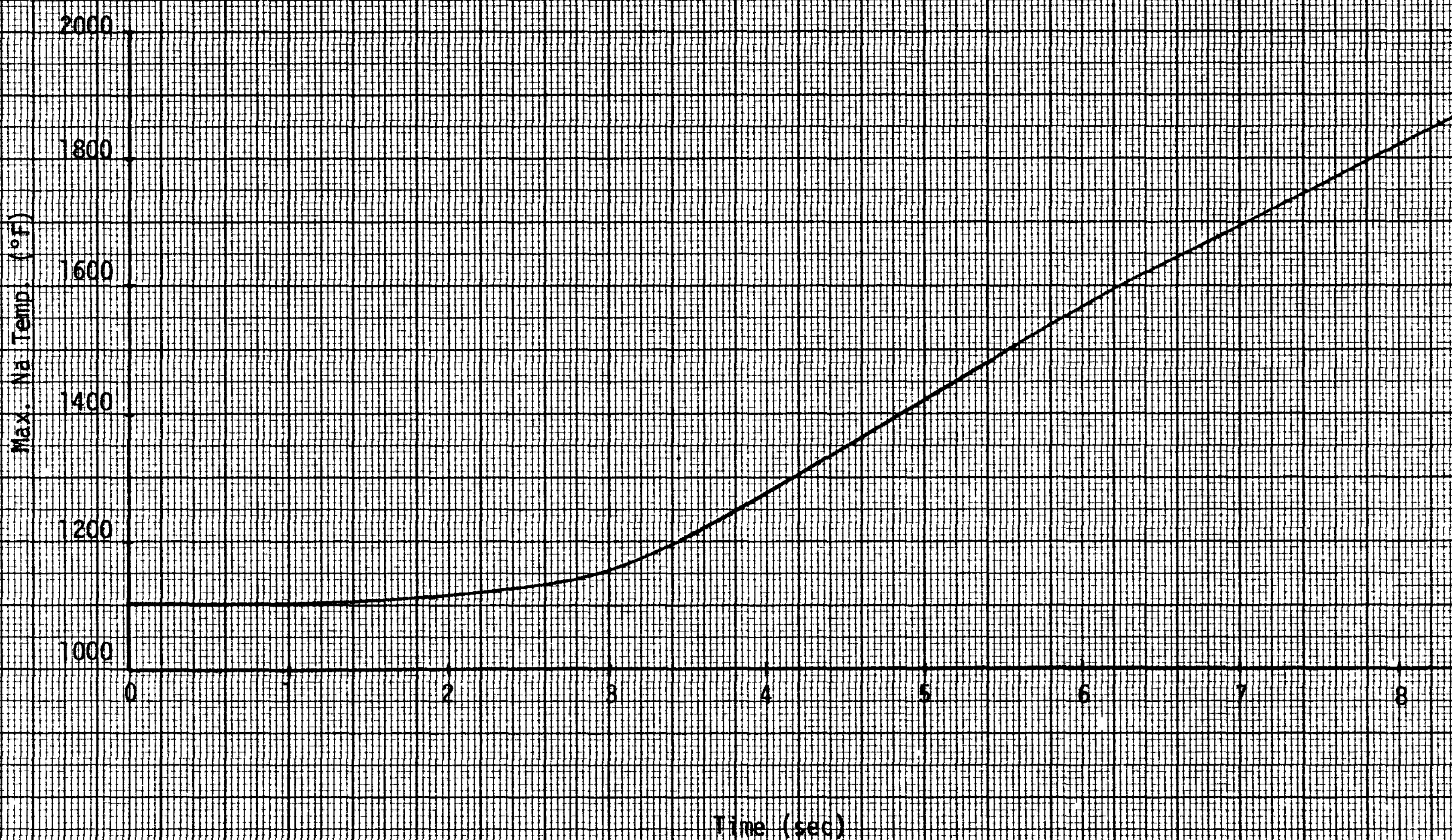


Figure 6.2-12

Maximum Coolant Temperature vs. Time for the SSE + FOD Event With No Scram

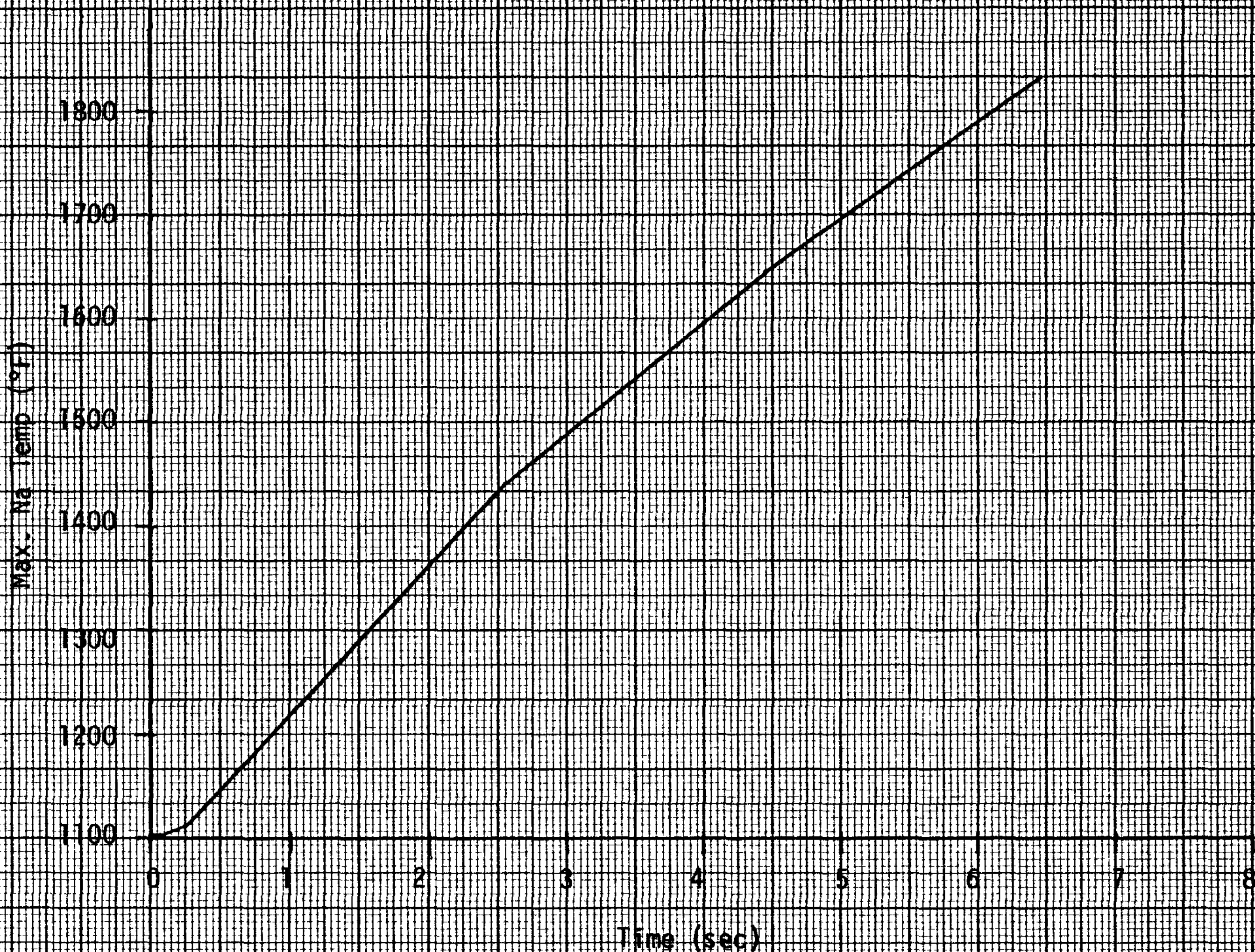


Figure 6.3-1

Peak Sodium Temperature vs. Delay Time for the TUC Event With a Scram Worth of $1.60
(Initial Peak Only)

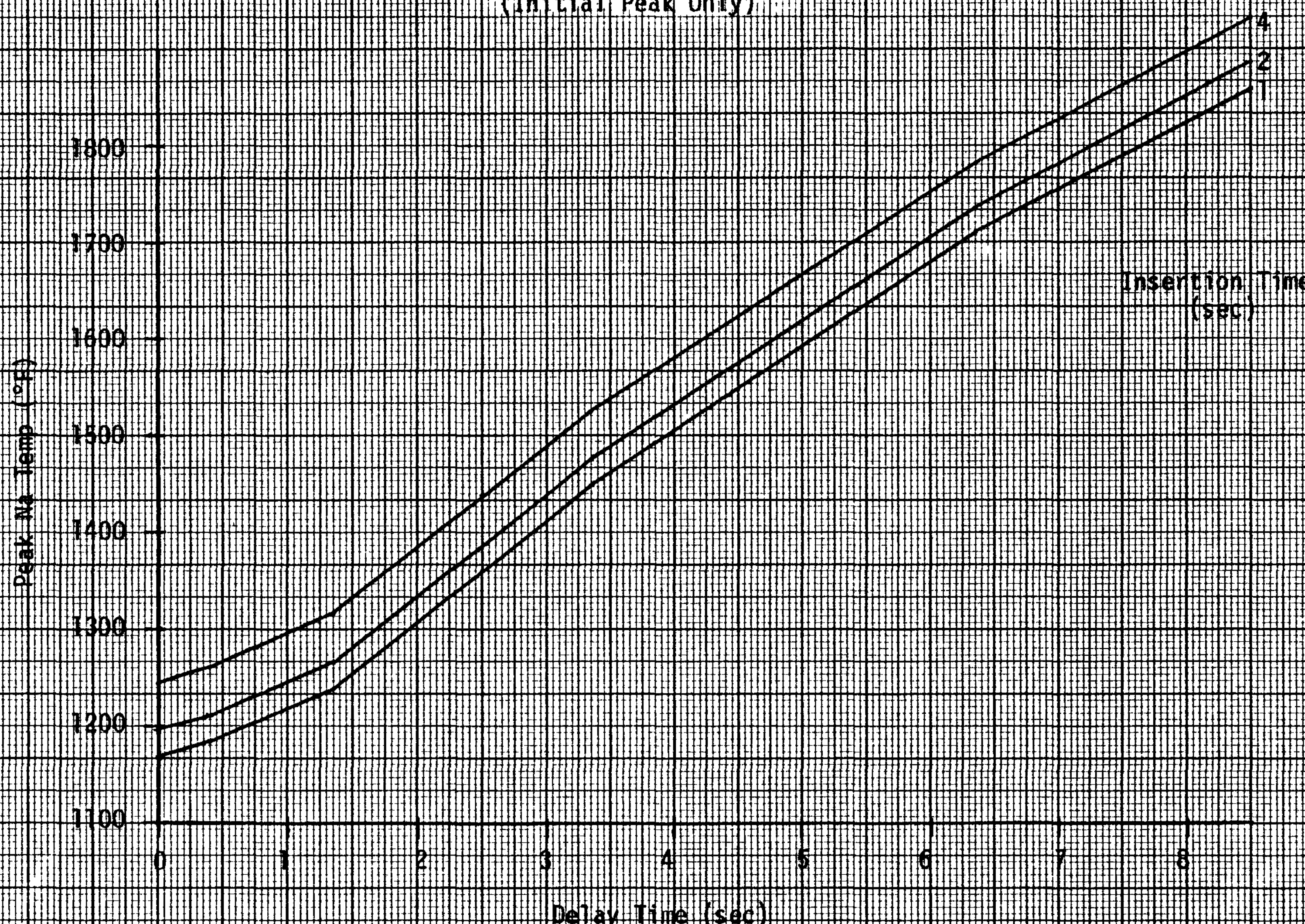
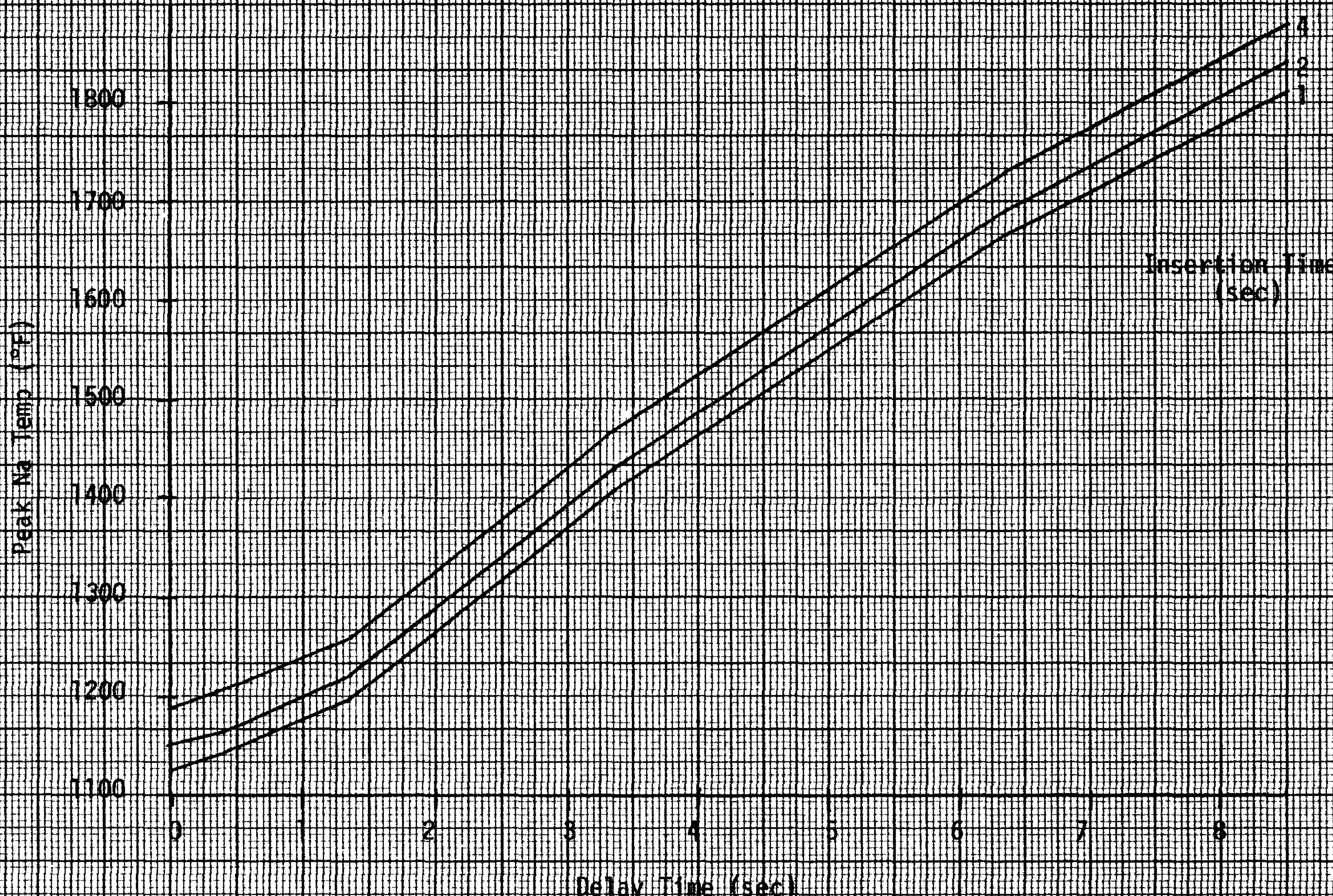


Figure 6.3-2

Peak Sodium Temperature vs. Delay Time For the TUC Event With Scram Worth of $4.00



The $1.60 scram worth initially turns the transient around, but since the specified CRBRP type flow coastdown is more rapid than the decrease in power the coolant temperature rises to its boiling point with a delay of only several (10 to 20) seconds depending on the event being evaluated. As previously discussed in Section 3, the $4.00 worth scram provides adequate long-term shutdown.

The peak sodium temperature versus delay time for the TOP (0.7¢/sec) event without pump trip is shown in Figure 6.3-3. For this transient the core response is largely independent of the scram worth provided it is greater than or equal to $3 and independent of the scram insertion times provided it is less than 5 seconds. A similar plot is provided in Figure 6.3-4 for the with pump trip case which does have some dependence on insertion time due to the flow coastdown.

The peak sodium temperature versus delay time for the TOP (6¢/sec) event without pump trip is shown in Figure 6.3-5. As in the previous case, their is very little dependence on the scram worth and the insertion time. Figure 6.3-6 provides similar data for the with pump trip case.

Figures 6.3-7 and 6.3-8 show the peak sodium temperature for the SSE event versus delay time and several insertion times for scram worths of $1.60 (initial peak) and $4.00 (absolute peak), respectively. As in the flow-coastdown event, a $1.60 scram is inadequate to provide long-term shutdown. In figure 6.3-7 only the initial peak sodium temperature is shown since sodium will eventually boil for this case.

6.4 Normalized Sodium Outlet Temperatures

The normalized sodium outlet temperatures of the form $\theta(t) = (T_{out}(t)-T_{in})/(T_{out}(o)-T_{in})$ for the above four transient events without scram can be used to estimate the sodium outlet temperature of the assemblies adjacent to the SASS rod when determining trigger temperatures. The normalized sodium outlet temperature versus time during the four transient events for the blanket and fuel assemblies are given in Figures 6.4-1 through 6.4-6 and Figures 6.4-7 through 6.4-12, respectively.

Figure 6.3-3

Peak Sodium Temperature vs. Delay Time For the TOP (0.76¢/sec) Event

(No Pump Trip)

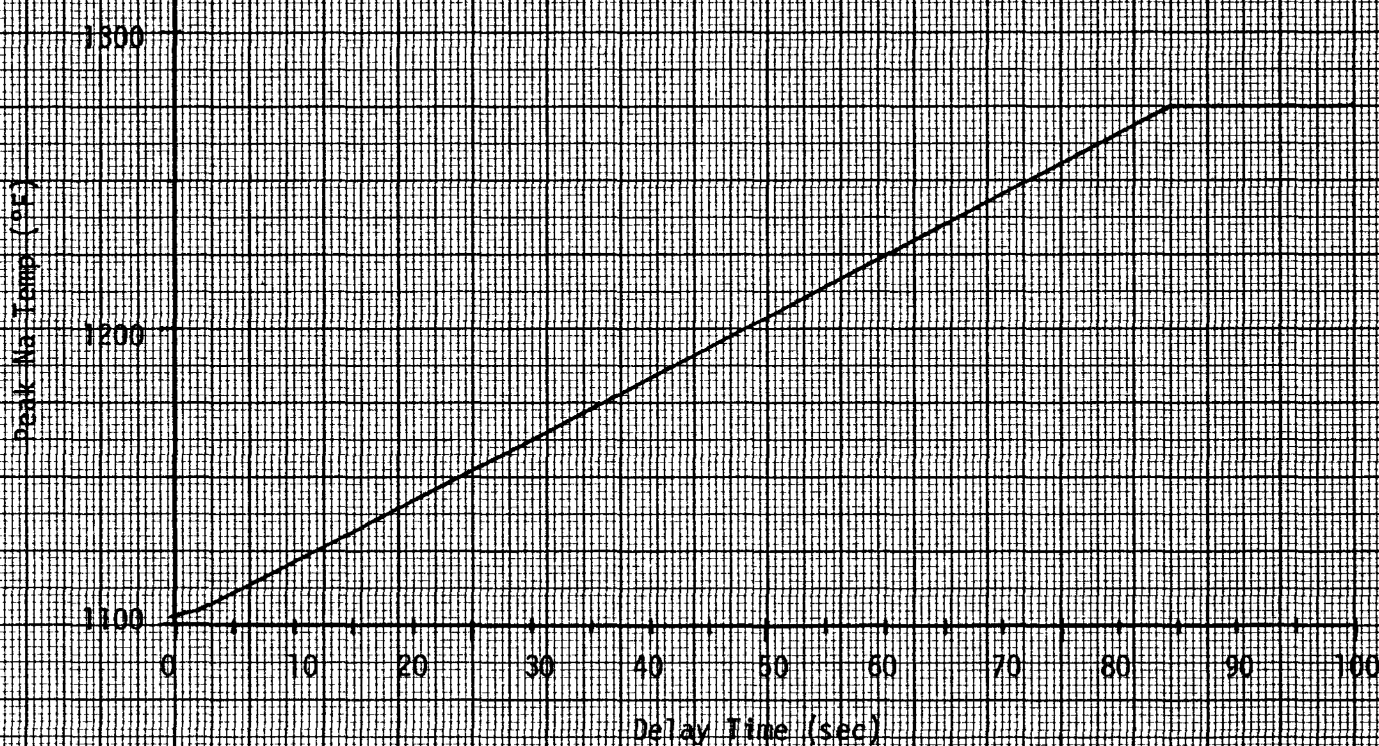


Figure 6.3-4

Peak Sodium Temperature vs. Delay Time for the TOP (0.76¢/sec) Event
(With Pump Trip)
(3$ Scram Worth)

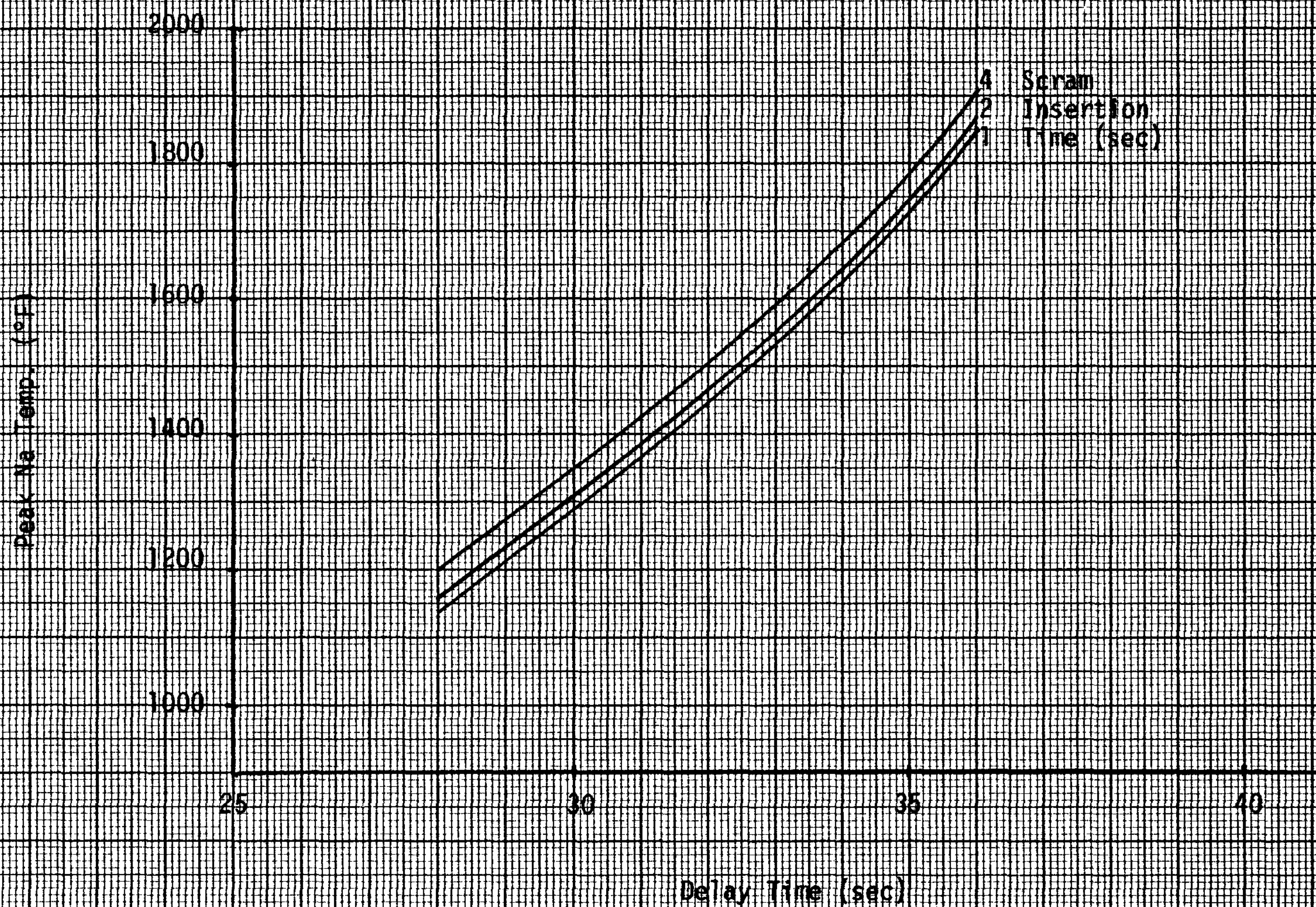


Figure 6.3-5

Peak Sodium Temperature vs. Delay Time For the TOP (6.1¢/sec) Event

(No Pump Trip)

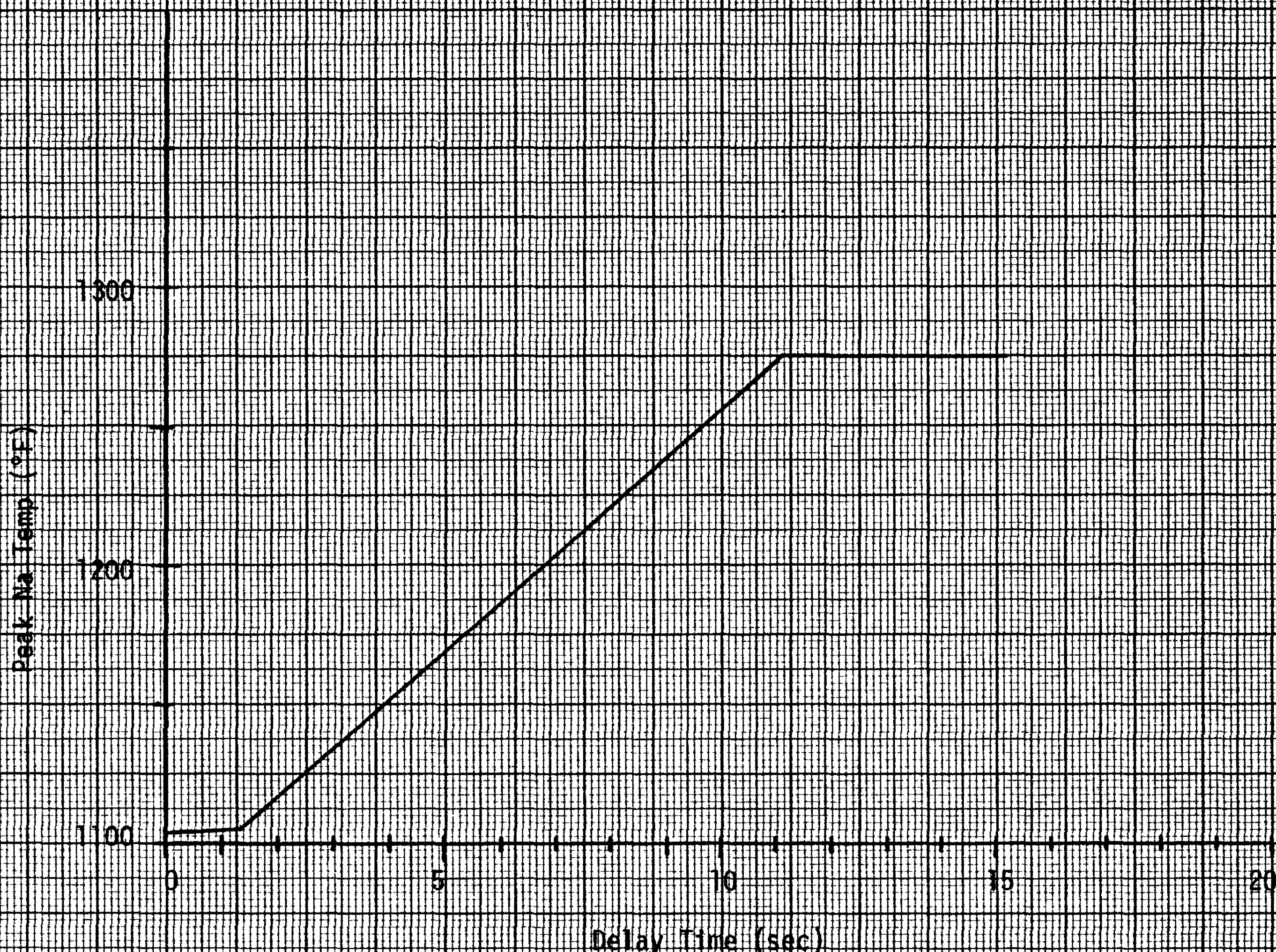


Figure 6.3-6

Peak Sodium Temperature vs. Delay Time for the TOP (6.1¢/sec) Event
(With Pump Trip)
(3$ Scram Worth)

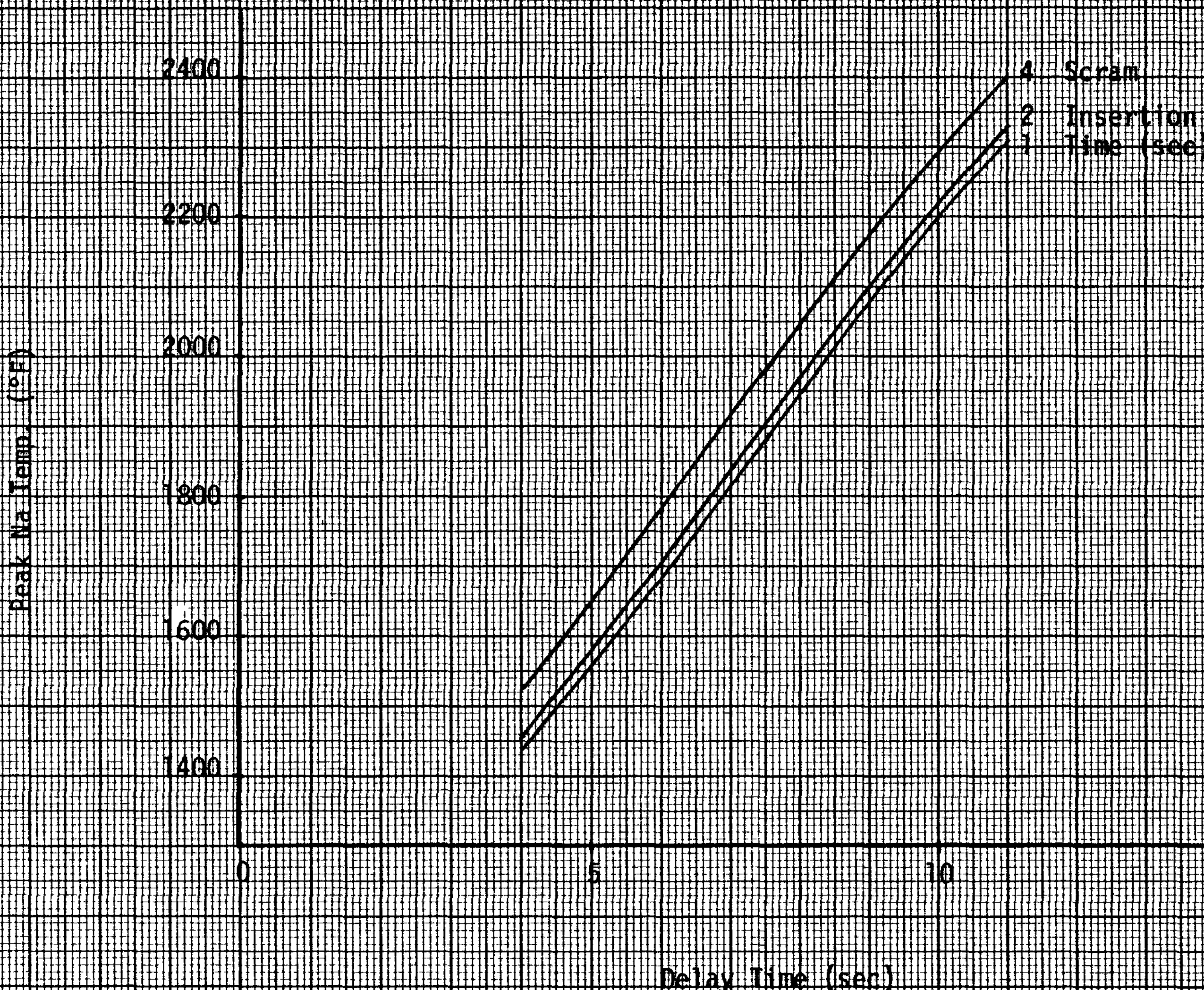


Figure 6.3-7

Peak Sodium Temperature vs. Delay Time For the SSE + FCD Event With a Scram Worth of $1.60

(initial peak only)

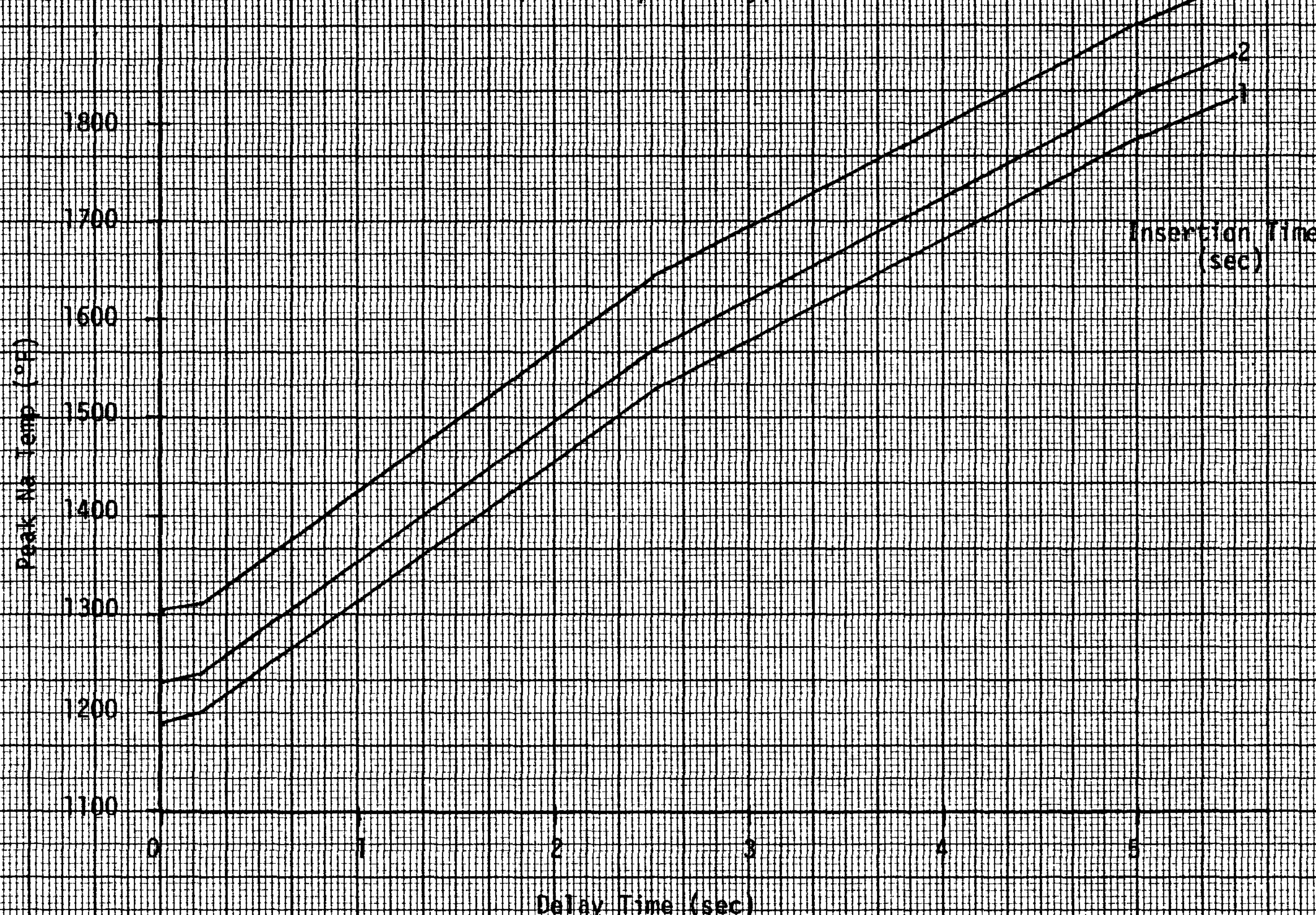


Figure 6.3-8

Peak Sodium Temperature vs. Delay Time For the SSE + FCD Event With a Scram Worth of $4.00

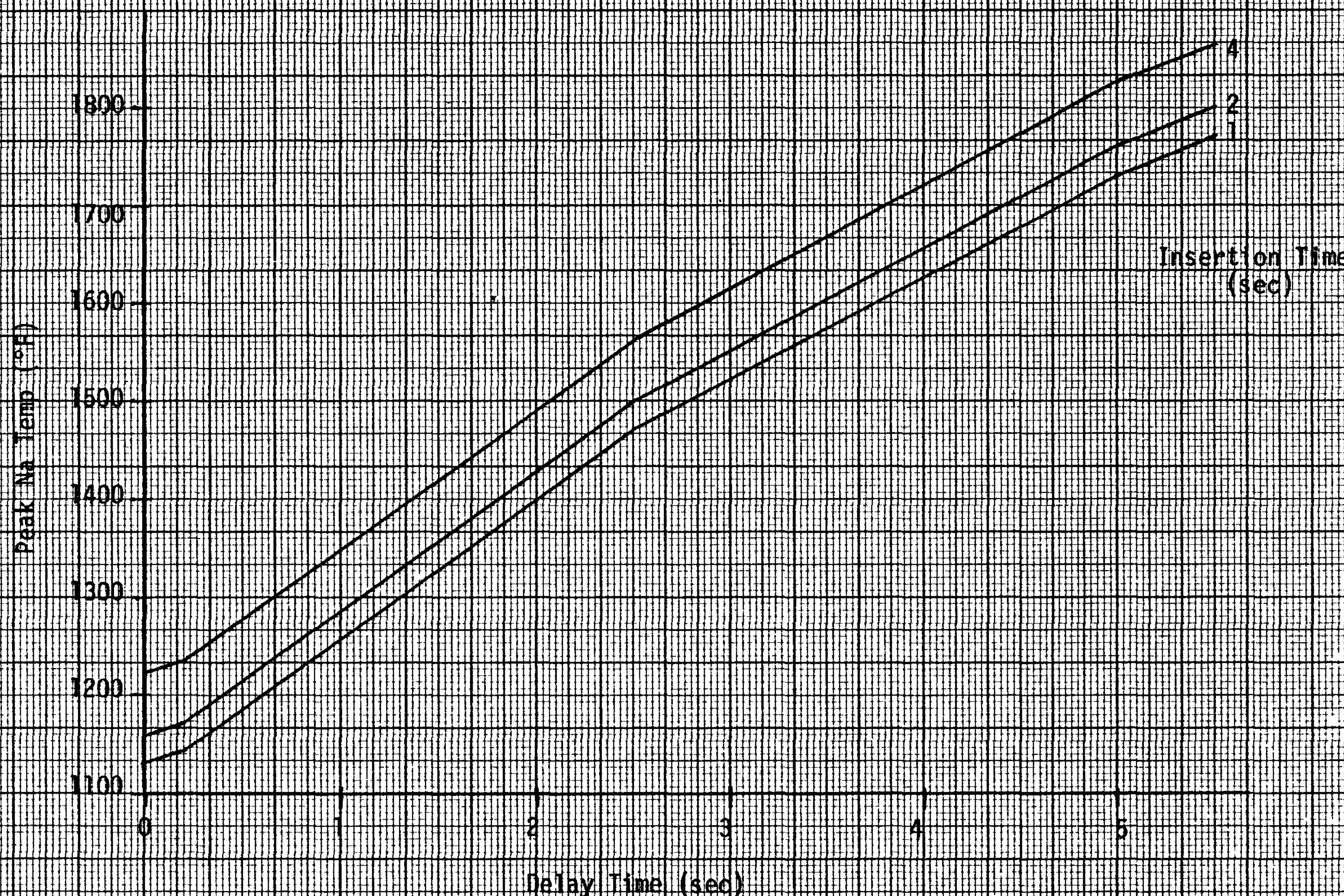


Figure 6.4-1

Blanket's Normalized Sodium Outlet Temperature vs. Time For the TUC Event With No Scram

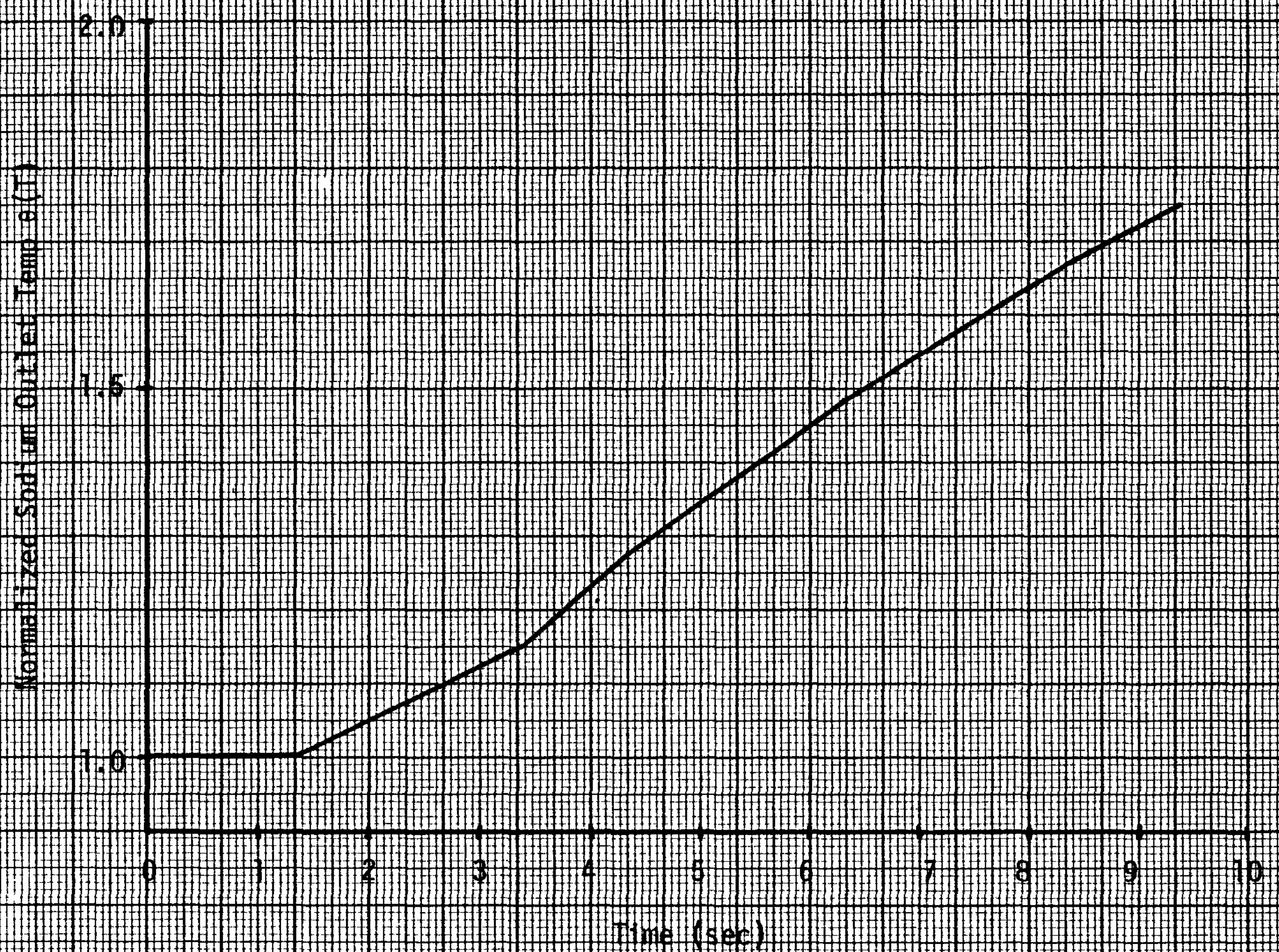


Figure 6.4-2

Blanket's Normalized Sodium Outlet Temperature vs. Time For the TOP (0.76¢/sec) Event With No Scram

(No Pump Trip)

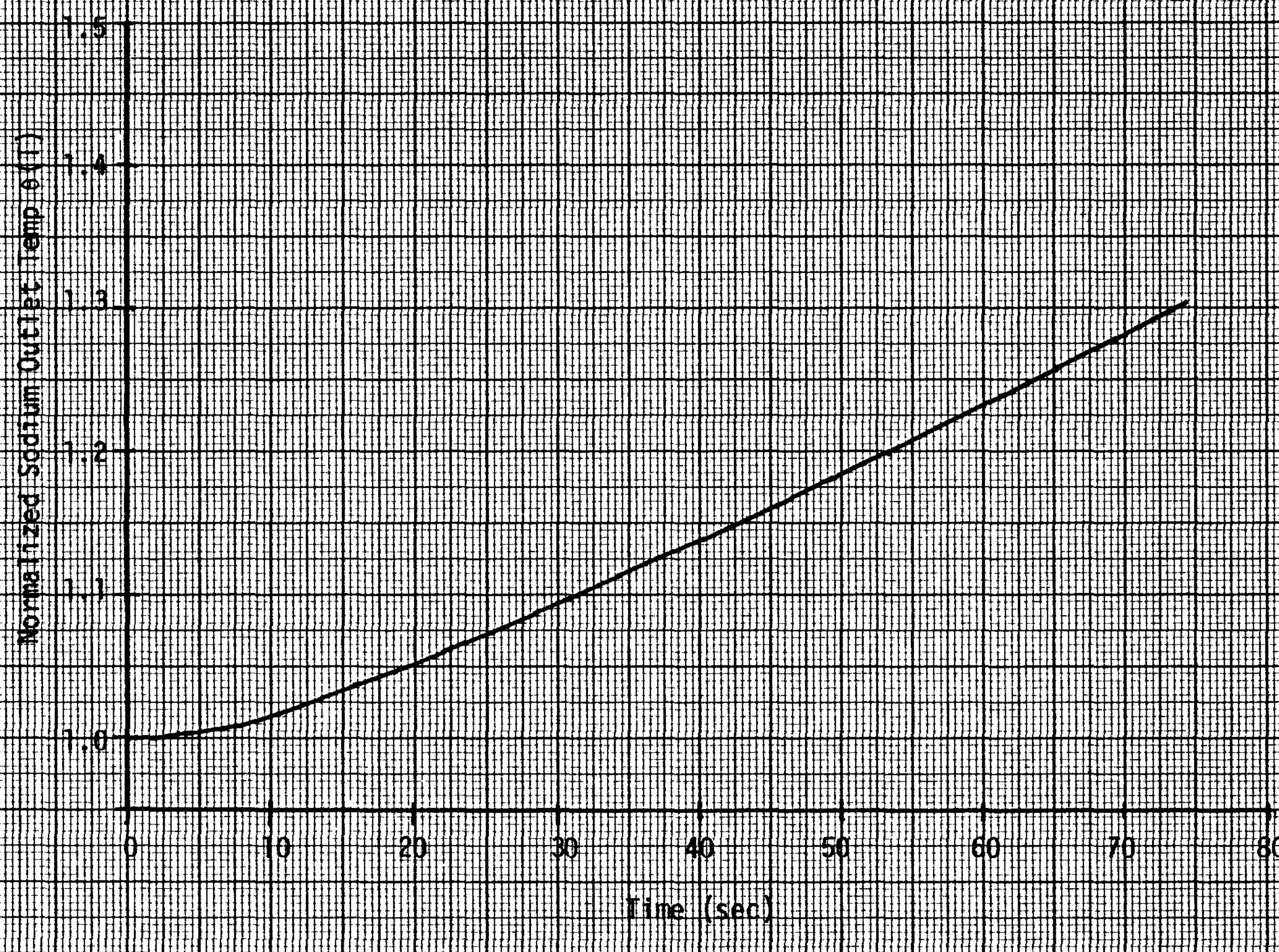


Figure 6.4-3

Blanket's Normalized Sodium Outlet Temperature vs. Time for the TOP (0.76¢/sec) Event With No Scram

(With Pump Trip)

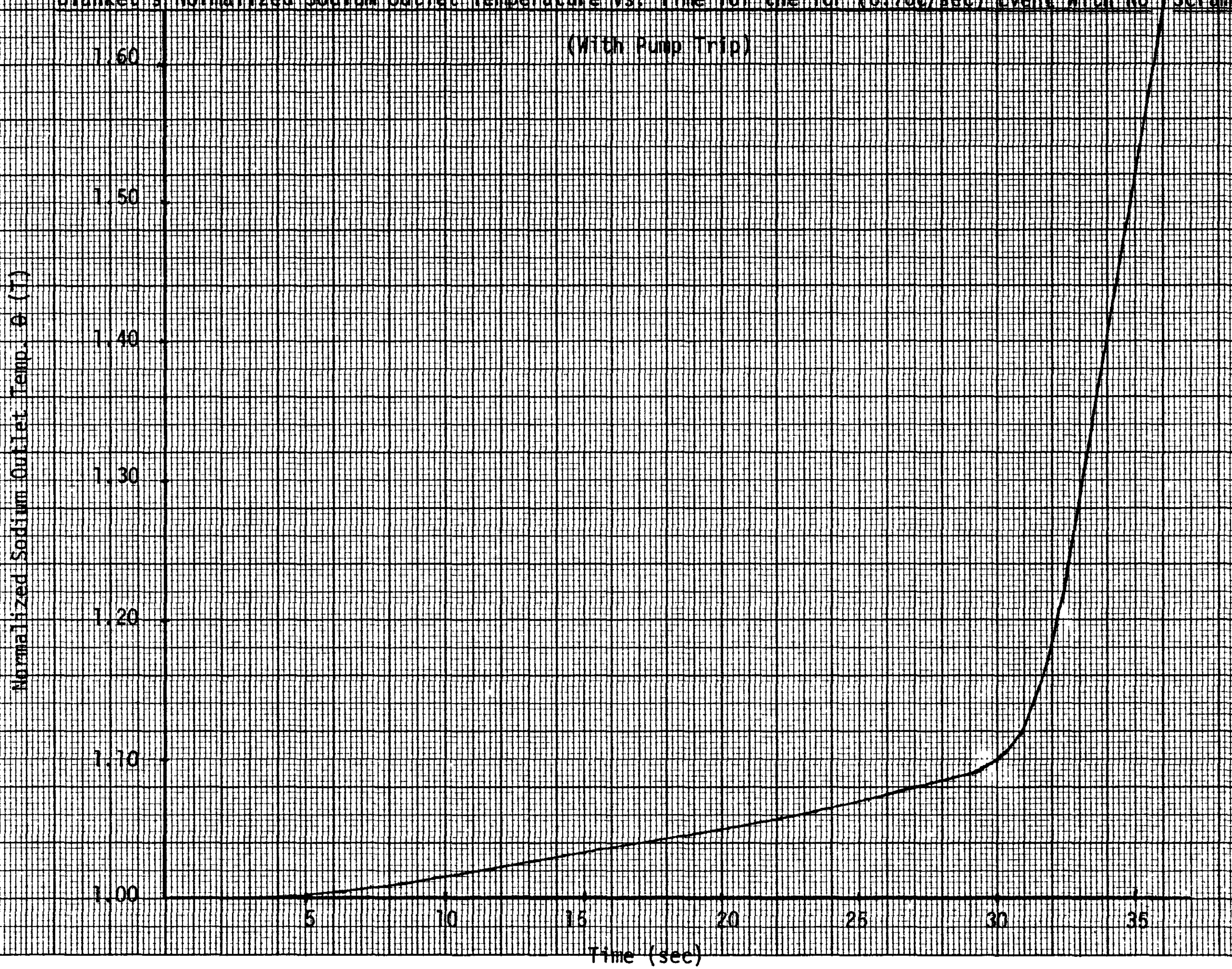


Figure 6.4-4

Blanket's Normalized Sodium Outlet Temperature vs. Time For the TOP (6.1¢/sec) Event With No Scram

(No Pump Trip)

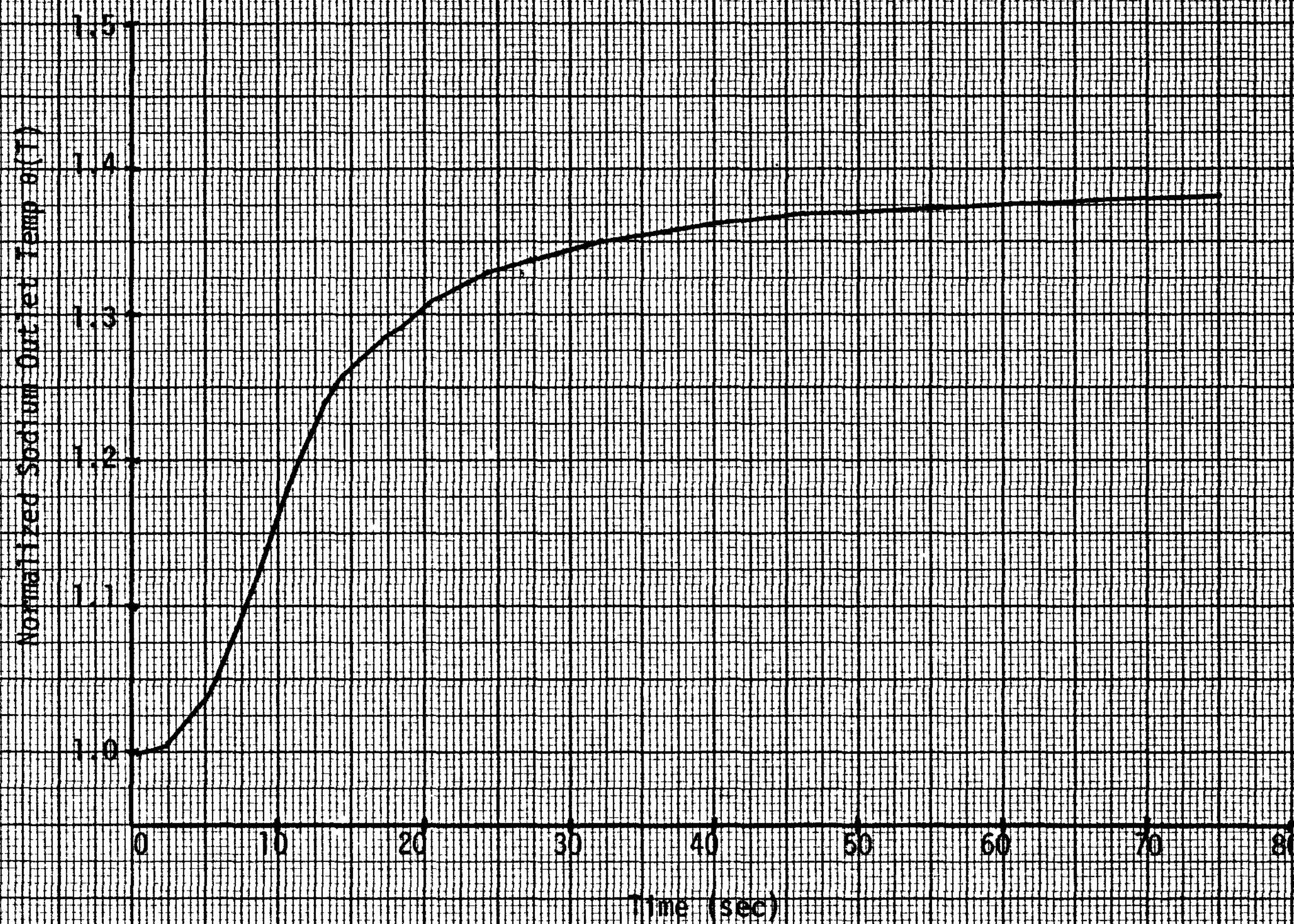


Figure 6.4-5

Blanket's Normalized Sodium Outlet Temperature vs. Time for the TOP (6.1¢sec) Event With No Scram
(With Pump Trip)

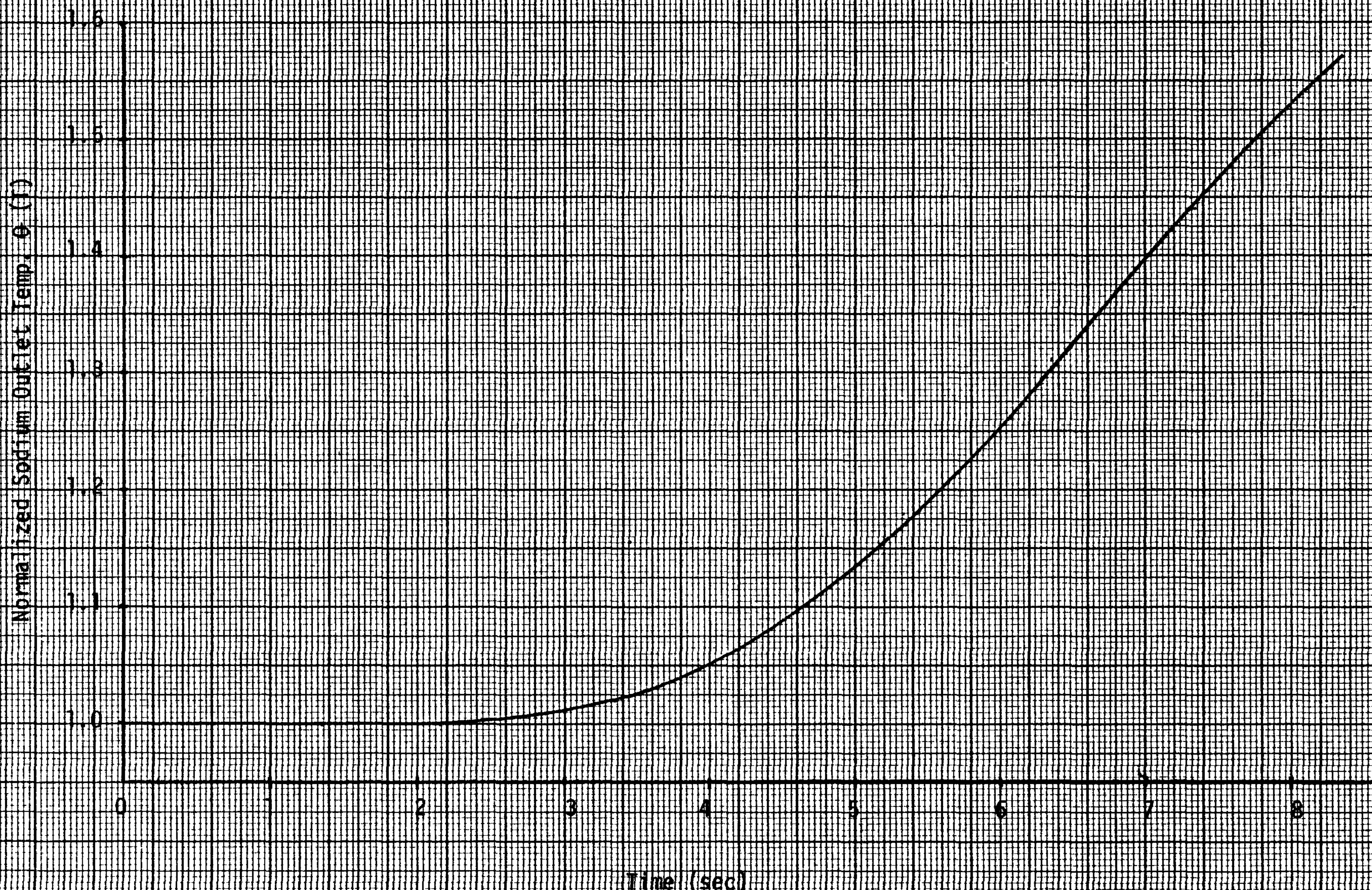


Figure 6.4-6

Blanket's Normalized Sodium Outlet Temperature vs. Time For the SSE + FCO With No Scram

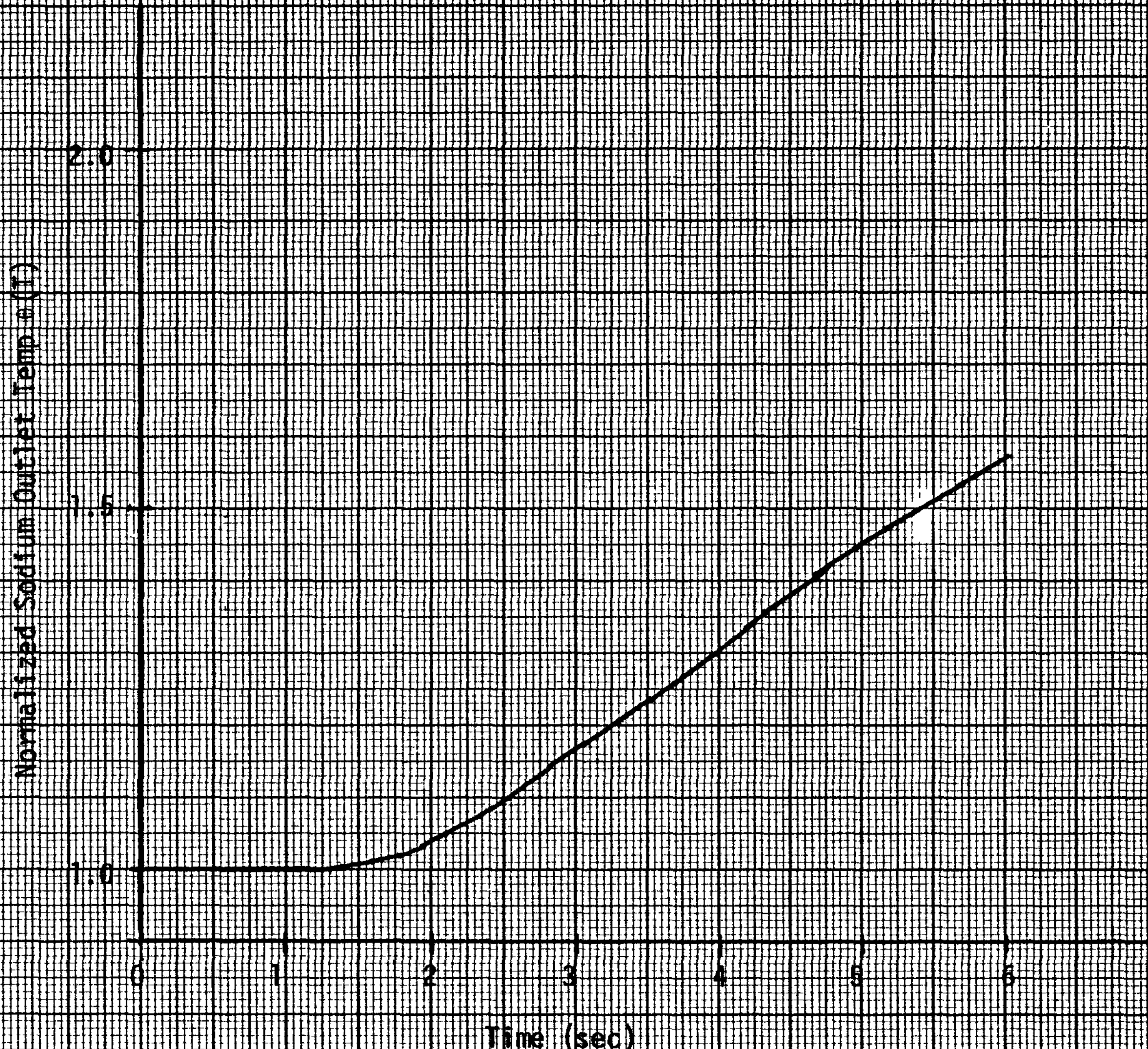


Figure 6.4-7

Fuel's Normalized Sodium Outlet Temperatures vs. Time

For the TUC Event With No Scram

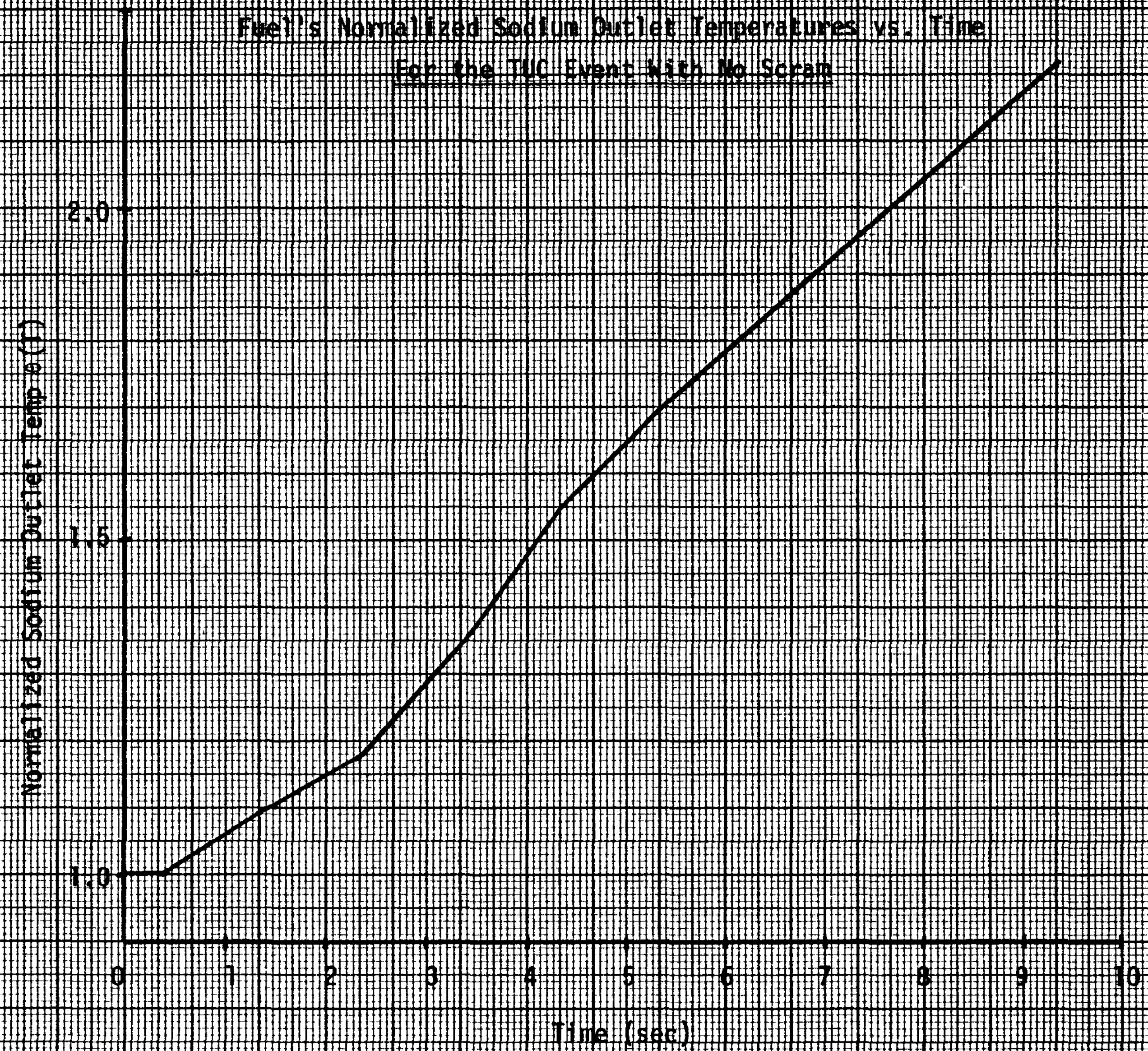


Figure 6.4-8

Fuel's Normalized Sodium Outlet Temperature vs. Time For the TOP (0.76¢/sec) Event With No Scram

(No Pump Trip)

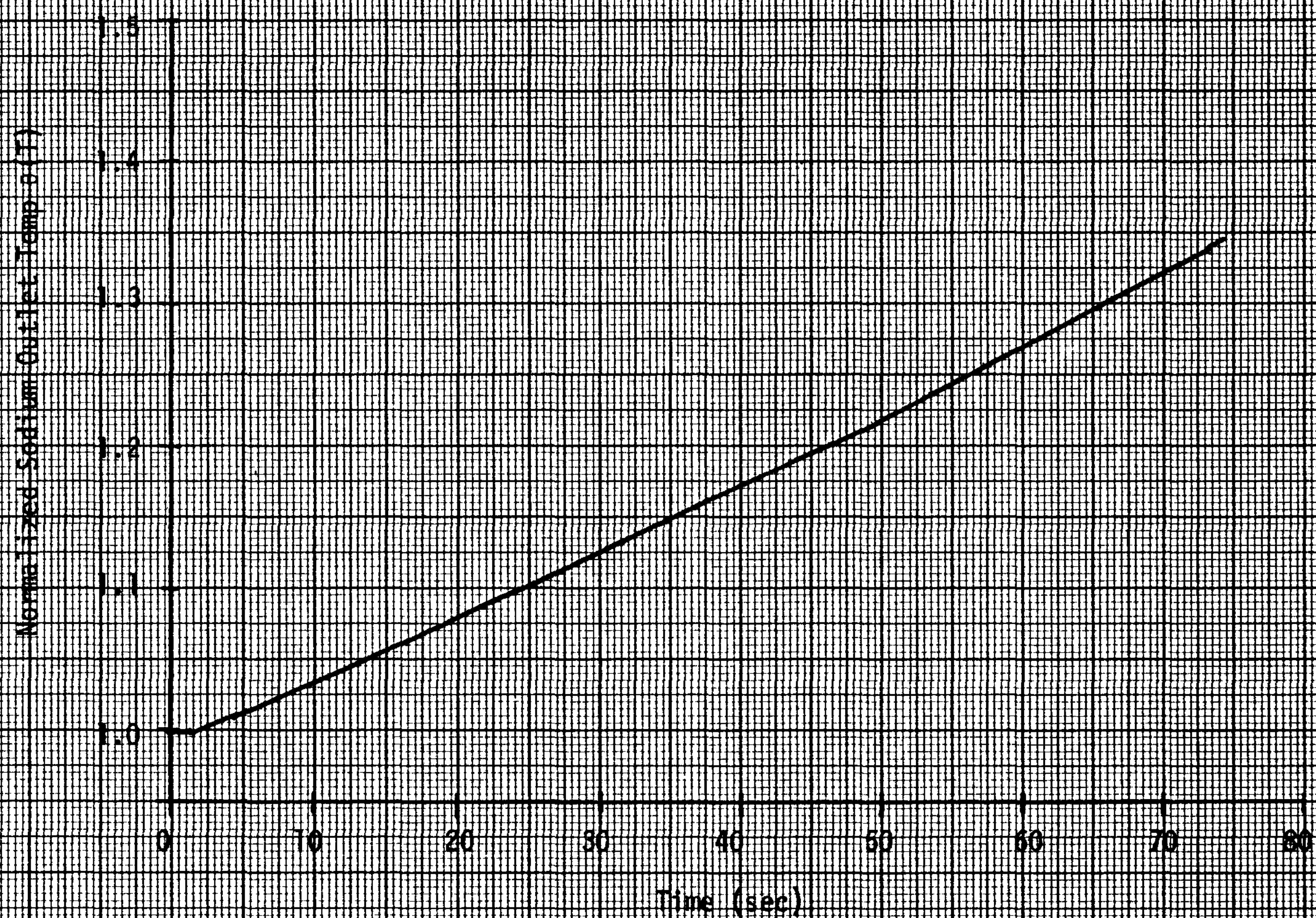


Figure 6.4-9

Fuel's Normalized Sodium Outlet Temperature vs. Time for the TOP (0.76¢/sec) Event With No Scram)

(With Pump Trip)

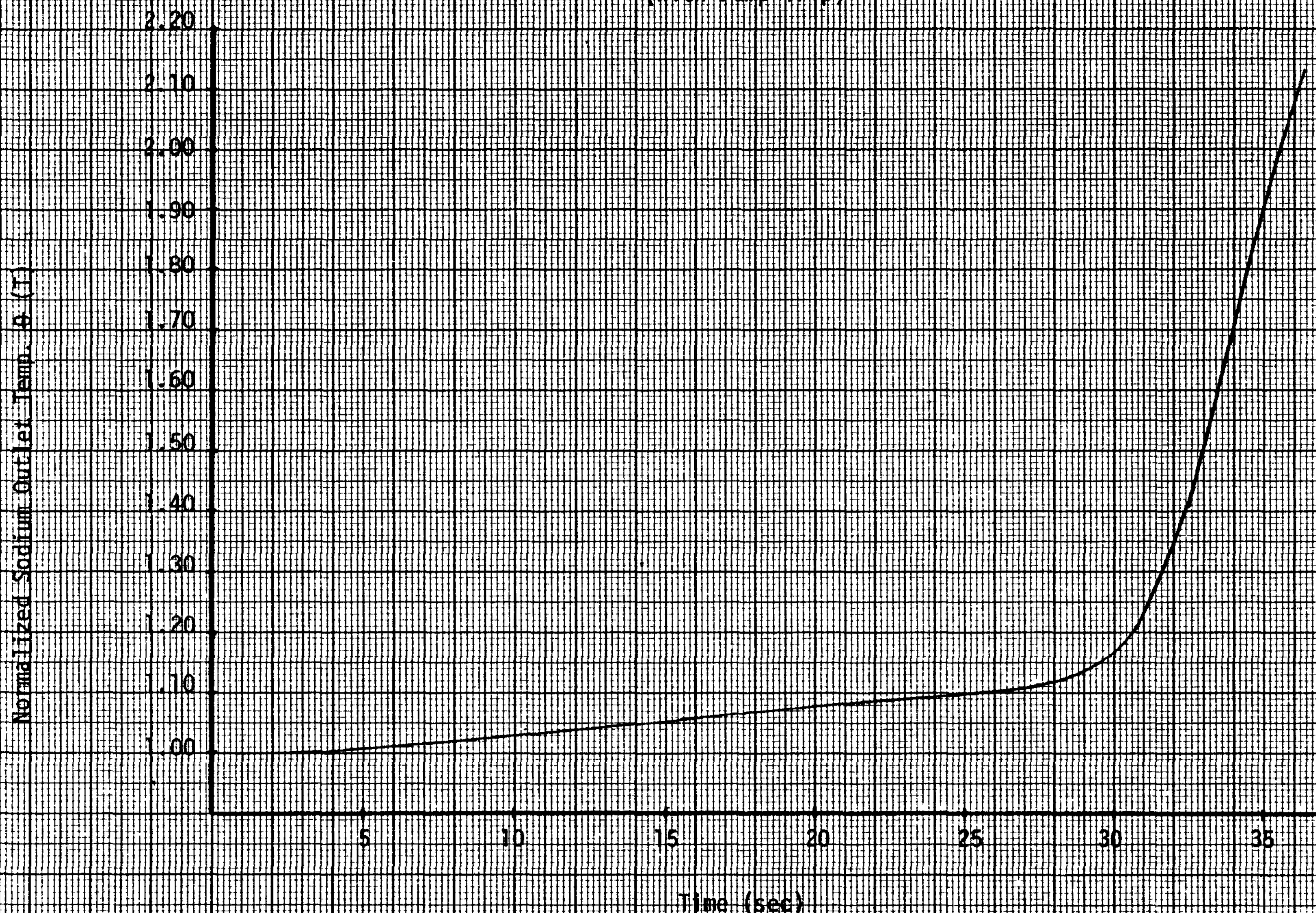


Figure 6.4-10

Fuel's Normalized Sodium Outlet Temperature vs. Time For the TOP (6.1¢/sec) Event With No Scram

(No Pump Trip)

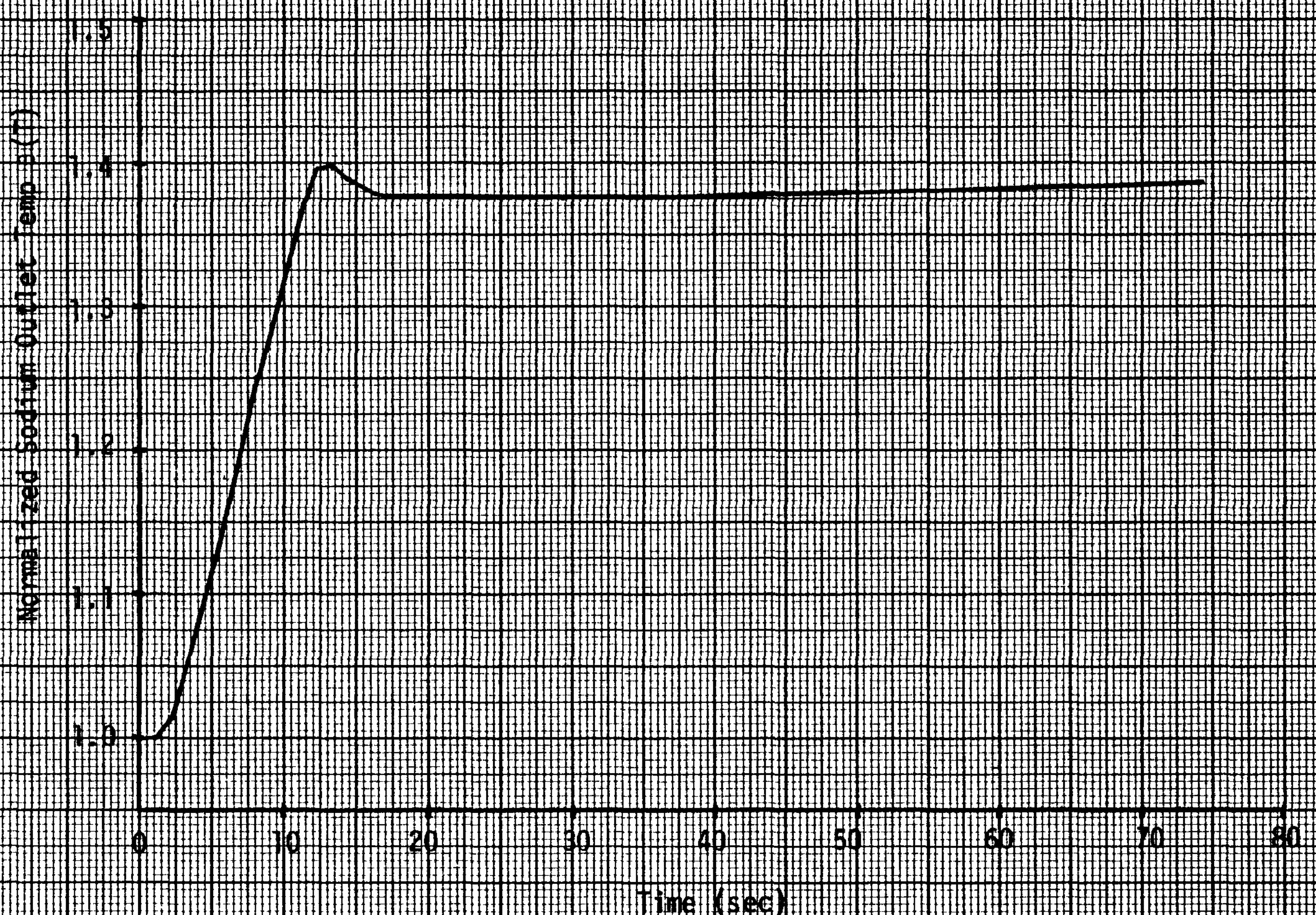


Figure 6.4-11

Fuel's Normalized Sodium Outlet Temperature vs. Time for the TOP (6.1¢/sec) Event With No Scram

(With Pump Trip)

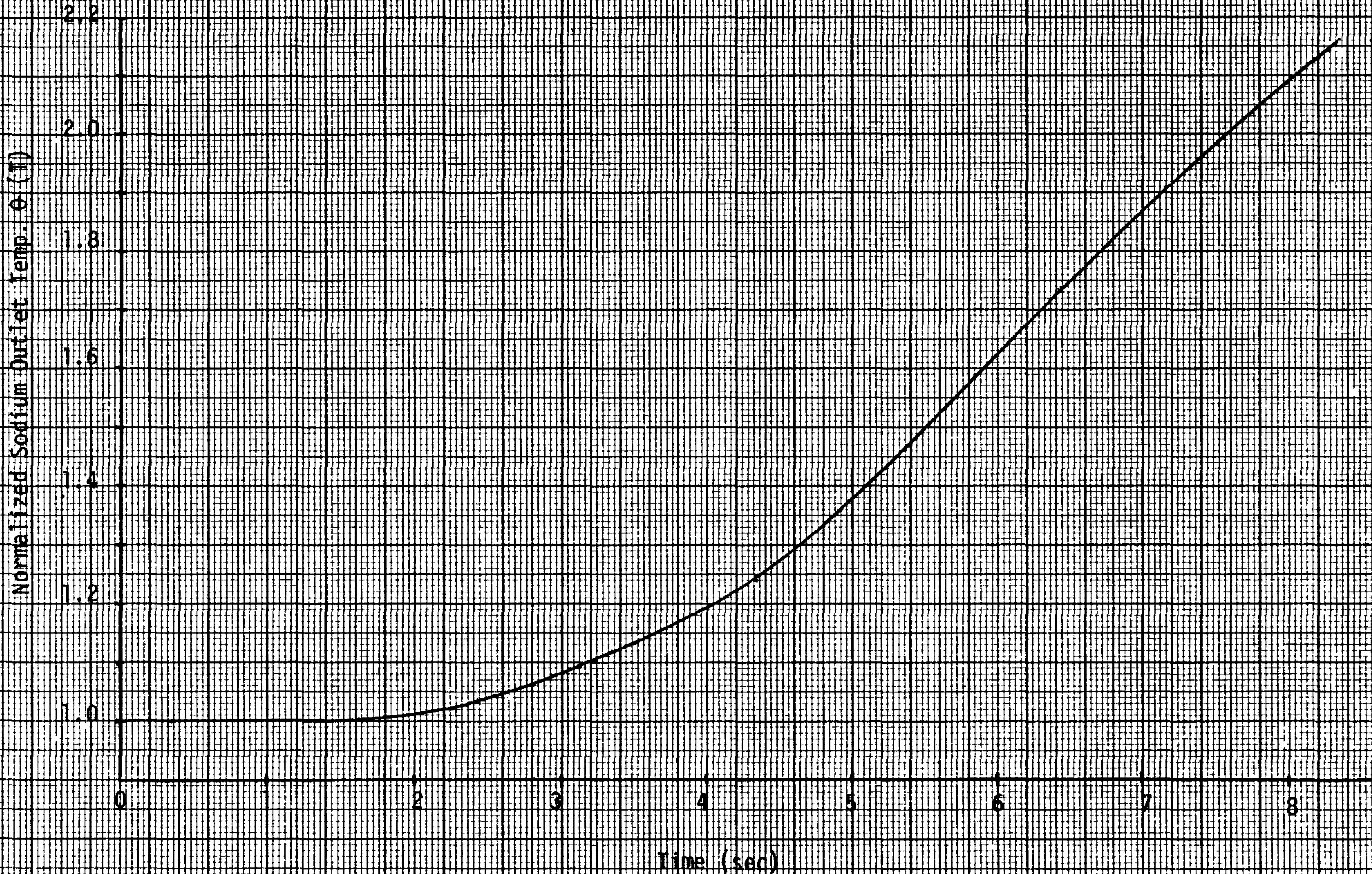
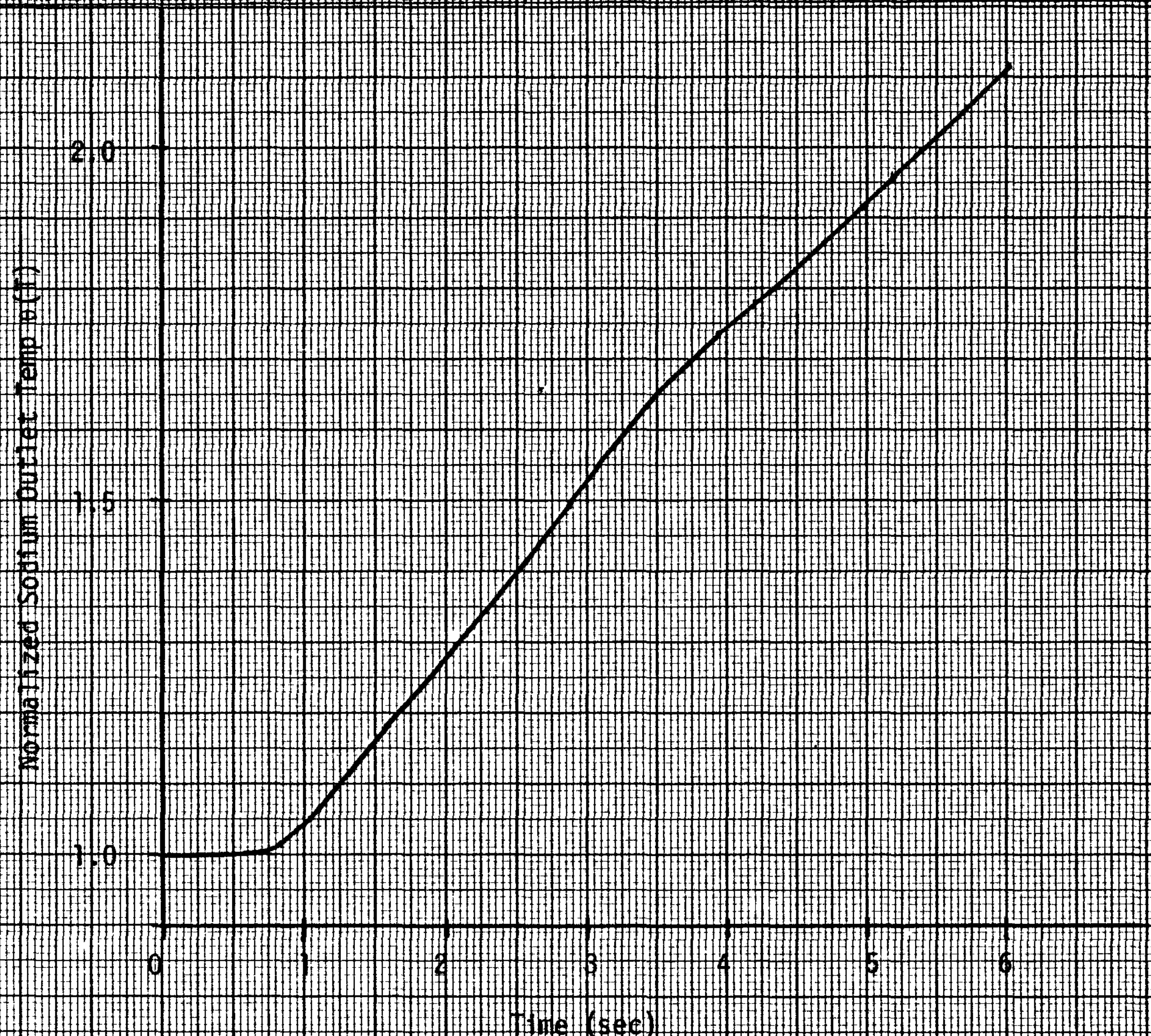


Figure 6.4-12

Fuel's Normalized Sodium Outlet Temperature vs. Time For the SSE + RCD Event With No Scram



6.5 SASS Response Time Requirements For The CDS Phase II Core

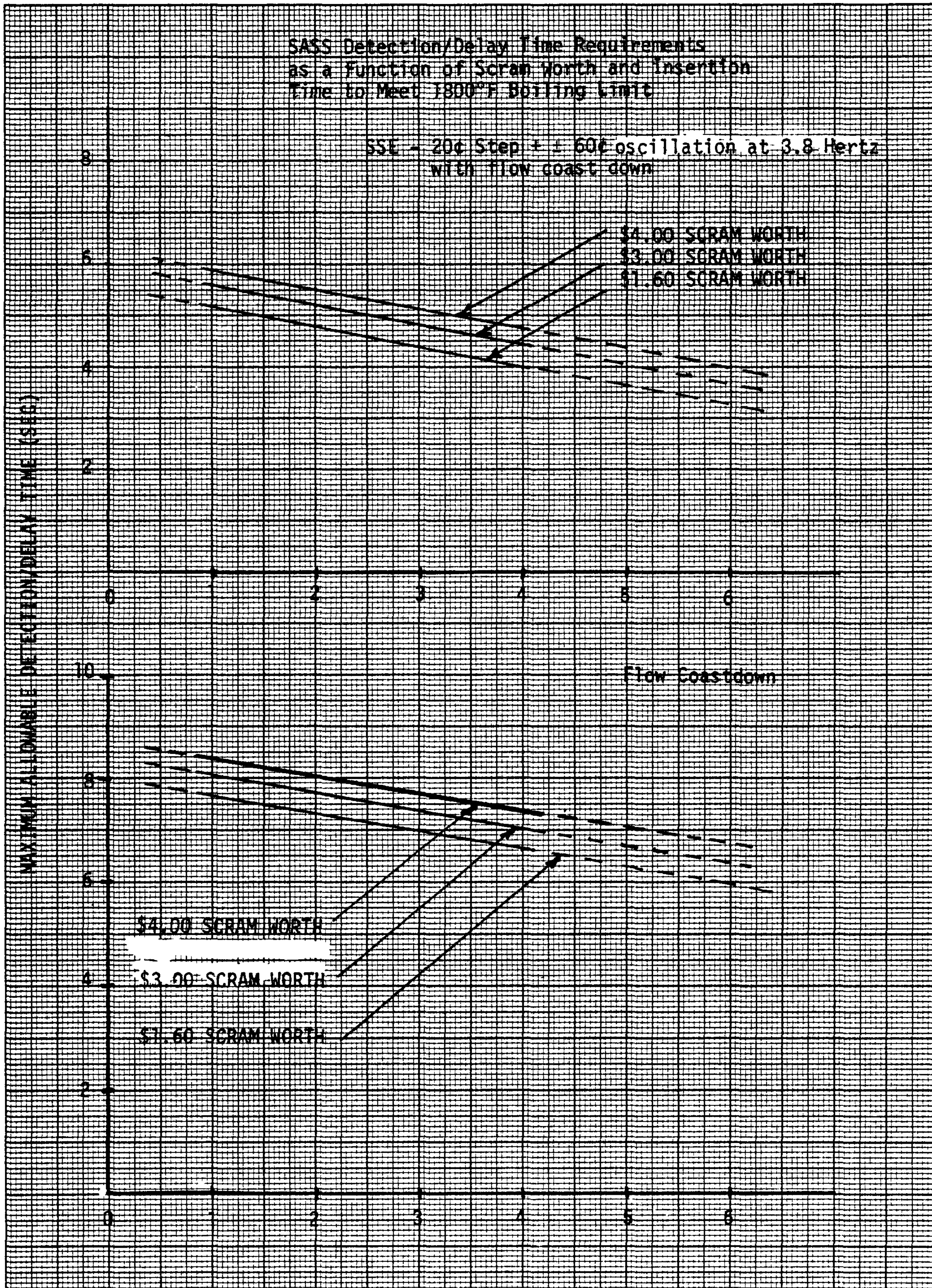
The response time requirements for SASS are determined by defining the relationship between the various response time characteristics of the SASS to the fuel melting, clad melting and coolant boiling limits for each of the design basis transients evaluated in Section 6.3. The response time characteristics of the SASS may be grouped into the detection/delay time, insertion time and scram worth.

6.5.1 Sodium Boiling Limit

The sodium boiling limit depends upon the absolute pressure at the top of the active core. The absolute pressure depends upon the static head and the dynamic pressure drop in the assembly of interest. In the CDS Phase II core the pressure at the top of the active core varies from 43 to 55 psig which would give a sodium boiling temperature between 1860 to 1940°F. Due to uncertainties in this static head (28.1 ft), thermal analysis uncertainties, and uncertainty in the axial and radial locations of peak sodium temperatures, 1800°F is assigned as the boiling limit for the CDS design.

The 1800°F boiling limit can be converted into an allowable detection/delay time as a function of the scram worth and scram insertion time by using the plots of peak sodium temperature from Section 6.3. Figure 6.5-1 shows the maximum allowable detection/delay time as a function of scram worth and scram insertion time for the SSE and flow coastdown (FCD) events. In section 4.2 it was determined that, based on reliability and shutdown margin requirements, at least 3 out of 4 SASS control positions must operate. Thus the $3 worth curve in Figure 6.5-1 shows the recommended maximum allowable detection and/or delay time as a function of the insertion time for both the SSE and FCD events based on the boiling limit. Neither transient overpower event without pump trip reached the boiling limit because of the inherent characteristics of the CDS Phase II Core. The TOP events with pump trip do reach the boiling limit and Figure 6.5-2 shows the recommended maximum allowable detection and/or delay time as a function of insertion time for both the .76¢/sec and 6.1¢/sec TOP events.

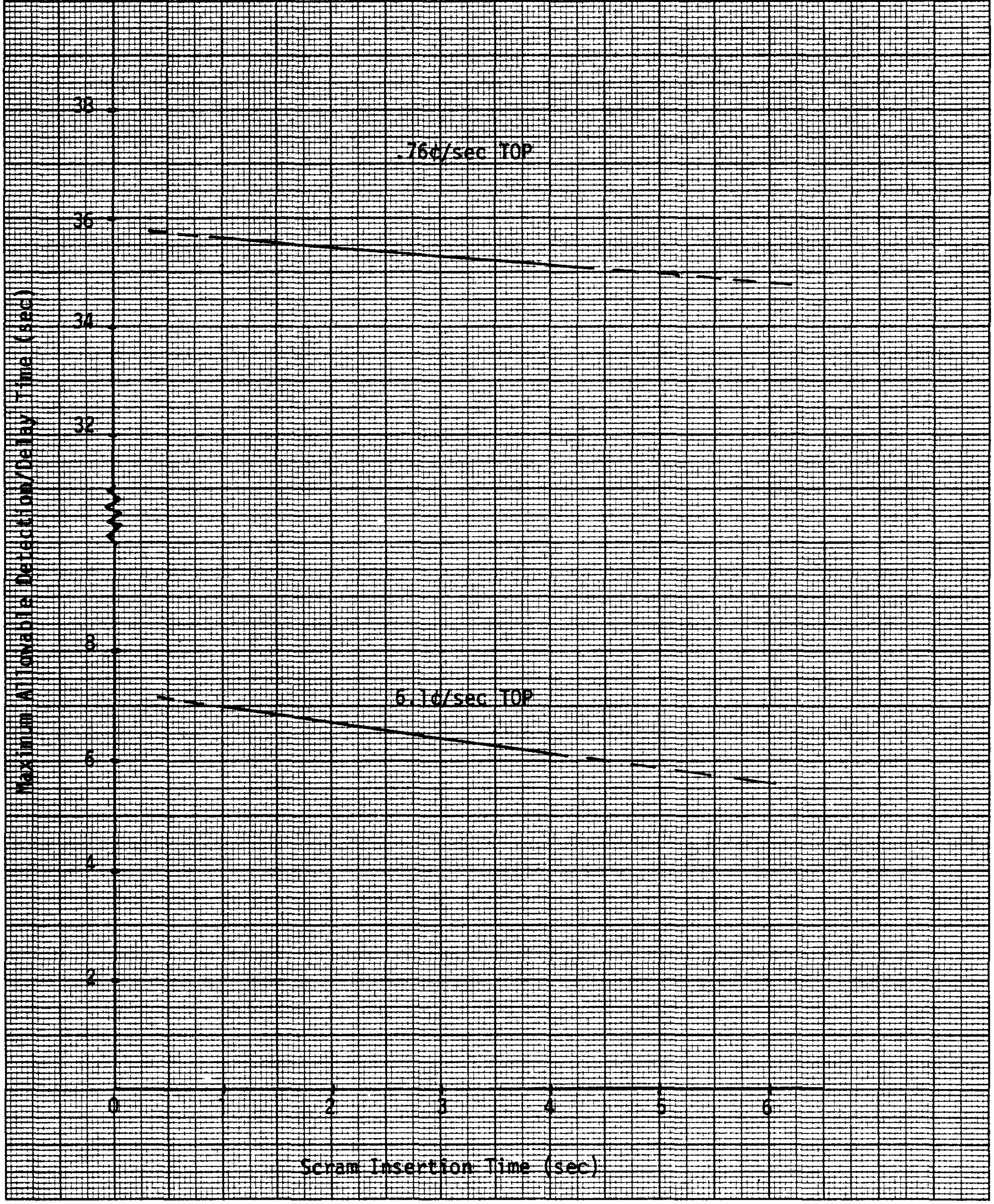
Figure 6.5-1



SCRAM INSERTION TIME (SEC)

Figure 6.5-2

SASS Detection/Delay Time Requirements As a Fucntion of the Insertion Time to Meet 1800°F Boiling Limit for the TOP Events with 3$ Scram Worth and Pump Trip



6.5.2 Cladding Temperature Limit

Since the boiling limit is 1800°F and the D-9 melting temperature is expected to be near 2400°F, the clad melt limit should not be limiting in any of the 4 transient.

6.5.3 Fuel Melting Limit

Based on past experience, only the TOP events and the SSE have a potential for being melt limited.

The TOP events without pump trip due to a control rod run out at 6.1¢/sec and .76¢/sec do not exceed a relative power of 1.52. Figure 6.5-3 shows a plot of the CDS fuel pin areal melt as a function of the relative power. This figure indicates that, for a 10¢/sec TOP and nominal conditions, the relative power must not exceed 1.67 to prevent fuel melting. For a 6¢/sec TOP and +2σ conditions normalized to the nominal peak conditions, the relative power must not exceed 1.56 to prevent fuel melting. It would initially appear that SASS would not be required to scram for these events. However, if the expected power shape change factor [6.5-1] due to a rod run out of 5 to 12 percent is applied to the CORTAC relative power predictions, the relative peak pin power could be in the range of 1.59 to 1.70, which would indicate the potential for some nominal peak pin melting in these events. Taking into account the above power shape factor uncertainty, point kinetic uncertainties and CORTAC-2D modeling uncertainties a 40% overpower limit is recommended for application to the CORTAC TOP results. Since the peak fuel temperature is relatively independent of the scram insertion time [6.5-2] (time required for rods to drop after actuation) and since the scram worth has been set at approximately 3$, the only other parameter that constrains the designer is the sum of the detection time and the delay time before rod motion begins. Figure 6.5-4 is a plot of the maximum allowable detection/delay time for the CDS Phase II core as a function of the reactivity ramp rate to meet the 40% over power limit for the TOP events without pump trip.

The TOP events with trip have the potential for being either boiling or fuel melt limited. The boiling limits are shown in Figure 6.5-3 to be in the range of 6-7 seconds for the 6.1¢/sec TOP and 35-36 seconds for

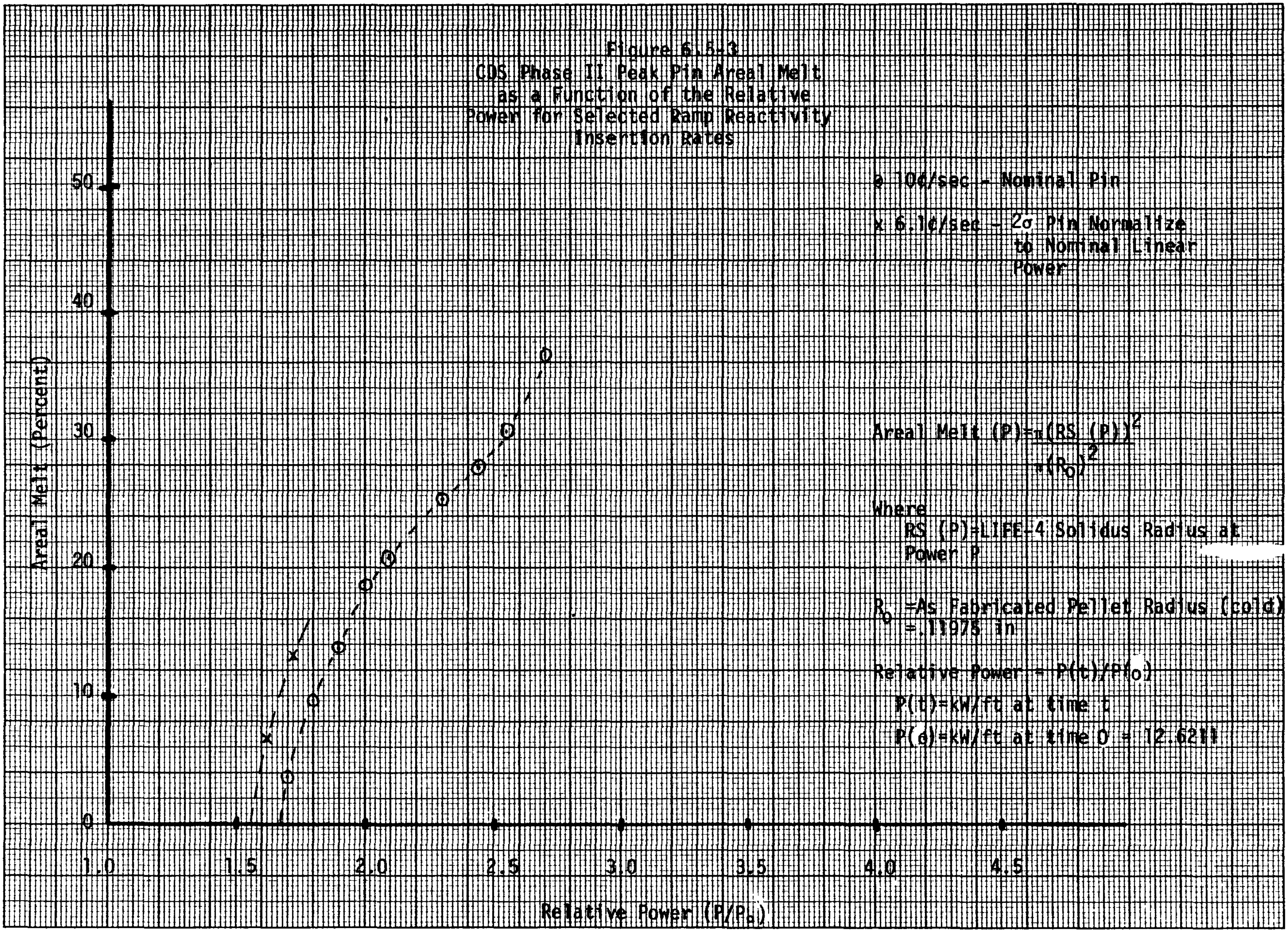
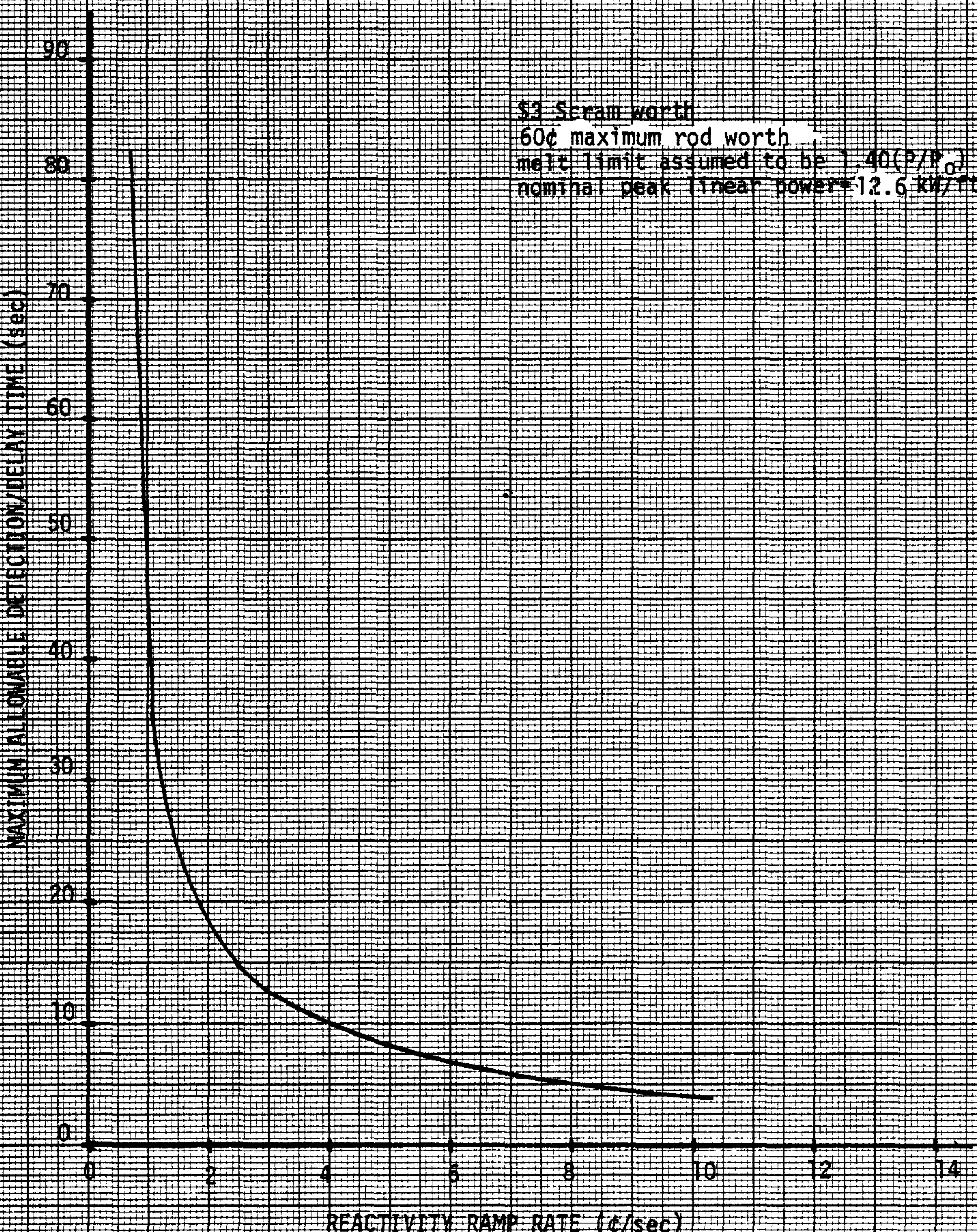


Figure 6.5-3
CDS Phase II Peak Pin Areal Melt as a Function of the Relative Power for Selected Ramp Reactivity Insertion Rates

Figure 6.5-4

Maximum Allowable Detection Time
as a Function of the Reactivity Ramp Rate
to Prevent Nominal Fuel Pin Melting
with No Pump Trip



the .76/sec TOP event. Figure 6.2-5 shows that the peak relative power for the 6.1¢/sec TOP does not exceed 1.24 which would become 1.30 to 1.39 with the power shape factor applied. This peak is just below the 40% overpower limit. For the .76¢/sec event the peak relative power does not exceed 1.15. Thus, the TOP events with pump trip appear to be boiling limited as can be seen more graphically from Figure 6.5-5 which is a plot of the nominal peak pins centerline temperature for the 6.1¢/sec TOP event with pump trip.

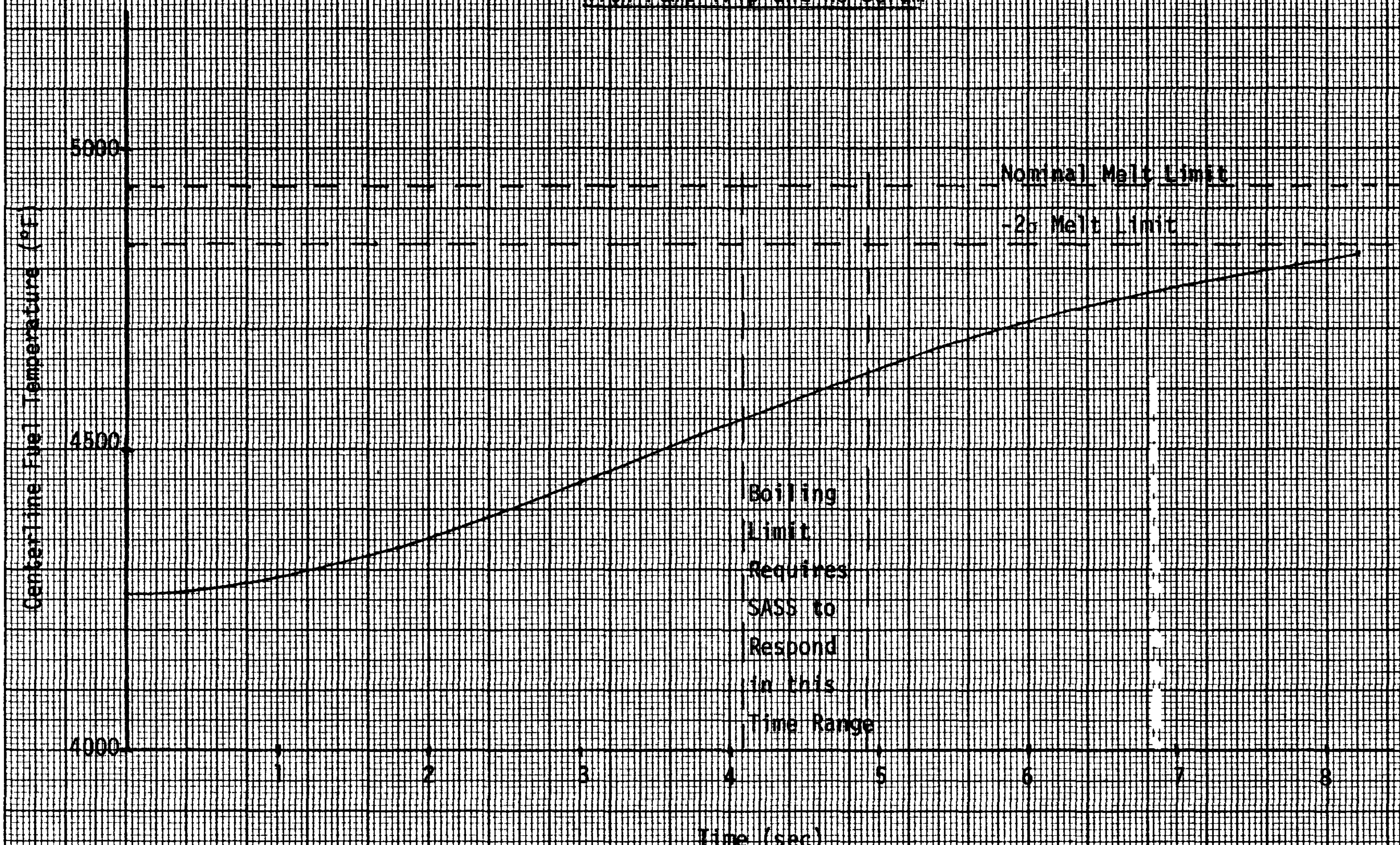
The SSE also has the potential for being either boiling or melt limited since the transient is a combination of an overpower and an undercooling event. The boiling limit for the SSE was described in Figure 6.5-1. Figure 6.5-6 shows, as determined by LIFE-4, that the nominal peak pin will probably not melt before the boiling limit would be imposed, but there is only a 60°F margin before the fuel melting limit is violated. If the SSE temperatures were constrained to be less than the -2σ melt limit, SASS would have to begin terminating the transient in approximately 2.4 seconds which would severely constrain the SASS designer's options.

The 40% overpower limit was not applied in the SSE analysis, because in the SSE the rods are uniformly withdrawn from the core due to the seismic axial acceleration. Rocking effects could give local reactivity effects; however, further seismic analysis needs to be done to determine this magnitude. The power shape effect also does not apply to the stick-slip reactivity, which is probably a uniform radial compaction causing a core wide reactivity increase.

Given the above reasoning, it is concluded that the SSE is currently predicted to be boiling limited and not fuel melt limited, but there is little margin to account for uncertainties in the pin thermal analysis. Refinement of fuel thermal properties describing irradiated fuel could change the SSE into a fuel-melt-limited event. For example, a 2% decrease in the radial average fuel thermal conductivity would cause fuel melting to be predicted at approximately 2.8 seconds. Therefore, it would be prudent for the SASS designer to investigate flux-related actuation devices and trip settings. An alternative to the flux trip would be a seismic trip from the vessel head vertical or horizontal accelerations. A seismic actuator would also provide protection for the case of no flow coastdown associated with the SSE which would be melt limited rather than boiling limited as well as the case when no reactivity or flow coastdown occurs.

Figure 6.5-5

Nominal Peak Pin Fuel Centerline Temperature for the 6¢/sec TOP Event With Pump Trip and No Scram



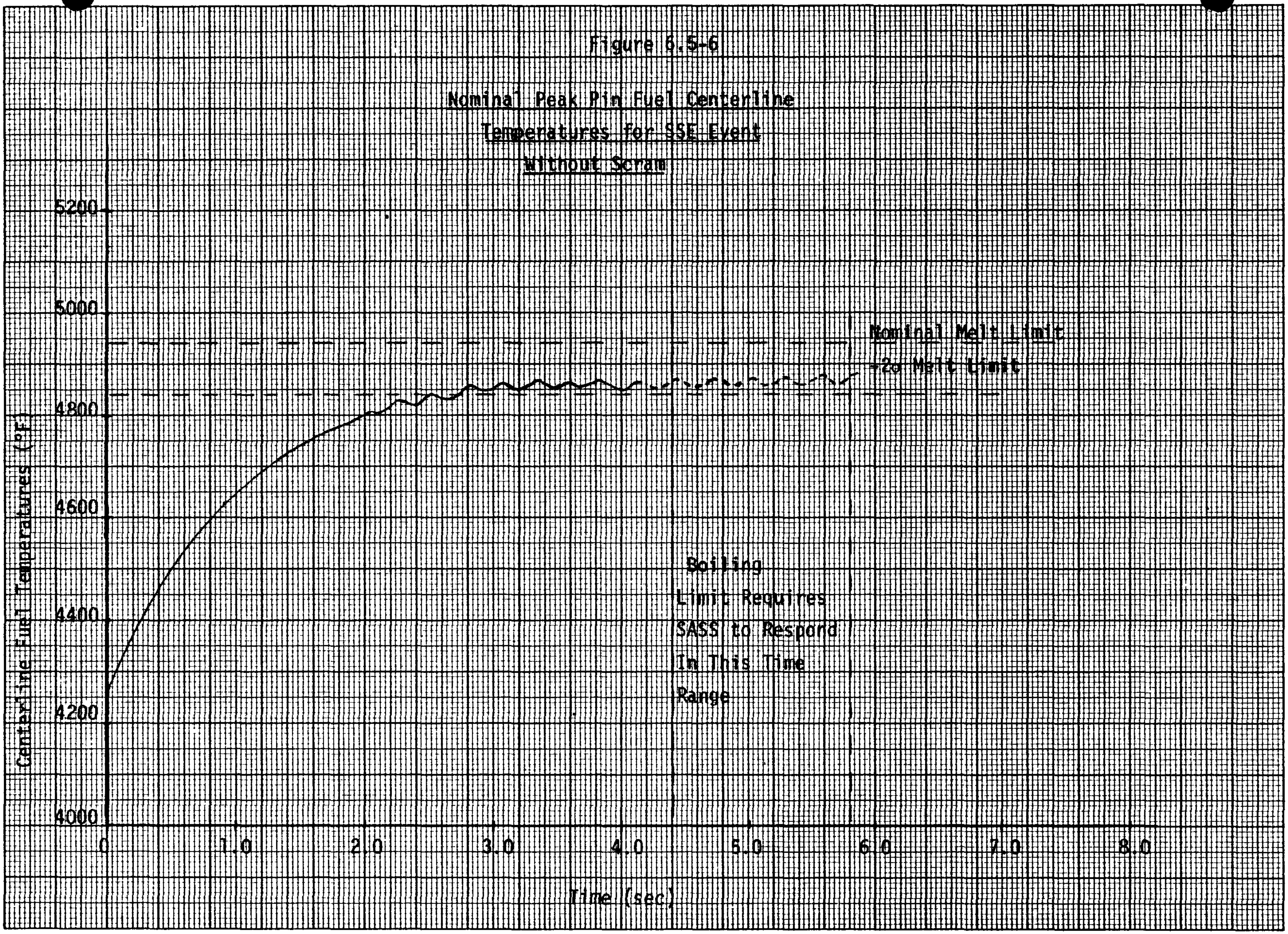


Figure 6.5-6
Nominal Peak Pin Fuel Centerline
Temperatures for SSE Event
Without Scram
Centerline Fuel Temperatures (°F)
5200
5000
4800
4600
4400
4200
4000
Nominal Melt Limit
+2σ Melt Limit
Boiling
Limit Requires
SASS to Respond
In This Time
Range
0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
Time (sec)

7.0 CONCLUSIONS

LOA-2 success, defined as limit core damage and maintain coolable geometry, has been translated into specific requirements which are independent of the core design. These requirements, in turn, have been used to define core-wide design criteria which limit core thermal and mechanical conditions such that LOA-2 success is assured with high confidence. To simplify the design process, the whole-core design criteria were replaced by a set of point or single-pin/sub-channel criteria. The adequacy of the single-pin/sub-channel criteria was demonstrated by applying them to the LDP core.

The impact of the recommended design criteria on SASS performance requirements for the scram parameters such as sensor delay time, latch actuation time, and rod insertion time was assessed. This analysis indicates that the design criteria impose reasonable requirements on SASS design. Assuming a SASS scram insertion time of 2 seconds and a $3 scram worth, the allowable detection time plus delay time for each of the selected design basis transients is as follows:

	Allowable Detection + Delay Time (Sec)	Limiting Point Criteria
Flow Coastdown (FCD)	7.7	Na Boiling
.76¢/sec TOP (no FCD at 15% Overpower)	78.0	Fuel Melting (40% overpower)
.76¢/sec TOP (with FCD at 15% Overpower)	35.5	Na Boiling
6.1¢/sec TOP (no FCD at 15% Overpower)	6.8	Fuel Melting (40% overpower)
6.1¢/sec TOP (with FCD at 15% Overpower)	6.3	Na Boiling
SSE + FCD	5.2	Na Boiling

The following conclusions may be drawn from the CDS Phase II core analysis when the recommended point SASS design criteria are applied:

a. The SSE event imposes requirements on SASS response time and sensor capabilities that are more limiting than those imposed by the other selected design events analyzed. Required detection plus delay times are shorter for the SSE (Figure

6.5-1) and fuel temperatures approach the melting point several seconds before coolant boiling occurs (Figure 6.5-6) although no nominal melting is predicted.

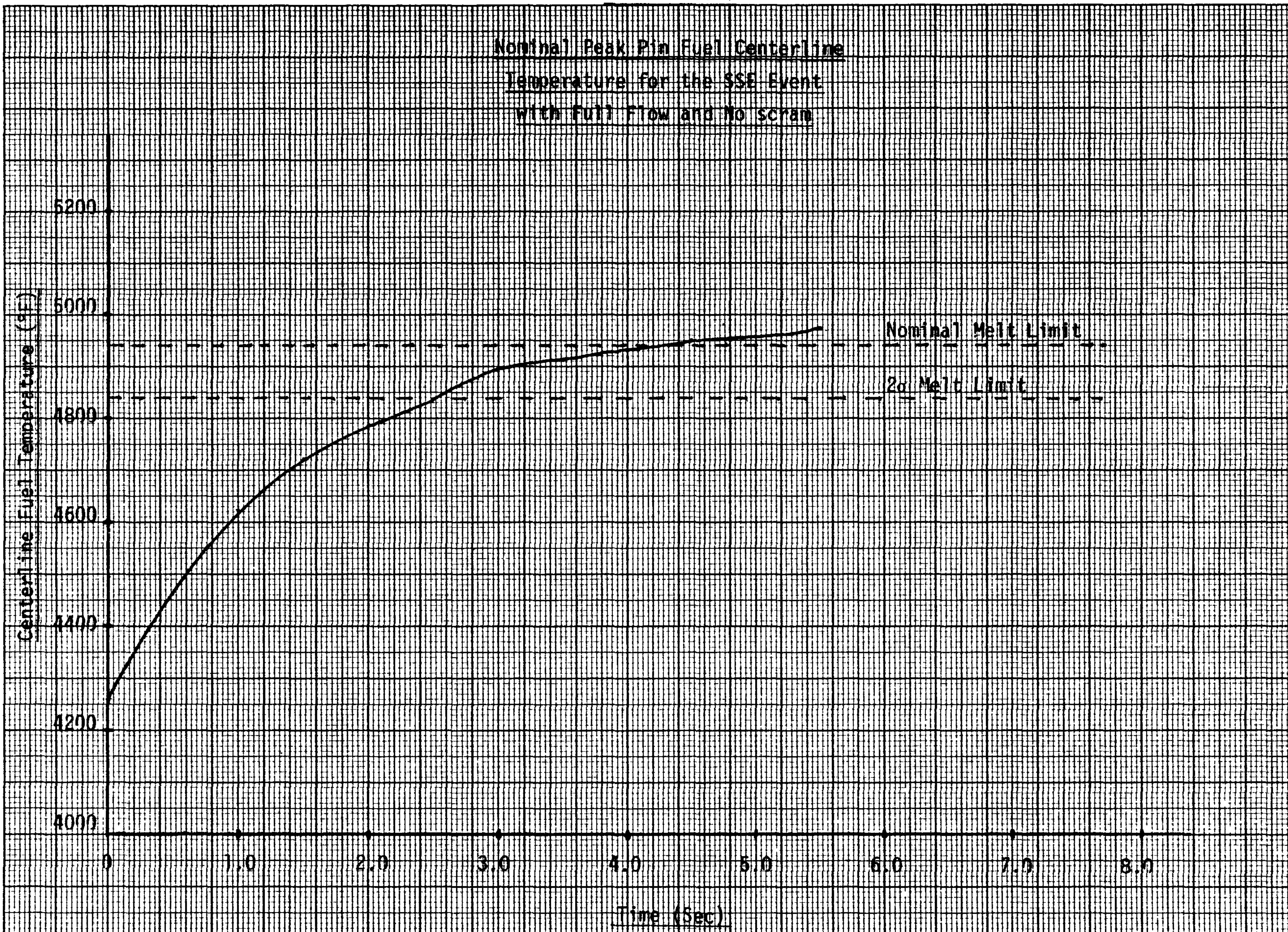
b. Required SASS response times for the SSE event are established in the current analysis by the point design requirement that no coolant boiling should occur. However, the fuel melting criterion is very close to being violated (Figure 6.5-6). Therefore, it is recommended that SASS designers consider faster response variables for the SSE such as flux-related sensors and trip settings and seismic acceleration sensors. The need for these is also apparent in the analysis of the TOP event without pump trip.

c. The SSE was assummed to produce a flow coastdown (FCD) and a reactivity insertion. However, the SSE could occur and induce neither of these driving functions or it could cause one or the other. The FCD portion of the SSE is covered by the design basis transients selected; however, the reactivity-driven TOP without a FCD is a part of the SSE not covered by the selected design basis event list. This event is estimated to be fuel melt limited in approximately 4.2 seconds as shown in Figure 7.0-1 which is even more limiting than with the FCD event. The SSE without the FCD should be incorporated as part of the design basis transient list for SASS.

d. The shortest detection plus delay time requirement imposed by an event other than the SSE is imposed on SASS by the TOP event with pump trip (Figure 6.5-2 vs Figures 6.5-1 and 6.5-4). The limiting point criteria for this event is no coolant boiling (Figure 6.5-5).

e. The maximum allowable detection plus delay time for the flow coastdown event is approximately 0.9 seconds longer than for the TOP event with pump trip (Figure 6.5-1 vs Figure 6.5-2).

FIGURE 7.0-1


Nominal Peak Pin Fuel Centerline
Temperature for the SSE Event
With Full Flow and No scram
Nominal Melt Limit
2σ Melt Limit
5200
5000
4800
4600
4400
4200
4000
Centerline Fuel Temperature (°F)
0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
Time (Sec)

REFERENCES

1.1-1 LMFBR Safety Program Plan, U.S. Department of Energy, Office of Reactor Research and Technology, August 1980.

1.1-2 Letter no. XL-898-90735/P2777, T. R. Sandke to S. G. Harbison, "Functional and Design Requirements for a Self-Actuated Shutdown System (SASS)," October 1, 1979.

1.2-1 "CRBRP Equipment Specification - Secondary Control Assembly," GE-ARSD Spec. #23A3952, Revision 13, Sheets 44 and 45.

2.1-1 "Risk Analysis methods Development, Thirteenth Quarterly Report, April-June, 1980," GEFR-14023-13 (July 1980).

2.1-2 Nuclear Regulatory Commission, Reactor Safety Study: An Assessment of Accident Risks in U. S. Commercial Nuclear Power Plants, NRC Report WASH-1400 (NUREG-75/014), NTIS, October 1975.

5.2-1 CRBRP-PSAR, Chapter 15, Section 15.2.1.1.1, pg. 15.2-5.

5.2-2 L. B. Levitt, et. al., "Liquid Metal Fast Breeder Reactor Conceptual Design Study - Ground Rules and Criteria for Task 1.0 - Proliferation Resistant Fuel Cycle," FBR-79-2 (79ESG-11325), November 21, 1979.

5.4-1 CRBRP-PSAR, Chapter 15, Section 15.2.2.3.1, pg. 15.2-48.

5.5-1 PLBR Phase II Extension Studies, Part II: Reactor Assembly," (GEFR-00260), September 1977, pg. 15.

6.2-1 J. N. Fox, T. R. Yackle, P. J. Fulford, CORTAC - A Core Restraint Transient Analysis Code: User's Manual," GEAP-14115 (August 1976); an updated for heterogeneous cores.

6.2-2 F. E. Drumm, et al., "The SAS2A LMFBR Accident-Analysis Computer Code," ANL-8138 (October 1974); updated SAS-3D version.

6.5-1 P. T. Choong and N. A. Deane, "CDS Task 1.3 - Core Configuration Trade-Off Study," (XL-153-00469) September 1980.

6.5-2 N. A. Deane, Y. S. Lu, R. J. McCandless, "Inherently Safe Core Design Concept Evaluation Summary and Design Requirements for Fiscal Years 1975 and 1976 (GEAP-14143) October 1976, pg. 153.

MAJOR CONTRIBUTORS

C. Alexander
S. L. Beaman
W. A. Brummond
L. B. Defensor
I. de la Fuente
E. L. Gluekler
K. E. Gregoire
E. Kujawski
J. T. Tatsumi

APPENDIX A

PRELIMINARY DEFINITIONS OF LOA-2 RELIABILITY GOAL, LOA-2 SUCCESS, AND LIMITED CORE DAMAGE

It would be desirable to use risk limits for light water reactors directly as a basis for defining LOA-2 success and for establishing SASS functional requirements. Clearly, it is unacceptable to adopt higher risk limits than the light water values in most categories. However, it may be consistent with the present risk assessment approach for LMFBR's reasonable to accept an equal risk of property damage, expecially in the range of small property damage. Therefore, the proposed definition of the top-level function of the SASS could be:

> Limit the expected-value risks of damage to the public to be $\leq$ the risks associated with light water reactors(e.g., the values in WASH-1400).

This statement is shown in Table 2.2-1 as the top-level goal to be met in order to assure safe accident termination within LOA-2. While the function statement suggested above clarifies the meaning of "LOS-2 success' and 'limit core damage' to some extent, it does not refer to LOA-2 specifically. Instead, a limit is placed upon the integral effect of all four lines of assurance such that a range of conditions could all correspond to LOA-2 success, depending upon the definitions of LOA's 1, 3, and 4 and the failure probabilities of these LOA's. While this situation is realistic and reflects accurately the fundamental concerns associated with LMFBR safety, it is difficult for the SASS designer to interpret and apply. There is no specification in the adopted function statement concerning the risk to the public associated with LOA-2 failure and success. The function statement specifies the probability of LOA-2 success (subject to allocation of risks between the lines of assurance, as discussed above), but it does not limit the damage to public health or safety associated with that success. Instead, it only limits the total damage to public health and safety associated with both LOA-2 success and LOA-2 failure. An additional condition is necessary (see Equations (A-2) through (A-3) below).

The methodology required to translate the proposed probabilistic function statement into practical design goals has been the subject of intensive development at General Electric since 1974. A recent GE Risk Assessment Study[2.1-1] of the CDS Phase II design assigned reliability goals (i.e., allocated risks) among the various CDS engineered systems in an economically optimum fashion. Using this set of goal values, it was assumed that all design reliability goals would be met and the risks of damage to the public resulting from CDS operation were evaluated. Comparing these calculated risks with the limiting LWR curves indicated that CDS risks would be generally one to two orders of magnitude below the limits. This study assumed no SASS was present in CDS, and LOA-2 was assumed to have a probability of failure of 20% to 80% per LOA-1 failure, depending upon the initiating event. Even with these conservatively high probabilities of LOA-2 failure, it is encouraging that the overall risk goals were met. When a SASS system was assumed to be included in the CDS design, the overall risks were reduced by a factor of 3 to 5, depending upon other features such as containment building design and vessel liner design. The probability of LOA-2 failure was reduced to approximately 4% to 20% when a SASS was assumed to be present.

To summarize the preceding discussion, it appears to be both necessary and feasible to define LOA-2 success and the top-level SASS function in terms of overall plant safety. An accepted approach to defining plant safety appears to be in place based on the risks associated with light water reactors. It is proposed that this approach be adopted as a basis for establishing functional requirements for LOA-2 engineered safety systems such as the SASS. Since the LOA-2 reliability goal is dependent upon plant design and the designs of other safety-related systems, it does not appear to be desirable to establish numerical values for SASS functional requirements without reference to the plant in which the SASS is to operate. Therefore, functional requirements defined in this document leave probability values to be determined (TBD) in order to make the stated requirements plant-independent. This is intended to indicate that risk allocation analyses are to be performed as part of the process of deriving specific SASS design criteria from the functional requirements presented here.

Top-Level Definition of "LOA-2 Success" and "Limited Core Damage"

Having defined the overall safety goal and the allowable probability of LOA-2 failure (or the methodology to be used to determine this probability), one must define the damage to public health and safety that can be allowed while claiming LOA-2 success. This, in turn, allows one to define "limited core damage." It is clear from the literature that LOA-2 success can be claimed only if damage to public health and safety is negligible. It is convenient to discuss the meaning of this limitation in connection with the following relationship describing the risk of observing damage to the public that is $\geq$ x:

$$P(x) = P(x/LOA2FAIL)*P(LOA2FAIL)+P(x/\overline{LOA2FAIL})*[1.0-P(LOA2FAIL)] \quad \text{(A-1)}$$

where

$P(x)$ = probability of observing damage to the public that is $\geq$ x, given failure of LOA-1.

$P(x/LOA2FAIL)$ = probability of observing damage to the public that is $\geq$ x, given failure of LOA-2.

$P(x/\overline{LOA2FAIL})$ = probability of observing damage to the public that is $\geq$ x, given LOA-2 success

$P(LOA2FAIL)$ = probability of LOA-2 failure

Note that $P(x/\overline{LOA2FAIL})$, the probability of observing damage to the public given LOA-2 success, is usually assumed to be negligible. This assumption is reasonable in most contexts, because LOA-2 success is defined in such a way that damage to the public is extremely unlikely if an accident is terminated within LOA-2. In the present discussion, the term involving

$P(x/\overline{LOA2FAIL})$ is also expected to be small, but is preserved in Equation (A-1) to facilitate the definition of LOA-2 success. Because the magnitude of $P(x/\overline{LOA2FAIL})$ depends in a sensitive manner on the definition of LOA-2 success, and vice versa, the primary objective here is to derive a reasonable limit for $P(x/\overline{LOA2FAIL})$, and a definition of LOA-2 success that is consistent with this.

The definition of $P(x/\overline{LOA2FAIL})$, as it is used here, deserves additional discussion, since the "probability of damage to the public given LOA-2 success" seems self-contradictory. Starting immediately after failure of LOA-1, and lasting until shortly before the time the accident is terminated within LOA-2, the probability of damage to the public increases as reactor operating conditions become more severe and/or core component failures occur. Depending upon the manner in which LOA-2 success is achieved (i.e., the engineered system(s) or inherent process(es) that terminate the accident sequence), the probability of damage to the public will increase sharply at the point in time when these systems or processes establish themselves as dominant factors. Therefore, given that LOA-2 success has occurred or will occur, one can define two (at least) values of $P(x/\overline{LOA2FAIL})$. These two values correspond to two different points in time: 1) the time during an accident sequence that will terminate within LOA-2 at which core conditions (e.g., coolant temperatures of fuel temperatures) are most likely to cause damage to the public, and 2) the time at which an accident sequence has already terminated within LOA-2. At this second point in time, the risk of damage to the public is very small, because core operating conditions are (presumably) no more severe than normal operating conditions. The meaning of $P(x/\overline{LOA2FAIL})$ in this document is the first situation described above. There is a risk of damage to the public caused by the challenge to the pressure vessel containment capability represented by environmental conditions acting just before accident termination within LOA-2. This challenge does not assume or depend upon accident propagation past LOA-2. The non-zero probability of damage to the public simply recognizes that any pressure and temperature acting on the pressure vessel could produce leakage into the containment building and beyond, whether or not "LOA-2 success" is achieved by limiting damage to a few fuel assemblies, etc.

The working definition of LOA-2 success proposed here is intended to specify a limiting set of core operating conditions and geometry beyond which uncertainty in the accident path increases sharply because of material motion, reactivity changes, abnormal coolant behavior, etc. This increase in uncertainty in the path of the accident sequence is believed to be more fundamental to the intent of LOA-2 than other characteristics (such as limited core involvement) which have been used to indicate LOA-2 success. This increase in uncertainty regarding the accident path is also directly related to the estimated probability of damage to the public, since the number of possible paths leading to damage to the public proliferates. Note also that the phenomena which lead to uncertainty in the accident path also lead to an increased probability of damage to the public, since they are associated with material phase changes, reactivity insertion, and significant changes in geometry.

Based on the preceding discussion, LOA-2 success is defined such that there is little difference in risk to the public, given LOA-1 has failed, if the accident terminates within LOA-2. The increase in risk to the public is much greater, given LOA-1 has failed, if LOA-2 also fails. We write this as

$$P(x/\overline{LOA2FAIL})P(\overline{LOA2FAIL})-P(x/LOA1FAIL)P(LOA1FAIL) \ll$$
$$P(x/LOA3FAIL)*P(LOA3FAIL)-P(x/LOA1FAIL)P(LOA1FAIL) \qquad (A-2)$$

or

(Risk of Damage $\geq$ x, given entry into LOA-3)-(Risk of Damage $\geq$ x, given entry into LOA-2)<<(Risk of Damage $\geq$ x given entry into LOA-4)-(Risk of Damage $\geq$ x, given entry into LOA-2).

The process of defining LOA-2 success can be viewed as moving the risk boundary between LOA-2 and LOA-3 without changing the LOA-1/LOA-2 boundary or the LOA-3/LOA-4 boundary. If the latter two boundaries are not changed, this means that the right-hand side of Equation (A-2) is a constant. Using this boundary condition in Equation (A-2) and defining a "safety factor" (F) yields

$$P(x/\overline{LOA2FAIL})P(\overline{LOA2FAIL})-P(x/LOA1FAIL)P(LOA1FAIL)<F*C \qquad \text{(A-3)}$$

Since we are given that P(LOA1FAIL) = 1.0, using Equation (A-1), and recognizing that P(x) in Equation (A-1) is equal to P(x/LOA1FAIL), inequality (A-3) reduces to

$$P(x/\overline{LOA2FAIL})P(\overline{LOA2FAIL})<*C \qquad \text{(A-3a)}$$

where

$P(x/\overline{LOA2FAIL})$ - probability of damage $\geq$ x to the public, given that LOA -2 success will occur, where the probability is evaluated using the worst environmental conditions occurring prior to accident termination.

$P(\overline{LOA2FAIL})$ = probability of LOA2 success.

F - A safety factor selected to assure that the left-hand side of Equation (A-2) is as small as desired ralative to the right-hand side.

C = the righthand side of Equation (A-2).

In Inequality (A-3a), the required probability of LOA-2 success is determined by the Risk Allocation analysis mentioned in the previous subsection. The total of the risks allocated to LOA-2 and LOA-3 are then fixed. Given this constraint, the division of risks between LOA-2 and LOA-3 is determined by Inequality (A-3a) such that uncertainty concerning the progression of events within LOA-2 is minimized in a cost-efficient manner. In addition, Inequality (A-3a) limits damage to the public that can be associated with any reasonable definition of LOA-2 success, as is required by current understanding of the LOA-2 concept.

An interesting feature of Inequality (A-3a) is that the limiting value of $P(x/\overline{LOA2FAIL})$ depends upon the expected risk of damage to the public for the particular plant being considered. This in turn, depends upon a number of plant design variables and the reliabilities of safety-related systems. Since $P(x/\overline{LOA2FAIL})$ is the key parameter which defines the amount of core damage that is allowable for LOA-2 success, this dependence on the plant design is of particular significance. Depending on plant design and the reliability of safety systems, allowable core damage for LOA-2 success can vary from 0.0 to relatively large values while satisfying Inequality (A-3a) and the top-level risk goals. Thus, within limits, one has the choice of relaxing core damage limits, relaxing reliability targets for various safety-related systems, eliminating some safety related systems, or maintaining a large difference between the risk associated with LOA-2 success and that associated with entry into LOA-3. The optimum combination of these options is neither clear nor simple to determine, and a disciplined cost-benefit analysis is recommended.

In the preceding paragraphs, it has been assumed that $P(x/\overline{LOA2FAIL})$ can somehow be limited by limiting "core damage." In the interests of defining "core damage" clearly, closer examination of this assumption is warranted. Since the intent of limiting $P(x/\overline{LOA2FAIL})$ is to limit the spread of contamination from the reactor core to beyond the site boundary, it is useful from an engineering point of view to consider the physical barriers that prevent the spread of contamination. The integrity of the first barrier, the fuel pin cladding, is extremely difficult to guarantee under the severe operating conditions that must be considered in the safety and licensing process. However, partial credit can be taken for the barrier provided by the fuel pin cladding, because cladding integrity is likely to be preserved in a significant fraction of the fuel pins in the core.

The next significant physical barrier to the spread of contamination is the pressure vessel. This barrier is followed by the containment building and the site location. The term "limit core damage" is one way of expressing the desire to limit the spread of contamination through the combined action of the first two physical barriers; integrity of the cladding in a portion of the core and integrity of the pressure vessel and its seals.

Since complete integrity of the cladding cannot be guaranteed, it appears most useful to focus upon pressure vessel integrity, and to define "core damage" such that vessel resistance to leakage is maintained.

The intent of the LOA-2 concept is to provide a high level of confidence that, if an accident is initiated, it will not propagate from an event involving loss of component structural integrity, material phase changes, or abnormal material motion in a few fuel or blanket assemblies to involvement of the whole core in such phenomena. This, in turn, is intended to limit the energy content of the core to low enough levels that pressure vessel ability to contain radioactive material is preserved with high reliability.

In order to meet the intent of LOA-2 with the required high level of confidence, it is necessary to avoid two situations:

1. Significant insertion of reactivity via material motion or phase change, and

2. Core component geometries, or rates of change in geometry, that are so different from the normal envelope of conditions that they cannot be described with confidence using existing analytical or experimental methods.

Both of these situations lead to significant uncertainty in the subsequent course of events, which violates the requirement that a high level of confidence be maintained in the outcome of the accident. Item 1 produces whole-core involvement as well as significant uncertainty.

One, or both, of the above situations always occurs well before the integrity of the pressure vessel is seriously challenged, so it is the high confidence required in the outcome of the accident that provides a practical definition of "LOA-2 Success," rather than the severity of the challenge to the pressure vessel or vaporized material.

Clearly, only limited coolant vaporization is allowed by the limit on reactivity insertion and by the restriction on geometry changes, but stable coolant boiling is acceptable. Pinhole cladding failures are not limiting, but failures that could produce coolant expulsion or allow fuel-coolant interaction are unacceptable.

It appears that the term "limit core damage" is more accurately stated as "preserve original geometry." While the definition of LOA-2 success requires that material phase changes and structural failures be limited to a fraction of the core, this is an indirect byproduct of the limitations on geometry changes anywhere in the core. For example, all the fuel assemblies in a core could have identical levels of environmental conditions and component structural failures without violating the definition of LOA-2 success, as long as the geometry was not disrupted, reactivity changes were small, and the pressure vessel was not challenged. Therefore, "limit core damage" can be restated as:

> Limit the change in thermal and mechanical conditions within subassemblies to maintain high confidence in the physical phenomena occurring in those assemblies.