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Mitigation of BWR Core Thermal-Hydraulic Instabilities in ATWS

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MITIGATION OF BWR CORE THERMAL-HYDRAULIC INSTABILITIES IN ATWS

Prepared for the

BWR OWNERS' GROUP

By GE Nuclear Energy

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CONTENTS OF THIS REPORT

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ABSTRACT

Previous analyses of BWR core thermal-hydraulic stability in anticipated transients without scram have concluded that the unmitigated oscillations may become large and irregular. Consequences of these oscillations do not constitute a new or significantly increased risk to the health and safety of the public, but the potential for localized fuel damage cannot be precluded. Because of this potential, mitigative operator actions to minimize any risk due to the oscillations are both desirable and appropriate. The BWR Owners' Group has therefore undertaken an evaluation of potential mitigative actions that may be incorporated in the future into the Emergency Procedure Guidelines. These studies indicate that timely operator action to reduce reactor water level and inititate the standby liquid control system can significantly reduce the duration of the large irregular oscillations and thereby the potential for undesirable consequences.

1.0 INTRODUCTION

This report presents the results of a BWR Owners' Group (BWROG) sponsored evaluation of postulated anticipated transients without scram (ATWS) combined with thermal-hydraulic instability in a boiling water reactor (BWR). Previous BWROG core thermal-hydraulic stability evaluations relative to the ATWS Rule, 10CFR50.62, are documented in NEDO-32047, "ATWS Rule Issues Relative to BWR Core Thermal-Hydraulic Stability". The bases for the ATWS Rule are summarized in that report, and the underlying acceptance criteria are identified for comparison with the results of the ATWS/stability analyses. Those analyses demonstrate that the potential for core thermal-hydraulic oscillations during an ATWS event:

(1) is not expected to result in any significant core distortion (i.e., that would impede core cooling, prevent safe shutdown, or threaten primary system integrity),

(2) presents no additional threat to primary system integrity, containment, or long-term cooling, and

(3) does not significantly increase the radiological consequences, which remain within 10CFR100 limits.

In addition, it is noted that the modifications required by the ATWS Rule adequately perform their intended function whether or not oscillations are present. It is concluded in NEDO-32047 that the technical basis for the current ATWS Rule is entirely adequate, notwithstanding the possibility of core thermal-hydraulic oscillations.

The potential for instabilities in ATWS events must also, however, be considered from an operational perspective. The BWROG Emergency Procedure Guidelines (EPGs) include, as part of their basis, a provision that all mechanistically possible plant conditions for which generic operational guidance can be provided are addressed, irrespective of the probability of occurrence. This report documents the results of BWROG investigations into options for operator guidance to respond to conditions symptomatic of an ATWS event with oscillations. These evaluations conclude that specific operator actions can indeed both reduce the likelihood of large irregular oscillations during an ATWS event and mitigate the consequences of the oscillations. It is important to note that the timing of the operator actions used in the mitigation analyses was selected with the objective of demonstrating the effectiveness of these actions when taken, not in any attempt to prescribe the actual timing.

2.0 SUMMARY AND CONCLUSIONS

2.1 SUMMARY OF PREVIOUS EVALUATIONS

The BWROG ATWS/stability analyses documented in NEDO-32047 (Reference 1) provide a representative but reasonably bounding set of expected reactor system responses. These detailed analyses were performed for both BWR/5 and BWR/6 reactor systems, resulting in responses which are conservative relative to the BWR fleet. The turbine trip event with scram failure, which results in high reactor power at natural circulation and high core inlet subcooling, was identified as the limiting transient. Initial conditions for the transient simulations were realistic, but were selected so as to enhance the likelihood of obtaining large oscillations during the transient. Calculations were performed using the TRACG computer code.

Results of these analyses demonstrated that the core may experience three instability regimes during an ATWS event. Unless the initiating event is an instability, the system is initially damped. Following a core flow decrease or inlet subcooling increase, the system will tend to go to a limit cycle instability. With very high inlet subcoolings and axial power peaked low in the core, oscillations may become large and irregular. These large oscillations are essentially moderator density-induced reactivity excursions.

For the limit cycle oscillations and most large irregular oscillations, the clad can experience boiling transition, but does not undergo any significant temperature increase. For an occasional large pulse, the highest-powered locations within the highest-powered fuel bundles may fail to rewet and may heat up over several oscillation cycles. The most limiting case resulted in exceeding 1500 K in less than 0.5% of the core volume.

It is concluded in NEDO-32047 that the potential for localized fuel damage does not threaten core geometry, coolability, or safe shutdown. Primary system integrity, containment integrity, and long-term shutdown and cooling are not affected by oscillations in the core. The total radiological consequences of the ATWS with oscillations are comparable to the consequences used in the ATWS licensing basis and are a small fraction of the 10CFR100 release. The BWR system response to ATWS with oscillations is therefore acceptable relative to the ATWS Rule basis criteria.

2.2 MITIGATION STUDIES SUMMARY

In addition to the analyses that concluded that the system response to ATWS with instabilities is within the ATWS licensing basis, the BWROG has performed evaluations of enhanced operator action guidelines which may further reduce any risk due to oscillations during an ATWS event. These evaluations support the development and implementation of specific EPG actions to mitigate oscillations and augment understanding of the instability phenomena.

A large number of both automatic and operator actions were considered. Operator actions to inject boron and reduce reactor water level were selected as the best options for mitigating oscillations in ATWS events. Both actions would be taken in response to symptoms indicative of an ATWS event based on the current EPGs; any enhancement to mitigate oscillations would change the symptoms for taking action, not the actions themselves. Because both actions are in the current EPGs, operators are already trained on implementation.

Calculations of the system response with operator actions to reduce reactor water level were based on the BWR/5 turbine trip evaluations described in NEDO-32047. Manual feedwater runback was started two minutes after the turbine trip. Various reinjection strategies and control water levels were evaluated. In all cases, the oscillations were clearly mitigated during feedwater runback and level reduction. Any level reduction below the injection elevation reduces the magnitude of the oscillations by steam condensation on the incoming coolant, which reduces the core inlet subcooling.

Boron injection calculations were also based on the NEDO-32047 turbine trip evaluations. The soluble boron from the standby liquid control system (SLCS) was assumed to reach the reactor about two minutes after the turbine trip. The magnitude of the oscillations was reduced as the concentration of boron in the core increased, with no oscillations present after about six minutes of injection.

3.0 EVALUATION BASES

3.1 SEQUENCES OF EVENTS

As described in NEDO-32047, the system response to a turbine trip without scram will bound the response to all other initiating events with respect to core thermal-hydraulic oscillations. The event is initiated from rated core power at the minimum allowable core flow. Following the turbine trip, the recirculation pump trip results in core flow runback on a high rod line to high power at natural circulation. Because the turbine has tripped, steam is dumped from the turbine bypass to the main condenser, but there is no extraction steam for the feedwater heaters. This results in a long-term supply of cold feedwater which maximizes the core inlet subcooling.

Operator actions modeled in these analyses are intended to identify potential mitigation strategies, and not necessarily to define a precise success path. Based on a review of the existing operator action guidelines in the BWROG EPGs and on the NEDO-32047 ATWS/stability analyses, boron injection and reactor water level reduction were identified as the having the highest potential for mitigating oscillations while minimizing the impact on the operator's ability to respond to the ATWS event. For the purpose of these analyses, the operator is assumed to start boron injection following onset of oscillations greater than 25% peak-to-peak amplitude on the average power range monitors (APRMs). Level reduction is assumed to be initiated after it has been determined that the alternate rod insertion (ARI) function has failed. The event sequences are discussed in Tables 4.1 through 4.5 The assumptions should in no way be interpreted as requirements for or commitments to the assumed operator response times.

3.2 CALCULATIONAL BASES AND METHODOLOGY

The calculations of the system response to the turbine trip ATWS event have been performed using the TRACG computer code on the same basis as that described in NEDO-32047. The analytical bases are therefore consistent with those used in previous ATWS analyses. In general, all inputs represent expected operating conditions with selected conservative parameters. For ATWS/stability calculations, parameters known to have a significant impact on core and fuel channel stability are chosen so as to enhance the likelihood of oscillations.

4.0 RESULTS OF ANALYSES

Calculations of the reactor system ATWS/stability response with operator intervention were performed using TRACG by restarting from the BWR/5 turbine trip analysis described in Section 5.2 of NEDO-32047. The reactor system model used in the TRACG simulation is based on a 251-inch BWR/5 reactor vessel and internals. For evaluations of boron injection, the system configuration is consistent with the ATWS Rule boron injection requirements. The model is initialized at rated core power, the minimum licensed core flow in the extended operating domain, and rated feedwater temperature. A bottom-peaked axial power distribution is used, within the constraints of meeting the licensed thermal limits. The three-dimensional neutronics model is configured to simulate a core-wide oscillation using quarter-core symmetry. The initiating event is an inadvertent turbine trip with recirculation pump trip (the end-of-cycle RPT). Core power and core flow coast down to a relatively high power at natural circulation core flow. The feedwater/level controller maintains reactor water level by matching feedwater flow to vessel steam flow. Because there is no extraction steam to the feedwater heaters, feedwater temperature decreases over time to a minimum value defined by the condenser discharge temperature. This section of the report describes the calculated system response to specific operator actions.

4.1 RPV WATER LEVEL REDUCTION

4.1.1 Feedwater Flow Runback

The purpose of this calculation is to characterize the rate and timing of the downcomer water level reduction with no action to maintain level within a particular band. Results of this calculation are used to restart calculations with additional operator actions. The initial response to the turbine trip is identical to that discussed in Section 5.2 of NEDO-32047. As shown in Table 4-1 and Figure 4-1, oscillations begin within 40 seconds. The symptom for initiating operator action, determination that ARI has failed , is reached at about 60 seconds into the event. With a 60 second delay for operator action, feedwater flow starts to ramp down at 120 seconds and terminates completely at 135 seconds (Figure 4-2). Thereafter, the water level drops continuously in the downcomer, reaching the Level 2 set point at about 180 seconds(Figure 4-3). It is assumed that automatic high pressure emergency core cooling system (ECCS) actuation is inhibited, which allows the level to continue to drop. The downcomer water level drops to the top of active fuel (TAF) at about 216 seconds. Oscillation magnitudes start to decrease within 20 seconds of feedwater runback, and are significantly smaller during the level reduction than with level maintained at the normal level in the NEDO-32047 results.

4.1.2 Level Maintained 1.6 Meters below Feedwater Sparger Elevation

This calculation is the first of several which examine the effect of maintaining reactor water level near a particular set point following feedwater runback. The sequence of events is summarized in Table 4-2. Starting with the calculation described in Section 4.1.1, water level is reduced and maintained 1.6 meters below the feedwater sparger. Figures 4-4 through 4-6 illustrate the consequences of this strategy. Level reaches the feedwater sparger elevation at about 150 seconds, and falls to the control level at about 190 seconds. Level is maintained with feedwater flow. Oscillation magnitudes start to decrease within 20 seconds of feedwater runback, and are significantly smaller during the level reduction. Oscillations with level controlled 1.6 meters below the sparger resume a limit cycle characteristic of about 60% peak-to-peak, which is small relative to results without the level reduction. The period of oscillations is about 2.3 seconds.

4.1.3 Level Maintained at Top of Active Fuel

The second of the level reduction strategies maintains level near the top of active fuel. As shown in Table 4-3 and Figures 4-7 through 4-9, water level is reduced as in the previous cases, but feedwater flow is reinstated so as to maintain level near TAF. As in the base event with no reinjection, it is assumed that high pressure ECCS is inhibited from automatic actuation at Level 2. When the downcomer level drops to the proximity of TAF at about 210 seconds, feedwater flow is restored to 30% of the rated value, gradually decreased to 25%, and then held constant. This manual feedwater flow control maintains the water level at about TAF (6.0 meters above the bottom of downcomer). The core power oscillations assume a steady limit cycle of about 45% peak-to-peak with a 2.5 second period.

4.1.4 Level Maintained at Minimum Steam Cooling Level

The lowest level at which water level is expected to be maintained is the minimum steam cooling reactor water level (MSCRWL). As shown in Table 4-4 and Figures 4-10 through 4-12, the calculation is similar to the case with level maintained at TAF. When the downcomer level drops to the proximity of TAF at about 215 seconds, feedwater water flow is restored to 15% of the rated value, gradually increased to 20%, and then held constant. Water level is maintained near the MSCRWL, about 5.0 meters above the bottom of downcomer. The core power maintains a steady limit cycle oscillation of about 45% peak-to-peak with a period of approximately 3.0 seconds.

4.2 BORON INJECTION

As in the level reduction calculations, the initiating event is an inadvertent turbine trip with end-of-cycle RPT. Table 4-5 describes the resulting sequence of events. The turbine bypass opens, core power and core flow coast down to a relatively high power at natural circulation core flow. The feedwater/level controller is operating and maintains the reactor water level at the normal water level set point. Oscillations begin within 50 seconds of the turbine trip, and the amplitude of power oscillation reaches 25% at around 60 seconds. The operator is assumed to initiate the standby liquid control system (SLCS) following detection of oscillations. For this calculation, SLCS is activated 90 seconds after the initiating turbine trip. A 30 second transport delay from the boron storage tank to the injection location in the high pressure core spray line is assumed. With an additional 20 second transport delay through the HPCS line to the upper plenum, the sodium pentaborate solution reaches the reactor vessel about 140 seconds after the turbine trip.

Results of this simulation are shown in Figures 4-13 through 4-18. With low boron concentration in the core, the core power and flow oscillations during the first 240 seconds are similar to those shown in NEDO-32047. The oscillations start to subside at about 325 seconds, and the amplitude of power oscillations drop to around 60% at 400 seconds. Oscillations are negligible beyond 500 seconds, after about six minutes of boron injection to the vessel.

Table 4-1.
SEQUENCE OF EVENTS FOR TURBINE TRIP ATWS WITH RPV WATER LEVEL REDUCTION

Time (sec)	Event
0	Reactor operating at 100% Power, 75% core flow.
	Turbine trip.
	Recirculation pump trip.
60	Core power oscillations reach 25%.
120	Feedwater runback starts.
135	Feedwater flow at zero injection.
162	Downcomer water level drops to feedwater sparger elevation.
180	Water level at Level 2.
216	Water level reaches elevation of TAF.

Table 4-2.

SEQUENCE OF EVENTS FOR TURBINE TRIP ATWS WITH RPV WATER LEVEL MAINTAINED 1.6 METERS BELOW FEEDWATER SPARGER

Time (sec)	Event
0	Reactor operating at 100% Power, 75% core flow.
	Turbine trip.
	Recirculation pump trip.
60	Core power oscillations reach 25%.
120	Feedwater runback starts.
150	Downcomer water level drops to feedwater sparger elevation.
190	Feedwater flow maintaining level.

Table 4-3.

SEQUENCE OF EVENTS FOR TURBINE TRIP ATWS WITH RPV WATER LEVEL MAINTAINED AT TAF

Time (sec)	Event
0	Reactor operating at 100% Power, 75% core flow.
	Turbine trip.
	Recirculation pump trip.
60	Core power oscillations reach 25%.
120	Feedwater runback starts.
135	Feedwater flow at zero injection.
210	Feedwater flow increased to 30% over ten seconds.
240	Feedwater flow to 25%.
	Water level maintained at TAF.

Table 4-4.

SEQUENCE OF EVENTS FOR TURBINE TRIP ATWS WITH RPV WATER LEVEL MAINTAINED AT MSCRWL

Time (sec)	Event
0	Reactor operating at 100% Power, 75% core flow.
	Turbine trip.
	Recirculation pump trip.
60	Core power oscillations reach 25%.
120	Feedwater runback starts.
135	Feedwater flow at zero injection.
215	Feedwater flow increased to 15% over 10 seconds.
240	Feedwater flow to 20%.
	Water level maintained at MSCRWL.

Table 4-5.

SEQUENCE OF EVENTS FOR TURBINE TRIP ATWS WITH SOLUBLE BORON INJECTION

Time (sec)	Event
0	Reactor operating at 100% Power, 75% core flow.
	Turbine trip.
	Recirculation pump trip.
60	Core power oscillations reach 25%.
90	SLCS starts.
120	Boron solution reaches HPCS line.
140	Boron solution reaches upper plenum.
480	Power oscillations less than 5% peak-to-peak.

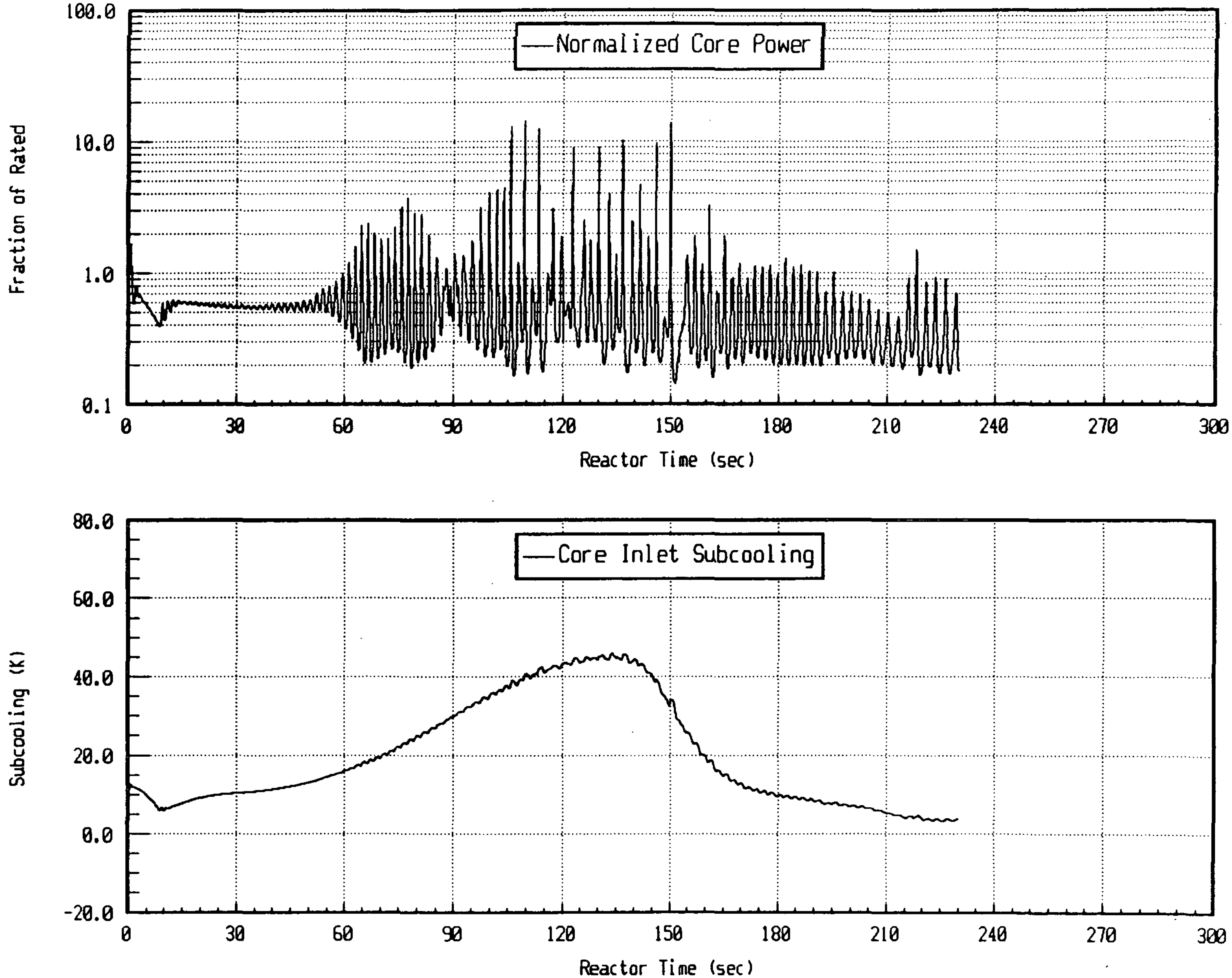

Figure 4-1. RPV Water Level Reduction – Core Power and Inlet Subcooling

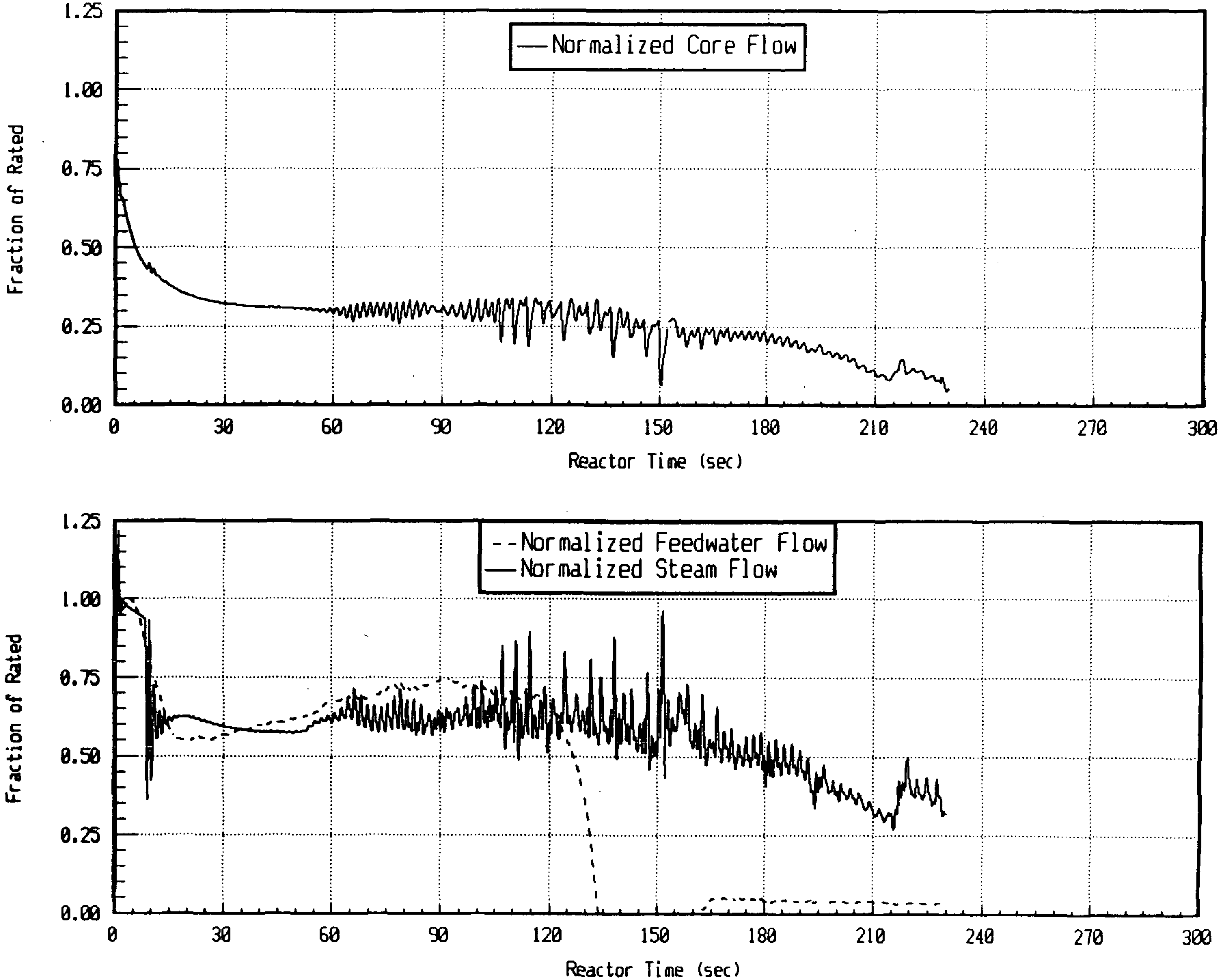

Figure 4-2. RPV Water Level Reduction – Core and Vessel Mass Flow Rates

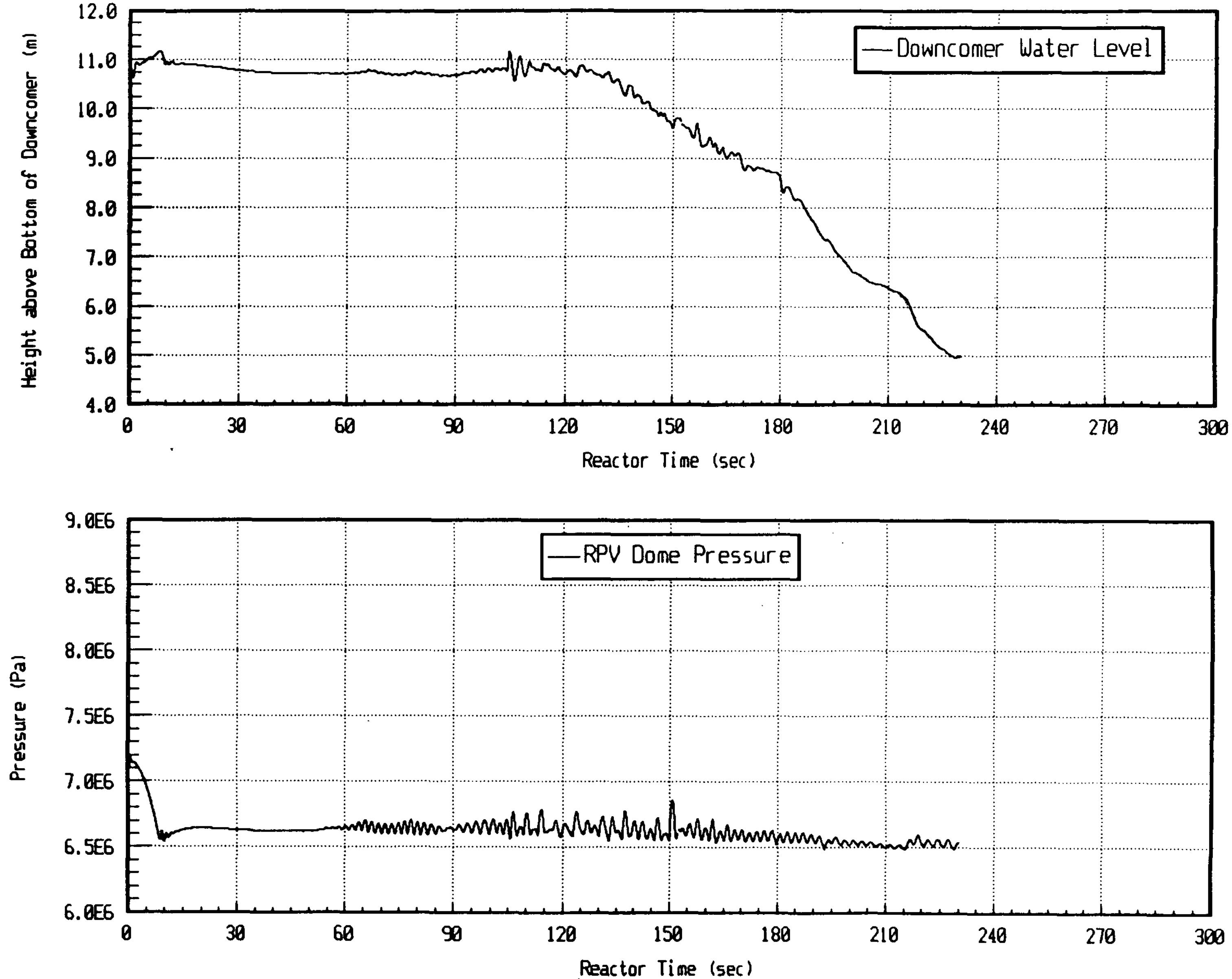

Figure 4-3. RPV Water Level Reduction – RPV Water Level and Dome Pressure

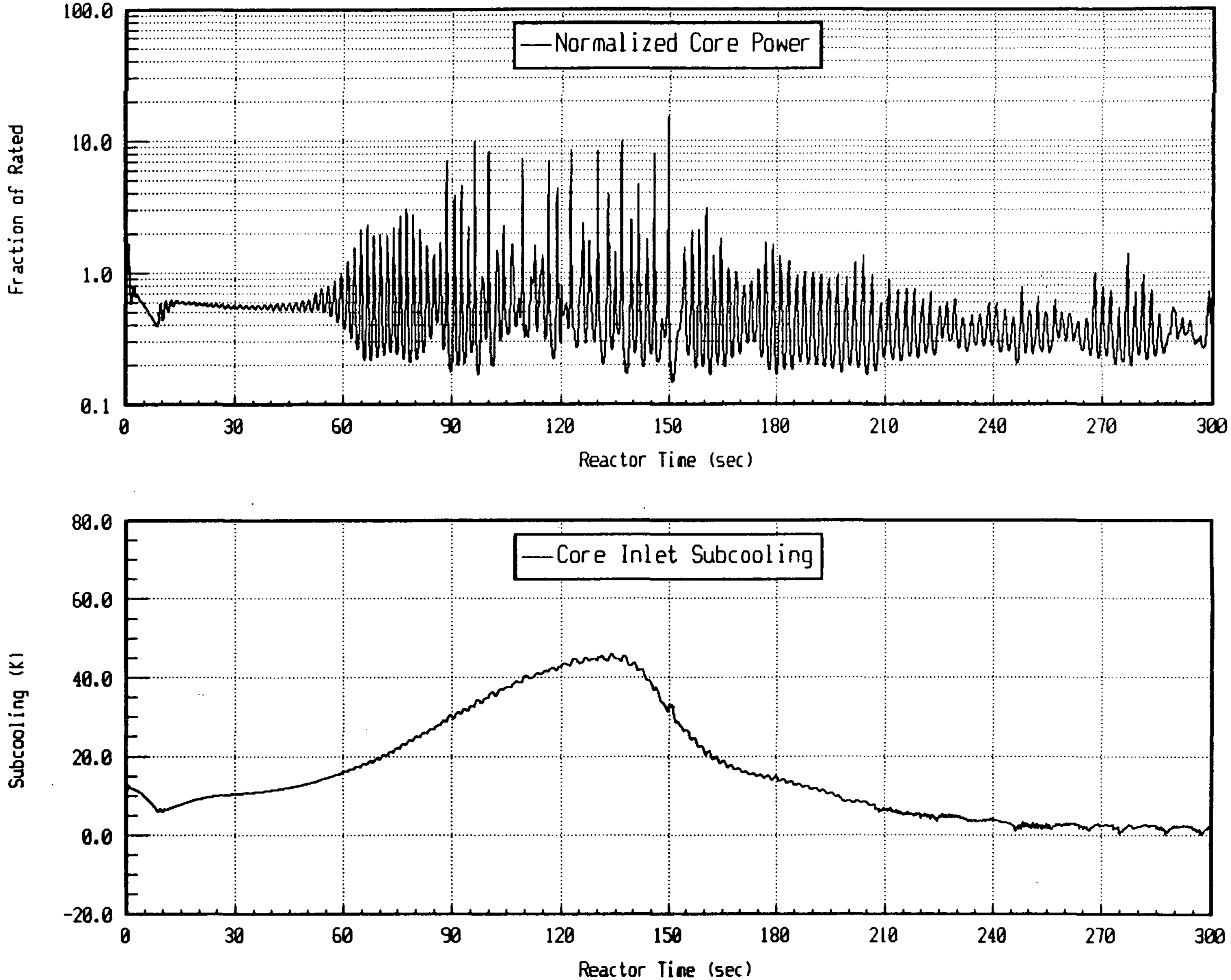

Figure 4-4. Level Control below Feedwater Sparger – Core Power and Inlet Subcooling

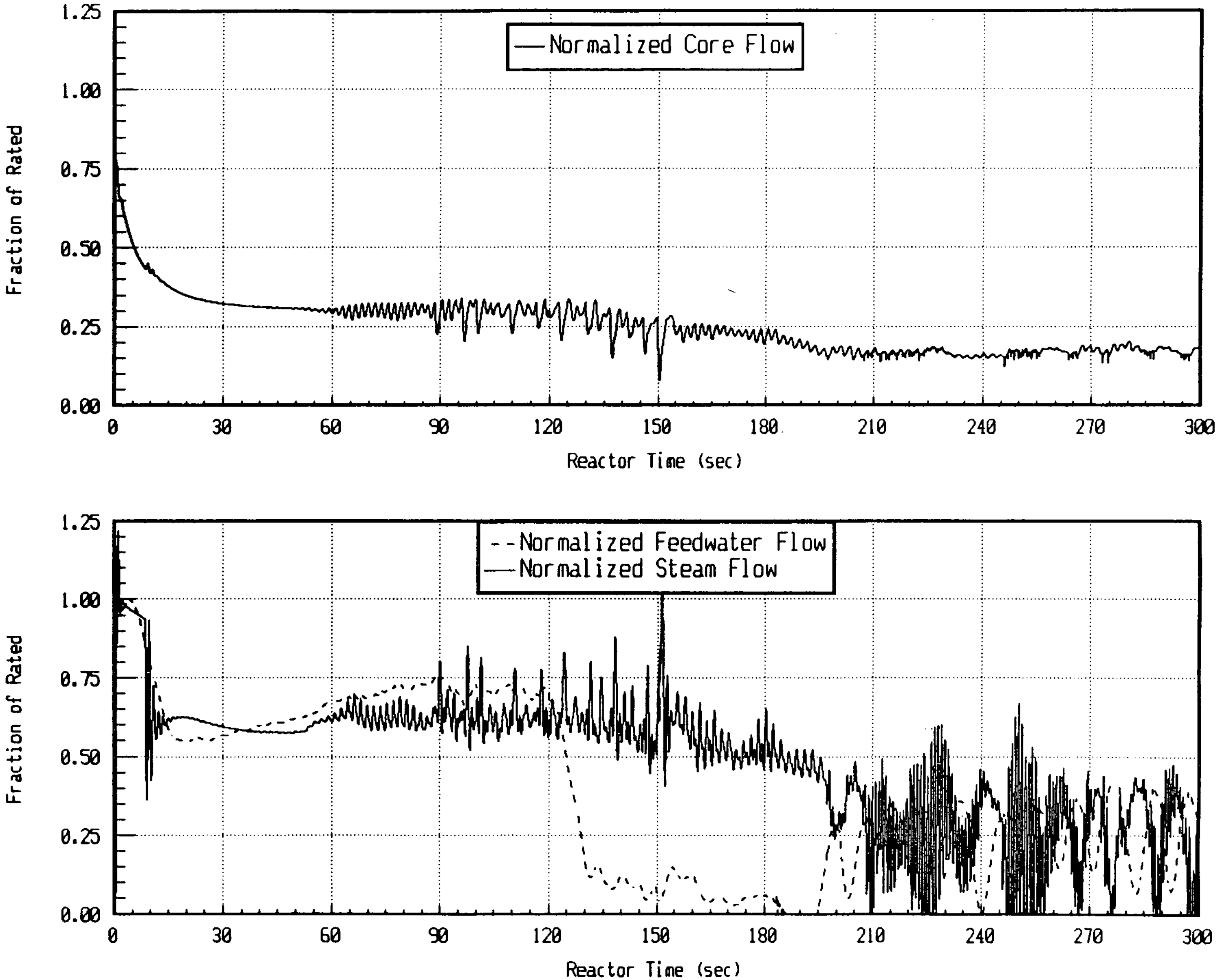

Figure 4-5. Level Control below Feedwater Sparger – Core and Vessel Mass Flow Rates

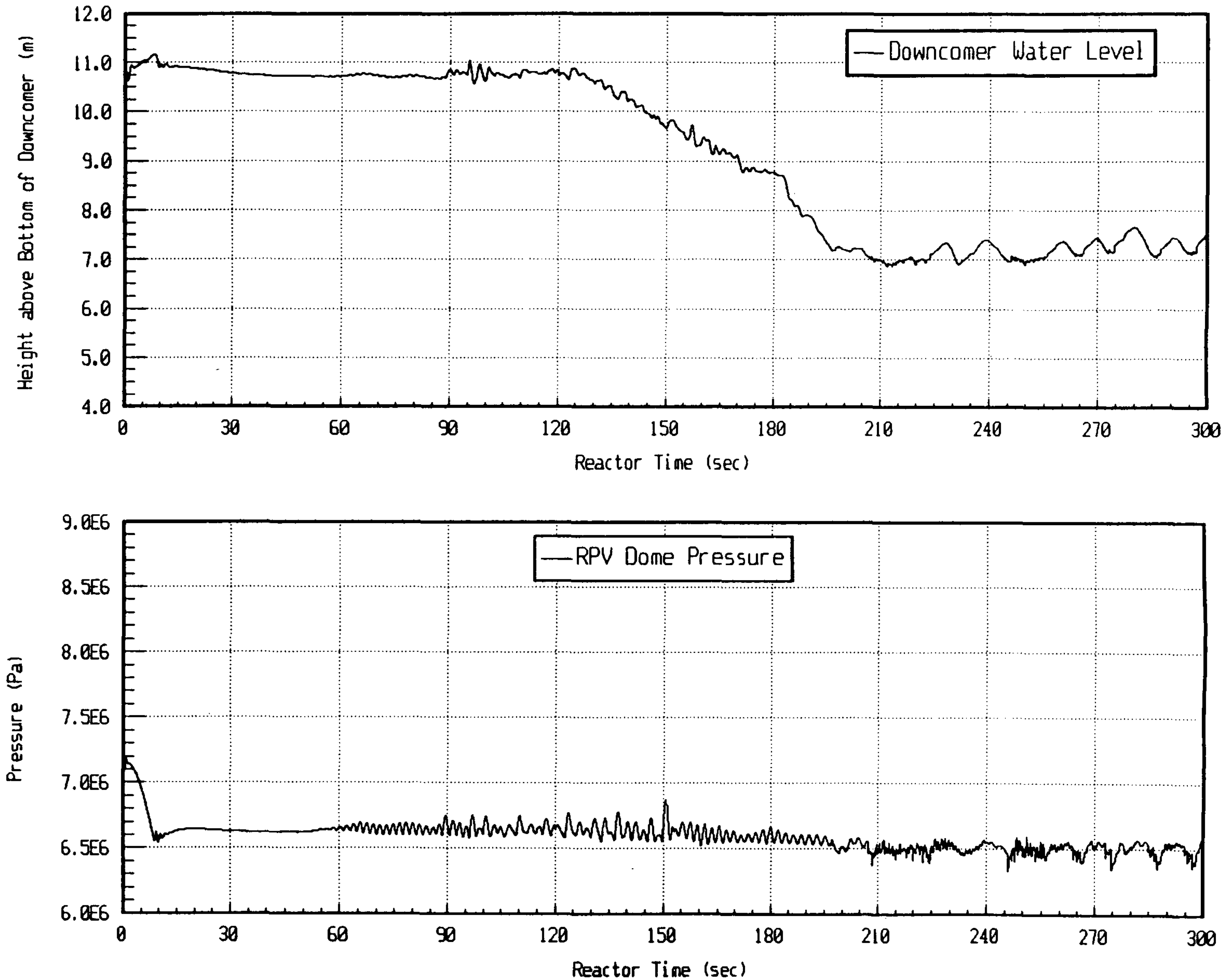

Figure 4-6. Level Control below Feedwater Sparger – RPV Water Level and Dome Pressure

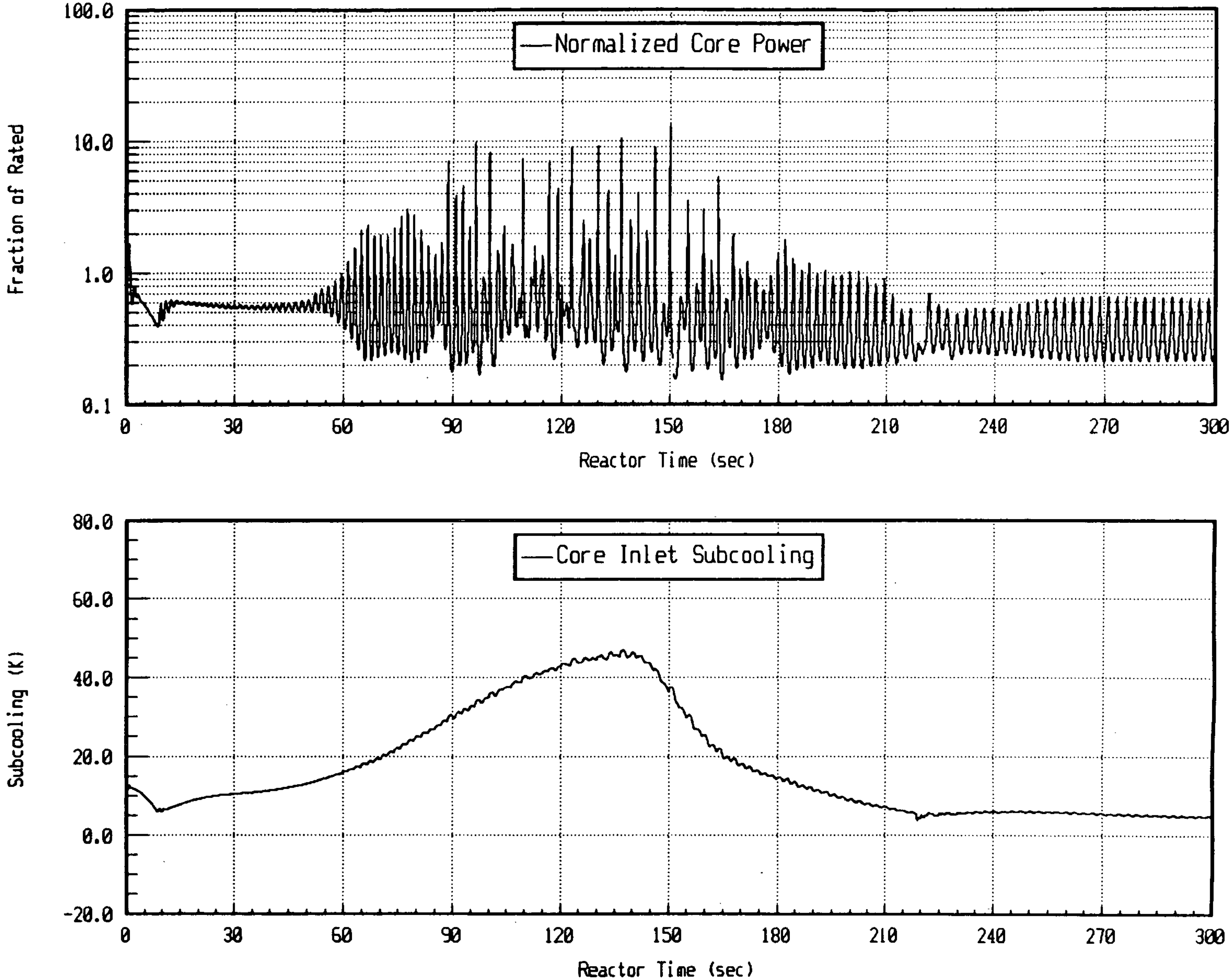

Figure 4-7. Level Control at TAF – Core Power and Inlet Subcooling

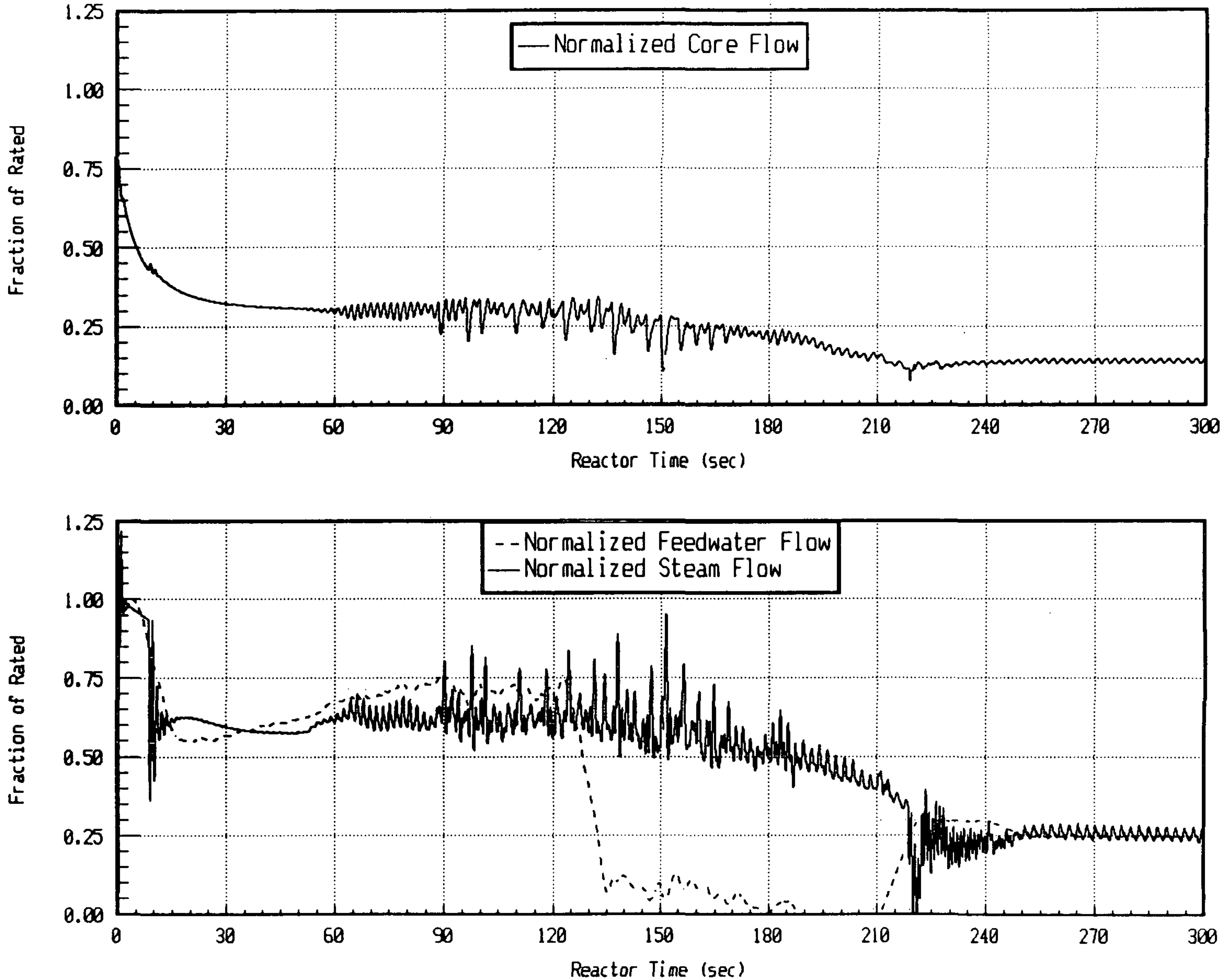

Figure 4-8. Level Control at TAF – Core and Vessel Mass Flow Rates

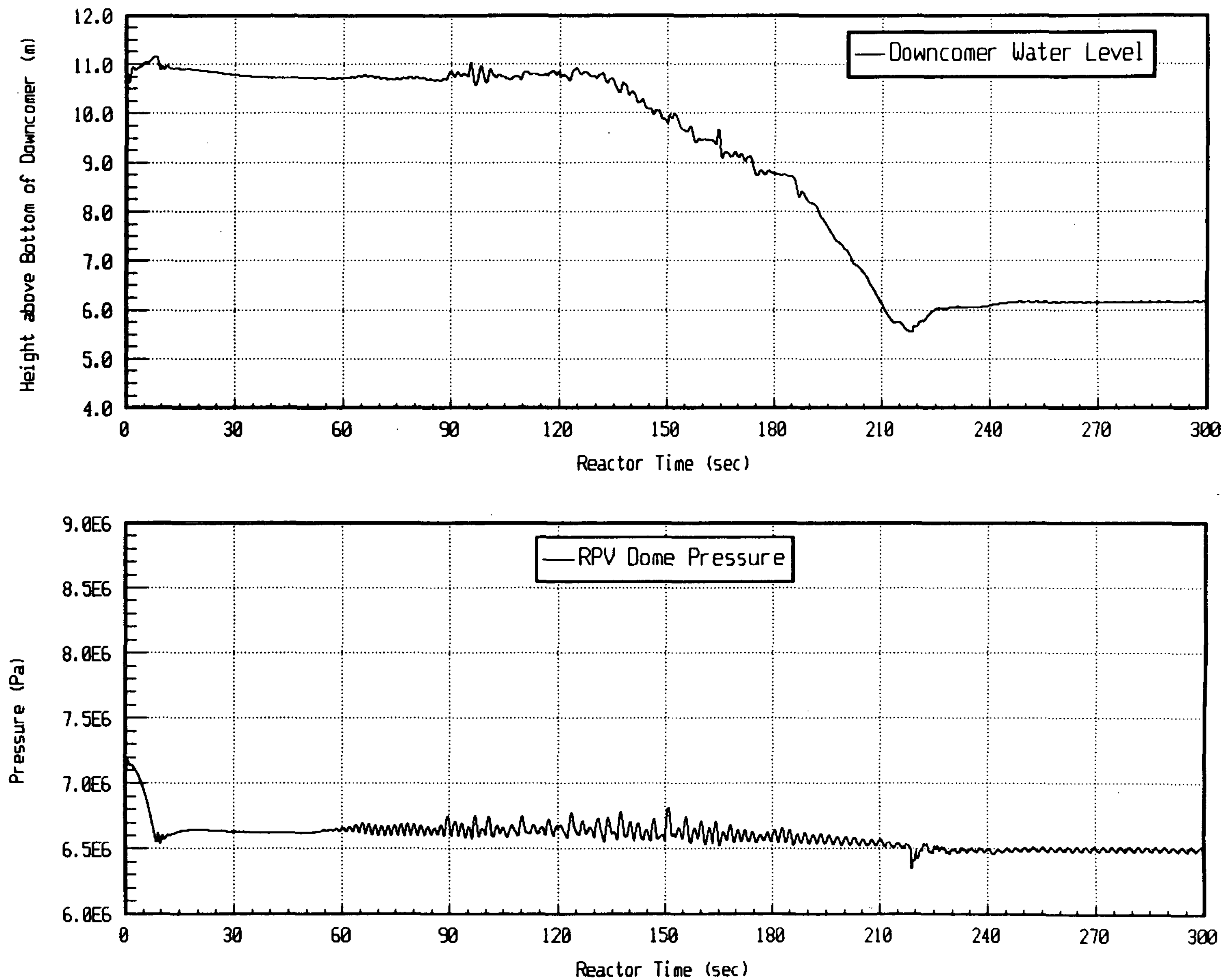

Figure 4-9. Level Control at TAF – RPV Water Level and Dome Pressure

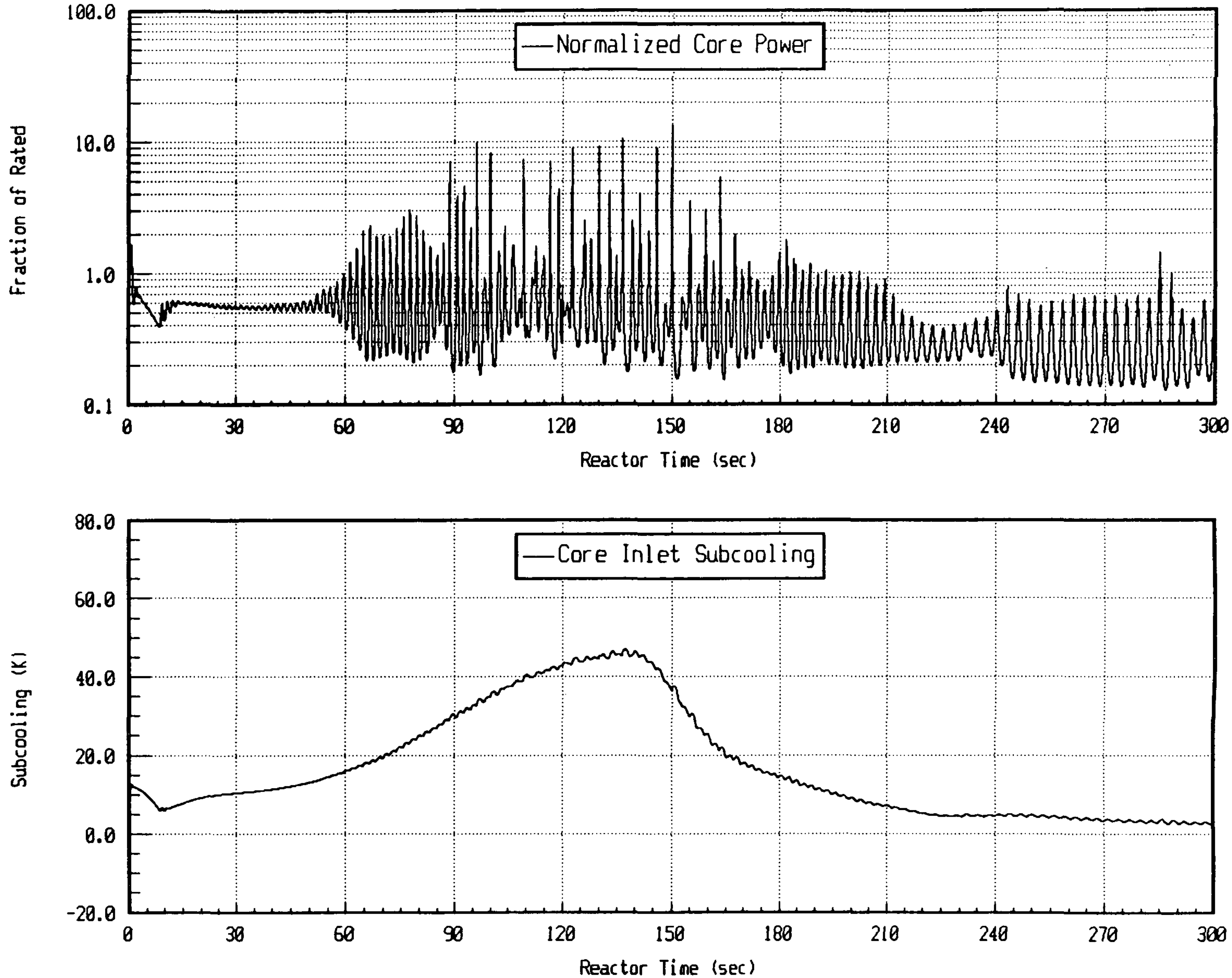

Figure 4-10. Level Control at MSCRWL – Core Power and Inlet Subcooling

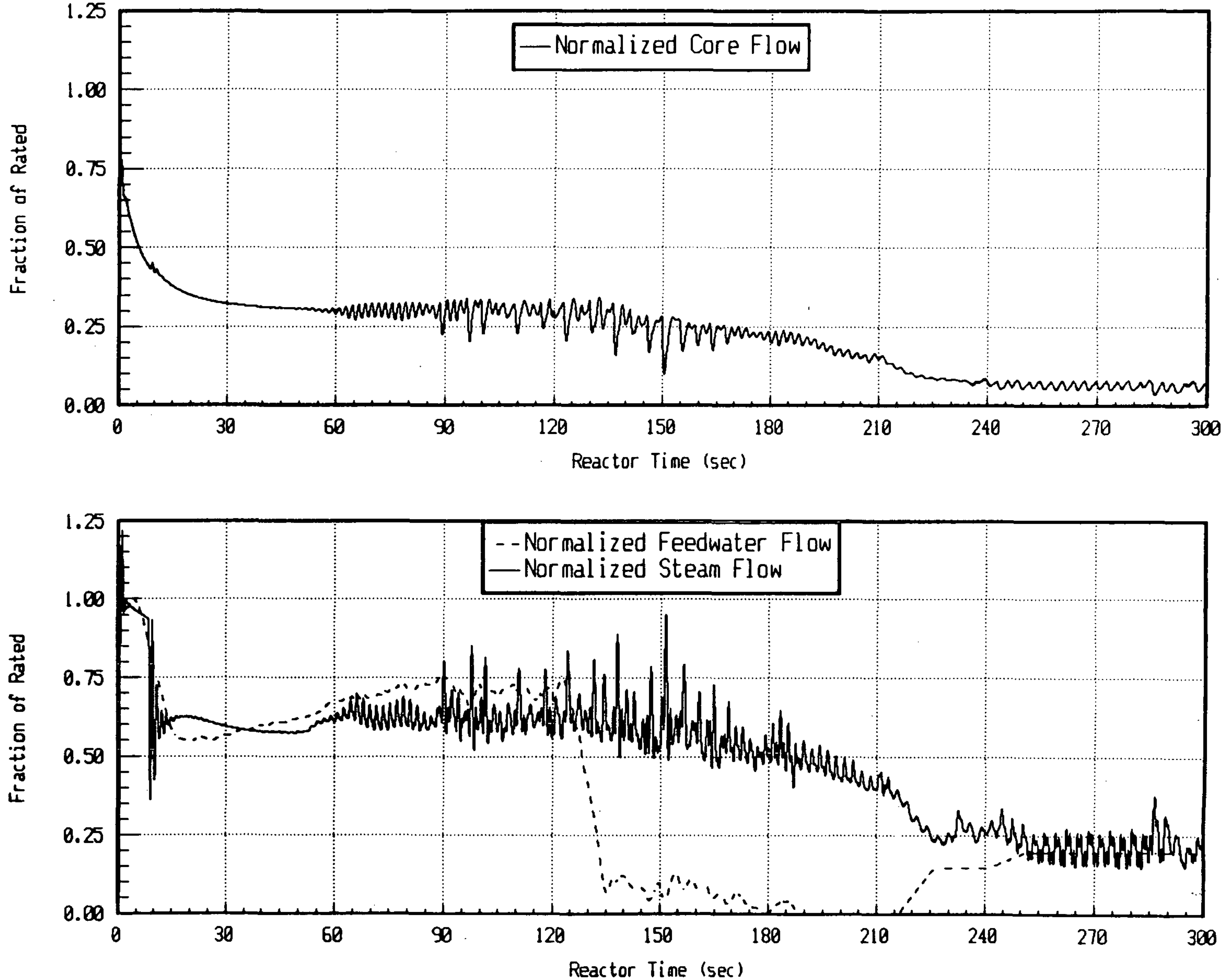

Figure 4-11. Level Control at MSCRWL – Core and Vessel Mass Flow Rates

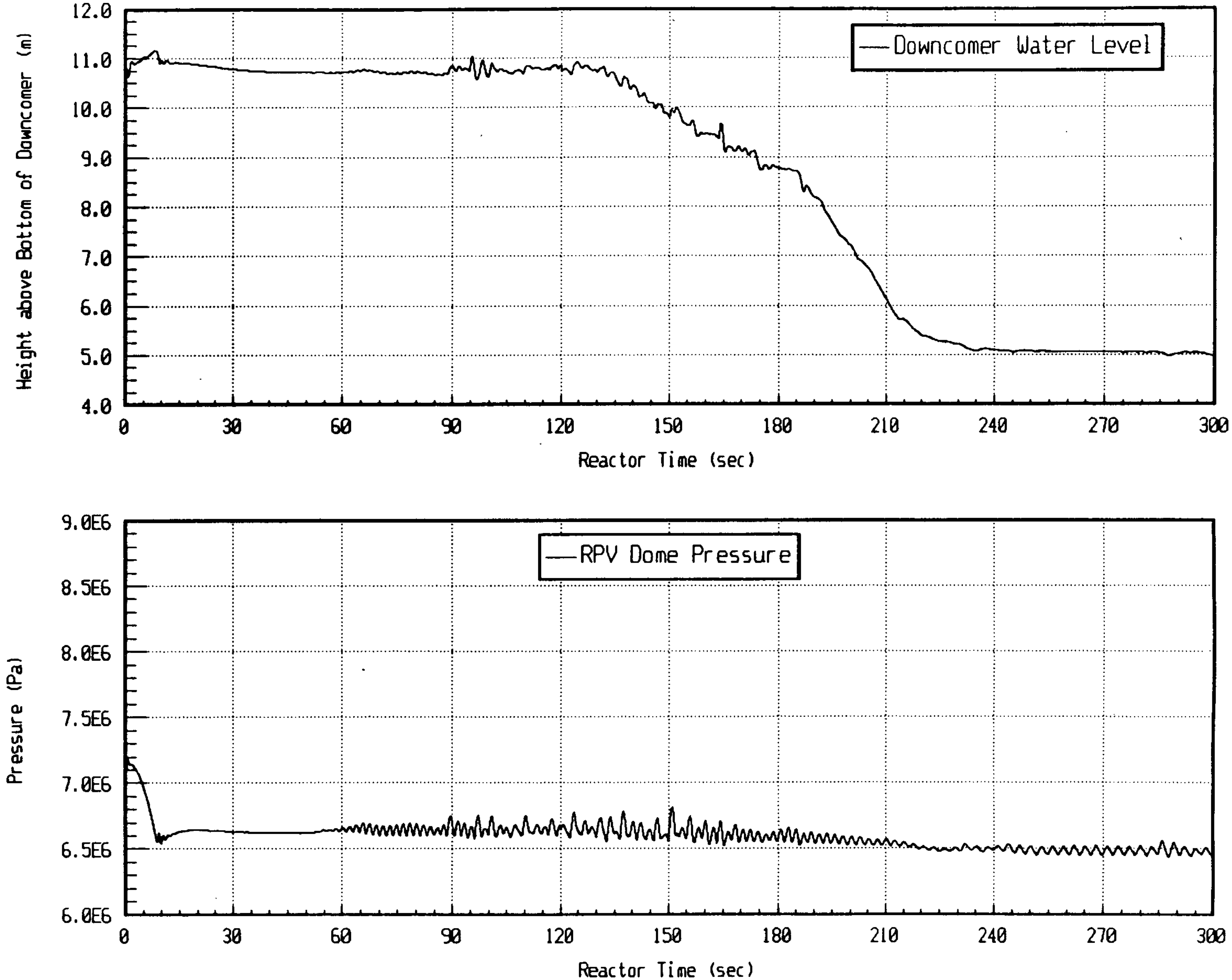

Figure 4-12. Level Control at MSCRWL – RPV Water Level and Dome Pressure

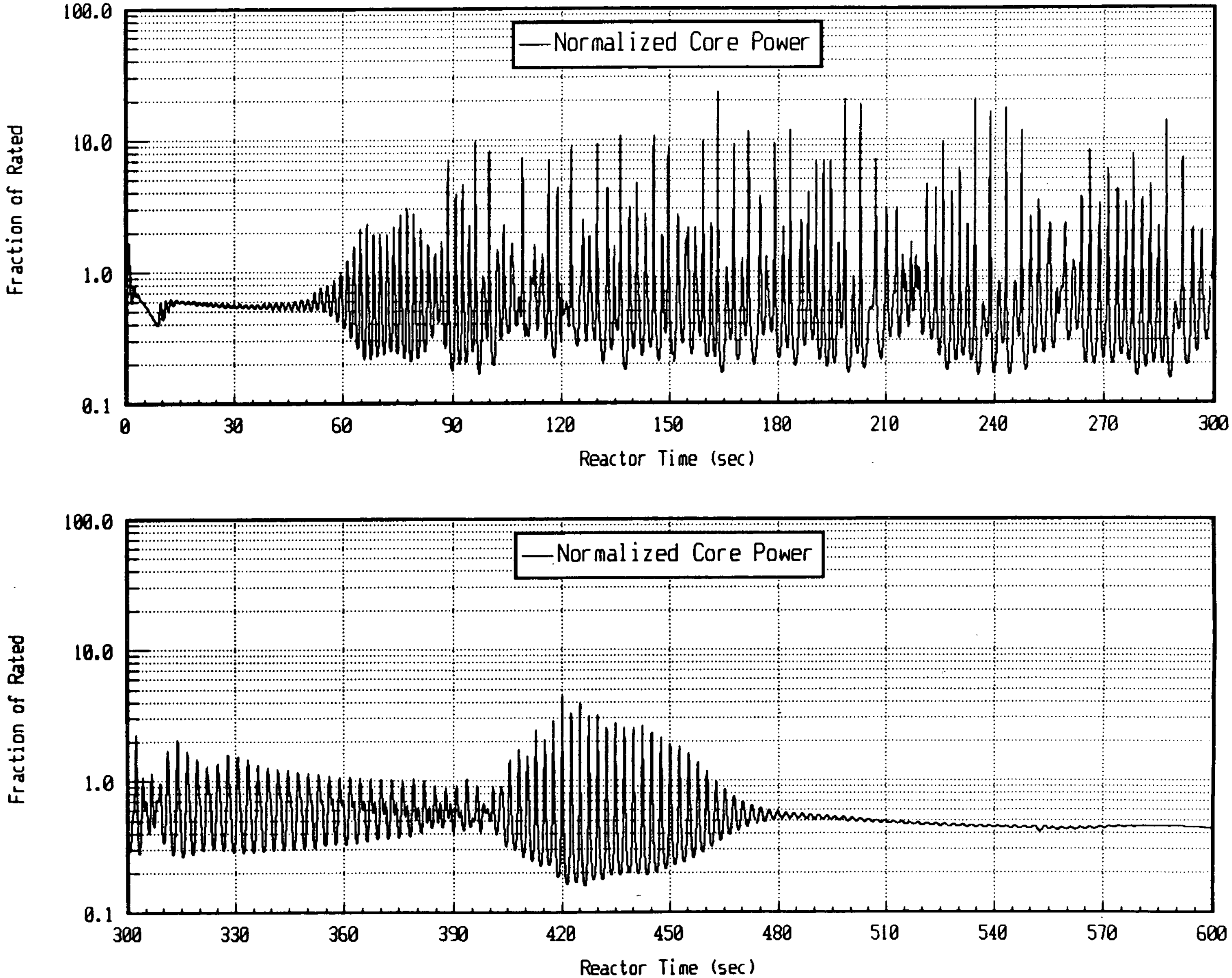

Figure 4-13. Boron Injection – Core Power

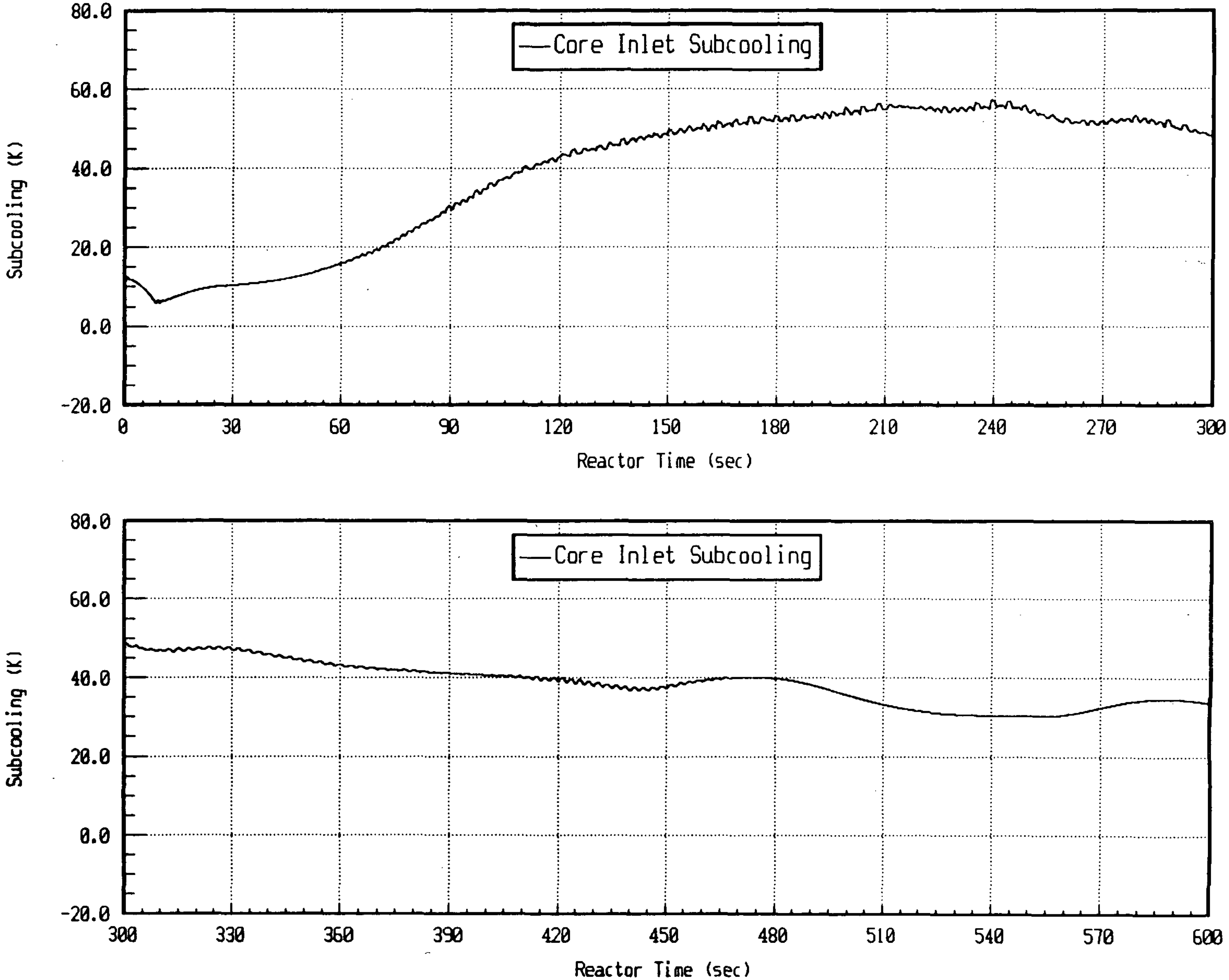

Figure 4-14. Boron Injection – Core Inlet Subcooling

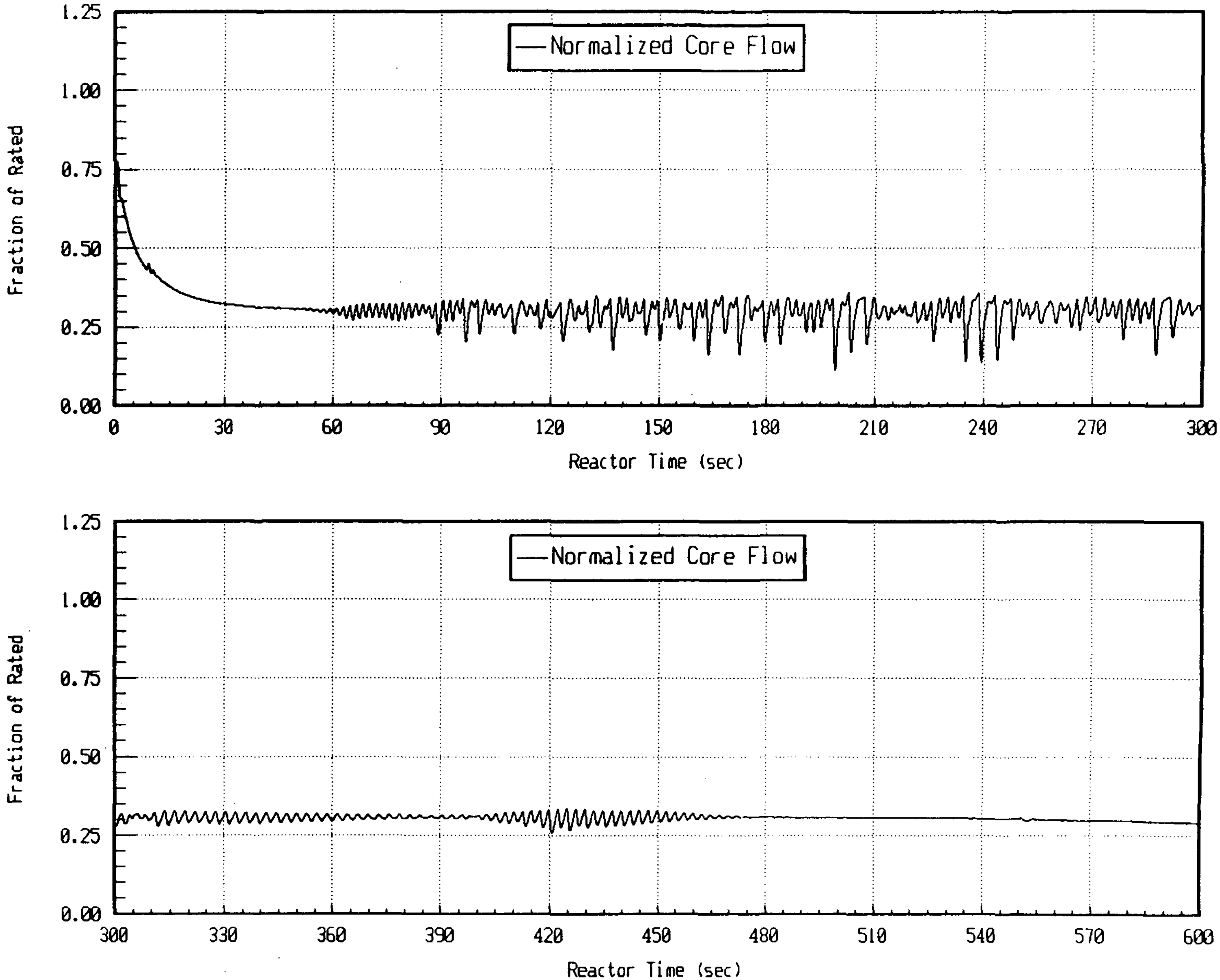

Figure 4-15. Boron Injection – Core Flow Rate

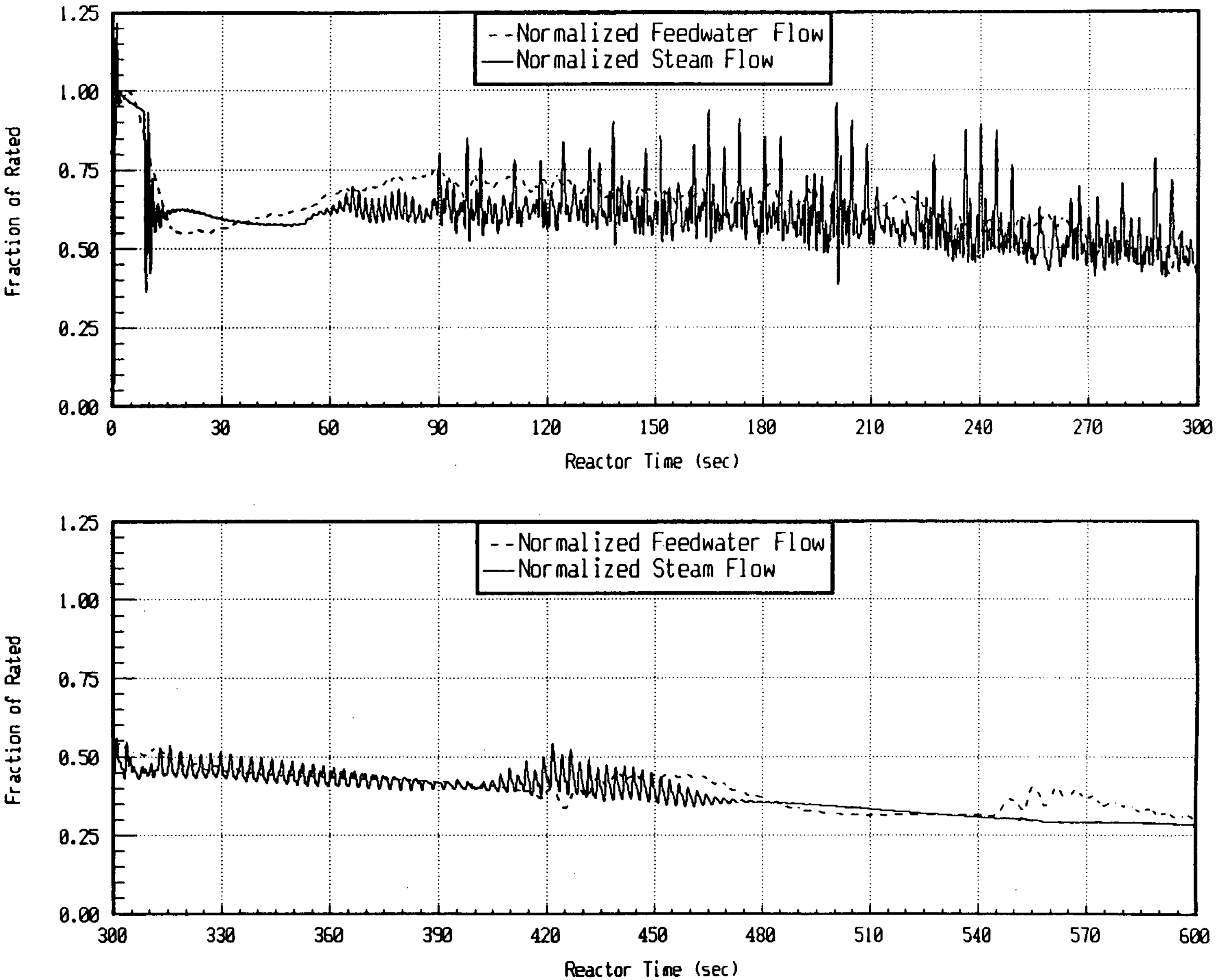

Figure 4-16. Boron Injection – Vessel Feedwater and Steam Flows

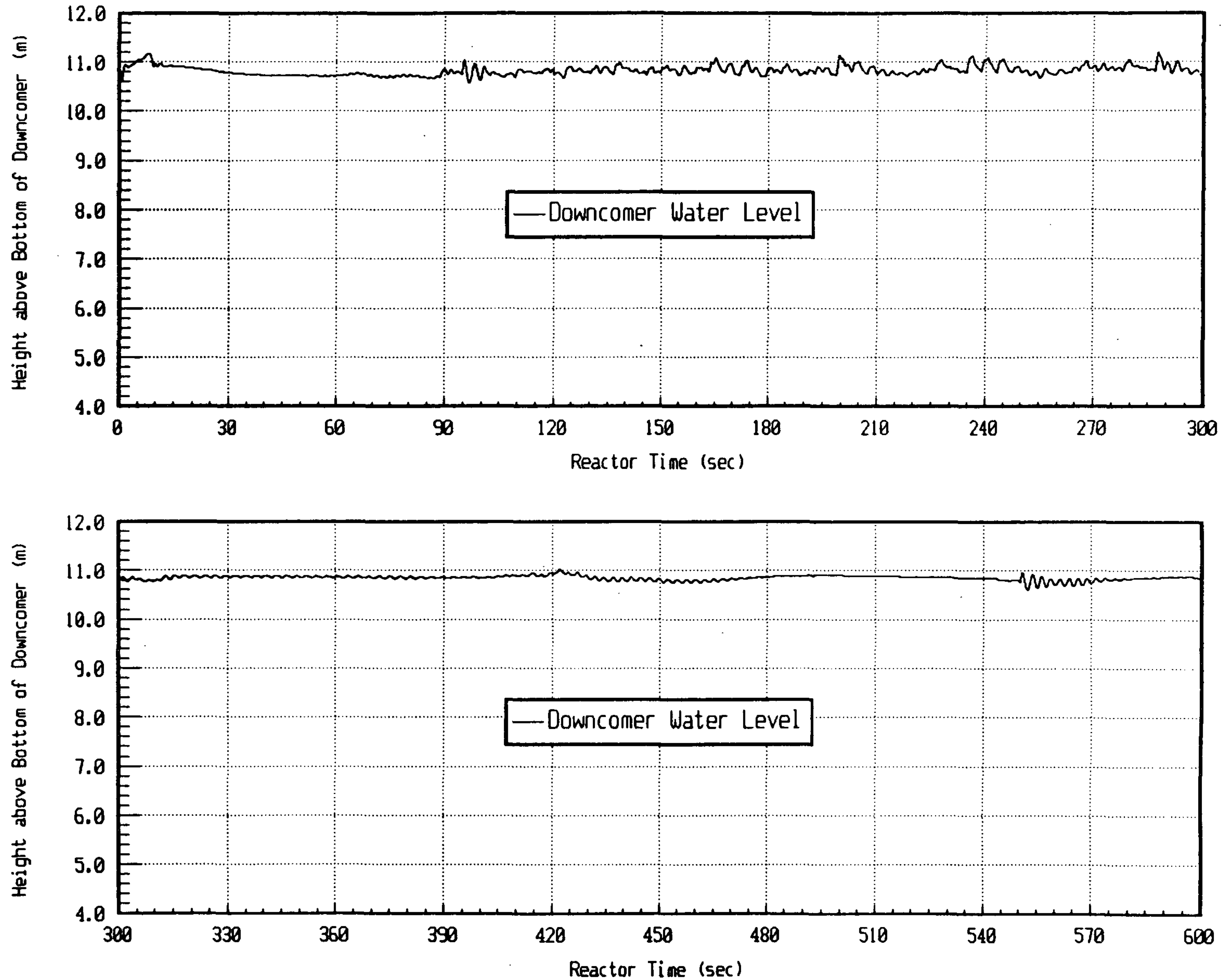

Figure 4-17. Boron Injection – RPV Water Level

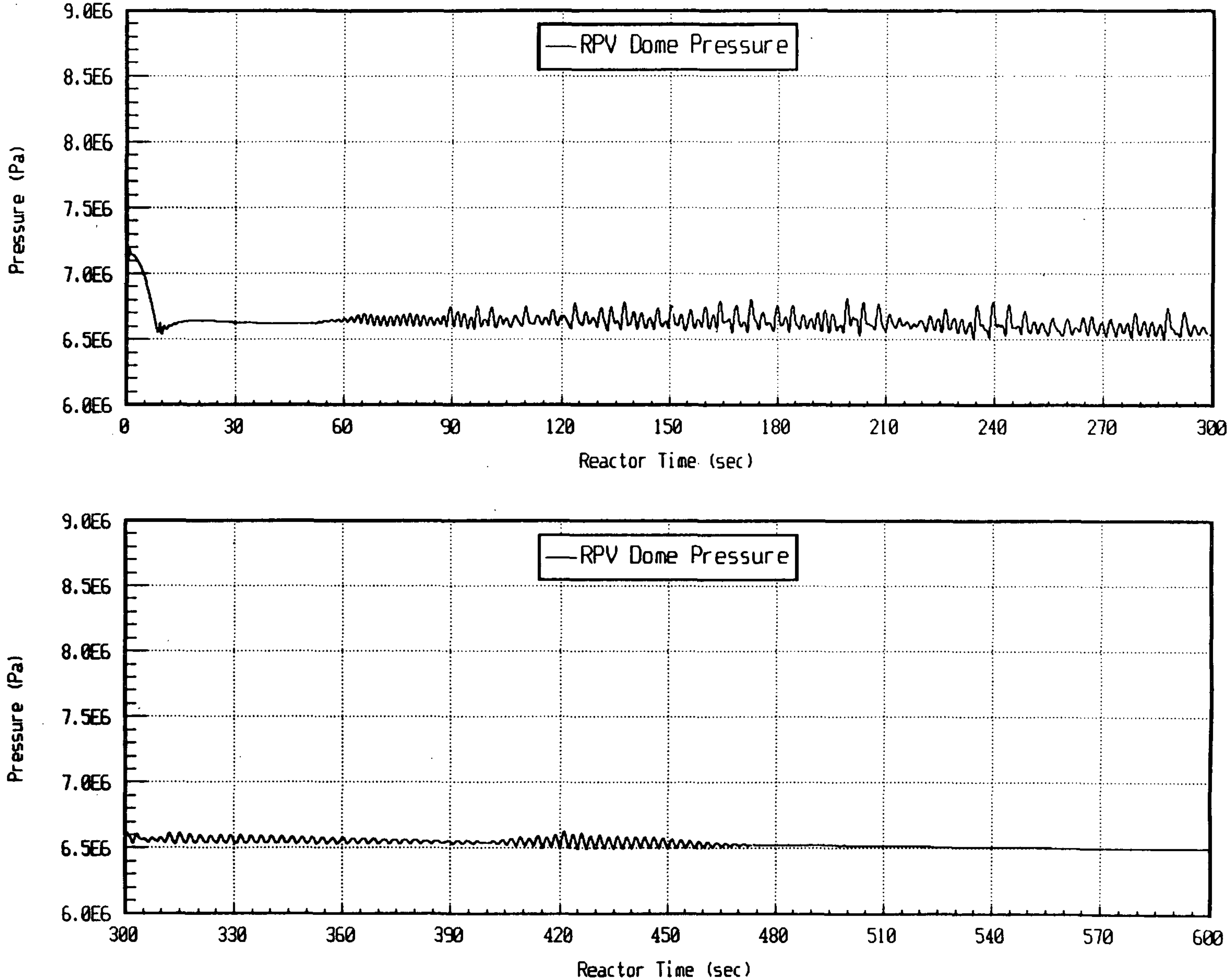

Figure 4-18. Boron Injection – RPV Dome Pressure

5.0 REFERENCES

1. NEDO-32047, "ATWS Rule Issues Relative to BWR Core Thermal-Hydraulic Stability", February 1992.