Pressurized Water Reactor
B&W Technology
Crosstraining Course Manual

Chapter 22.0

Plant Operating Limits

TABLE OF CONTENTS

22.0 PLANT OPERATING LIMITS 1
22.1 Introduction 1
22.2 Reactor Core Safety Limits 1
22.3 Core Operating Limits Report (COLR) 3
22.4 Axial Power Imbalance (API) Protective Limits 3
22.5 Power Distribution Limits 3
22.5.1 Regulating Rod Insertion Limits 4
22.5.2 Axial Power Shaping Rod (APSR) Insertion Limits 5
22.5.3 Axial Power Imbalance (API) Operating Limit 5
22.5.4 Quadrant Power Tilt (QPT) 6
22.5.5 Power Peaking Factors 7
22.6 Summary 7

LIST OF FIGURES

Figure 22-1 RCS Temperature/Pressure Safety Limits
Figure 22-2 Typical API Protective Limits (Measurement System Independent)
Figure 22-3 Typical API RPS Trip Setpoints
Figure 22-4 Typical Regulating Rod Insertion Limits (4 RCPs)
Figure 22-5 Typical API Operating Limits - Full Incore Conditions (4 RCPs)
Figure 22-6 Typical API Operating Limits - Excore Conditions (4 RCPs)
Figure 22-7 Typical API Operating Limits - Minimum Incore Conditions (4 RCPs)
Figure 22-8 Minimum Incore System Conditions for API Measurement
Figure 22-9 Minimum Incore Detector System for QPT Measurement
Figure 22-10 Composite Family of Curves for Typical API Limits (4 RCPs)

This page intentionally blank.

22.0 PLANT OPERATING LIMITS

Learning Objectives:

1. Define the following terms:

   a. Axial Power Imbalance (API)
   b. Rod Index
   c. Quadrant Power Tilt (QPT)
   d. Heat flux hot channel factor ($F_Q(Z)$)
   e. Enthalpy rise hot channel factor ($F^N_{\Delta H}$)

2. Describe how the API Operating Limits and QPT Limits relate to the measurement system independent limits, and how they vary when different measurement instruments are used.

3. Explain the bases for:

   a. Core Safety Limits
   b. Power Distribution Limits

22.1 Introduction

This section discusses the Babcock & Wilcox (B&W) Technical Specification (TS) Core Safety Limits (TS 2.1.1) and Power Distribution Limits (LCO Section 3.2). The limits and the reasons for the limits are similar to those associated with Westinghouse plants.

22.2 Reactor Core Safety Limits

General Design Criterion (GDC) 10 - Reactor Design, 10 CFR Part 50, Appendix A, requires that the reactor core and associated coolant, control, and protection systems shall be designed with appropriate margin to assure that specified acceptable fuel design limits are not exceeded during any condition of normal operation, including the effects of Anticipated Operational Occurrences (AOOs). Technical Specification (TS) reactor core Safety Limits ensure that the GDC 10 requirements are satisfied. These Safety Limits define:

- the maximum local fuel pin centerline temperature (TS 2.1.1.1),
- the minimum departure from nucleate boiling ratio (DNBR) (TS 2.1.1.2), and
- the reactor coolant system (RCS) temperature/pressure operating region (Figure 22-1) (TS 2.1.1.3).

Observing the Core Safety Limits protects the fuel cladding, the first barrier to the release of radioactive material, by preventing overheating of the fuel and cladding and possible cladding perforation. The fuel cladding must not sustain damage during normal operation and AOOs.

Satisfying the Core Safety Limits ensures that:

- the fuel centerline temperature stays below the melting point,
- the DNBR is greater than the safety analysis limit,
- the average enthalpy in the hot leg is less than or equal to the enthalpy of saturated liquid, and
- the core exit quality is within the limits of the DNBR correlation.

Additionally, operation within the RCS temperature/pressure operating region keeps the reactor from reaching a Safety Limit when operating up to design power.

If the TS Core Safety Limits are maintained, then the following fuel design criteria are not exceeded:

1. There must be at least 95% probability at a 95% confidence level (the 95/95 DNB criterion) that the hot fuel rod in the core does not experience DNB; and

2. The hot fuel pellet in the core must not experience centerline fuel melting.

The proper functioning of the Reactor Protection System (RPS) and the main steam safety valves prevent violation of the Safety Limits.

Observing the Core Safety Limits involves monitoring the axial power imbalance. Axial power imbalance (API) is defined in TS as the percent of rated thermal power (RTP) in the top half of the core minus the percentage of RTP in the lower half of the core. The API Protective Limits are specified in the core operating limits report (COLR). (See section 22.3 below for more details on the COLR.) Operating within the API Protective Limits ensures that the Safety Limits are not violated. (The API Protective Limits are described in section 22.4 below).

Although satisfying the Core Safety Limits prevents damage to the fuel and/or cladding during normal operation and AOOs, it does not ensure that the fuel and/or cladding will not be damage during accidents. Operating within the Power Distribution Limits (TS 3.2) establishes the operating envelope that defines the initial conditions assumed in accident analyses. If the plant is operated within the Power Distribution Limits, then fuel and/or cladding damage should be limited during an accident. (The Power Distribution Limits are described in section 22.5 below.)

22.3 Core Operating Limits Report (COLR)

The API Protective Limits and Power Distribution Limits can vary with the core fuel cycle, in accordance with variations in the fuel loading characteristics. In the past, utilities have submitted TS amendments in order to change the limiting values for new fuel loadings. Currently, most utilities have developed a COLR, which specifies the limiting values. In accordance with the requirements for the COLR in the administrative controls section of the TS, the COLR is revised and submitted to the NRC without the need for TS amendments. The TTC B&W COLR is referenced to plant-specific information that is intended to be representative of the operating plants' COLRs.

22.4 Axial Power Imbalance (API) Protective Limits

The API Protective Limits are a family of curves that creates an acceptable operating region based on the number of operating reactor coolant pumps (RCPs), core thermal power and percentage axial power imbalance. Operating within the API Protective Limits ensures that the Core Safety Limits are not violated. The core reload analysis is used to produce the measurement system independent API Protective Limits. The measurement system independent API Protective Limits are the least restrictive boundaries that will maintain the Core Safety Limits (Figure 22-2). The more restrictive RPS trip setpoints (i.e., Flux/Delta Flux/Flow trip envelope, Figure 22-3) are derived from the measurement system independent API Protective Limits.

22.5 Power Distribution Limits

The Power Distribution Limits are operating limits that establish the initial conditions assumed in the accident analyses. Power Distribution Limits support compliance with Core Safety Limits by maintaining local core conditions within design limits. The B&W Power Distribution TS Limits are:

- Regulating Rod Insertion Limits (TS 3.2.1)
- Axial Power Shaping Rod (APSR) Insertion Limits (TS 3.2.2)
- Axial Power Imbalance (API) Operating Limit (TS 3.2.3)
- Quadrant Power Tilt (QPT) (TS 3.2.4)
- Power Peaking Factors (TS 3.2.5)

Fuel cladding damage does not occur when the core is operated outside of these limits during normal operation, as long as the API Protective Limits are observed. However, unacceptably extensive clad damage could result if an accident occurred simultaneously with a violation of one or more of these limits. Operating within the Power Distribution Limits precludes core power distributions that violate the following fuel design criteria:

- During a large-break loss of coolant accident (LOCA), the peak cladding temperature must not exceed 2200°F.

- During a loss of forced reactor coolant flow accident, there must be at least 95% probability at the 95% confidence level that the hottest fuel rod does not experience DNB.
- During an ejected rod accident, the fission energy input to the fuel must not exceed 280 calories/gram.
- The control rods must be capable of shutting down the reactor with a minimum required shutdown margin (SDM) with the highest worth rod stuck fully withdrawn.

The primary parameters used to monitor and control the core power distribution are the regulating rod position, APSR position, API, and QPT. These parameters are normally used to monitor and control the core power distribution because their measurements are continuously observable. Limits are placed on these parameters to ensure that the core power peaking factors are met during an accident and that the fuel design criteria are not violated. The Power Distribution Limits are described in more detail in the following sections.

22.5.1 Regulating Rod Insertion Limits

The limits on regulating rod sequence, group overlap, and insertion positions are specified in the COLR. The limits must be maintained because they ensure that the resulting power distribution is within the range of analyzed power distributions and that the SDM and maximum ejected rod worth are maintained. The overlap between regulating groups provides more uniform reactivity insertion rates during regulating rod movement. The overlap illustrated in Figure 22-4 is 20%.

The regulating rod insertion limits are a family of curves that specify a permissible operating region, restricted operating region, and prohibited region. There are different curves for different RCP combinations and different times in core life. The B&W convention is to express these insertion limits in terms of rod index, which is equal to the sum of the regulating rods withdrawal percentages (Figure 22-4). As an example: if Group 5 is withdrawn to 100%, Group 6 is withdrawn to 80%, and Group 7 is withdrawn to 0%, then the rod index is 180 (100 + 80 + 0). If Group 5 is withdrawn to 90%, Group 6 to 10%, and Group 7 to 0%, then the rod index is 100 (90 + 10 + 0). If Group 5 is withdrawn to 100%, Group 6 to 90%, and Group 7 to 10%, then the rod index is 200 (100 + 90 + 10).

Figure 22-4, a typical Regulating Rod Insertion Limit curve (4 RCPs operating), illustrates the permissible operation region, restricted region, and prohibited region for a B&W plant. Operating in the Prohibited Region would produce a shutdown margin (SDM) less than the minimum required value or an ejected rod worth greater than the allowable value. Operating in the Restricted Region potentially violates the heat flux hot channel factor limits, $F_Q(Z)$, or the enthalpy rise hot channel factor, $F_{\Delta H}^N$, limits. (The limits on $F_Q(Z)$ and $F_{\Delta H}^N$ are described in section 22.5.5 below.)

22.5.2 Axial Power Shaping Rod (APSR) Insertion Limits

The limits on APSR insertion maintain the power distribution within the range assumed in the accident analyses. The APSR insertion limits are defined in the COLR. The APSRs may be positioned as necessary for transient Axial Power Imbalance (API) control. At a specified time in core life, maximum insertion limits (usually fully withdrawn) apply.

22.5.3 Axial Power Imbalance (API) Operating Limit

The API Operating Limits maintain the validity of the assumptions regarding the power distributions in the accident analyses of LOCAs and loss-of-flow accidents. The API limits are provided in the COLR. Operation within the API limits given in the COLR is the acceptable region of operation.

Recall that axial power imbalance (API) is defined in TS as the percent of rated thermal power in the top half of the core minus that of the lower half of the core. As stated above, the measurement system independent API Protective Limits ensure that the Safety Limits are not violated; they are the least restrictive boundaries that will maintain the Safety Limits. The API Reactor Protection System setpoints are more restrictive than the Protection Limits because they must account for instrument errors & uncertainties and for measurement system observability.

The API Operating Limits are the most restrictive. There are different limits for different RCP combinations and different limits depending on how axial power imbalance is measured. Axial power imbalance can be measured using the incore instruments (the normal method) or the excore nuclear instruments. The limits are adjusted because of measurement uncertainties and are described below.

- Full Incore Conditions - The least restrictive of the API Operating Limits (Figure 22-5). The measurement requires at least 75% of the incore detectors in each quadrant to be operable.

- Excore Conditions - More restrictive than the Full Incore Conditions (Figure 22-6).

- Minimum Incore Conditions - The most restrictive of the API Operating Limits (Figure 22-7). A specific set of nine detectors is needed to perform the API determinations. The Minimum Incore Conditions, as illustrated in Figure 22-8 and described in TS 3.2.3, requires the following:

    - There must be three detector strings with three operable neutron detectors per string.
    - One of the operable detectors of each string must be located at the core mid-plane, one detector of each string must be located in the same axial plane in

the upper half of the core, and one detector of each string must be located in the same axial plane in the lower half of the core.

- The axial planes in each core half must be symmetrical about the core mid-plane.
- The detector strings shall not have radial symmetry.

A composite of a typical family of API Limits curves (4 RCPs) is presented in Figure 22-10. The figure is intended to illustrate which limits are more restrictive.

22.5.4 Quadrant Power Tilt (QPT)

Quadrant power tilt is defined by the following equation:

$$QPT = 100\% \left[\frac{power\, in\, any\, quadrant}{average\, quadrant\, power} - 1 \right]$$

The limits on QPT must be maintained to prevent the core power distribution from exceeding the design limits. Similar to API, the QPT limits are provided in the COLR. The measurement system independent QPT limits given in the COLR are determined by the reload safety evaluation. Operation beyond the measurement system independent limits could invalidate core power distribution assumptions used in the accident analyses. The measurement system independent limits are the least restrictive boundaries.

Like API operating limits, the QPT can be measured using the incore instruments (the normal method) or the excore nuclear instruments. The limits are adjusted because of measurement uncertainties and are described below.

- Full Symmetric Incore System - More restrictive than the measurement system independent limits. The full incore system requires at least 75% of the detectors in each quadrant to be operable. The operable detectors <u>must also include</u> the specific set of 16 detectors needed to perform the Minimum Incore Detector System measurement requirements (described below).

- Excore Detector System - More restrictive than the Full Incore System.

- Minimum Incore Detector System - Most restrictive limits. A specific set of 16 detectors is needed. The Minimum Incore Detector System, as illustrated in Figure 22-9 and described in TS 3.2.4, requires the following:

    - Two sets of four detectors shall lie in each core half (eight detectors/core half).
    - Each set of detectors shall lie in the same axial plane. The two sets in each core half may lie in the same axial plane.

- Detectors in the same plane shall have quarter-core radial symmetry.

22.5.5 Power Peaking Factors

The limits on the power peaking factors, the heat flux hot channel factor, $F_Q(Z)$, and the enthalpy rise hot channel factor, $F_{\Delta H}^{N}$, ensure that the core operates within the bounds assumed in the accident analyses.

The heat flux hot channel factor, $F_Q(Z)$, is defined as the maximum local fuel rod linear power density divided by the average fuel rod linear power density. The heat flux hot channel factor is a measure of the maximum fuel pellet power density in a fuel rod. Observing the $F_Q(Z)$ limits given in the COLR prevents power peaking that would exceed the ECCS analysis and limits peak cladding temperatures to 2200°F during a LOCA.

The enthalpy rise hot channel factor, $F_{\Delta H}^{N}$, is defined as the ratio of the integral of the linear power along the fuel rod with the minimum DNBR to the average integrated fuel rod power. The enthalpy rise hot channel factor is a measure of the maximum total power produced in a fuel rod. Observing the $F_{\Delta H}^{N}$ limit provided in the COLR prevents DNB during a loss-of-forced-reactor-coolant-flow accident.

The limits on $F_Q(Z)$ and $F_{\Delta H}^{N}$ are verified using the incore instruments to obtain a power distribution map (3-D flux map). These power peaking factors are not routinely monitored, but rather are measured if one of the other power distribution parameters exceeds its limit. The heat flux hot channel factor and enthalpy rise hot channel factor limits are preserved when the limits on regulating rod insertion position, APSR position, API, and QPT are satisfied.

22.6 Summary

General Design Criterion 10, Reactor Design, requires that the fuel cladding must not sustain damage during normal operation and AOOs. The TS Core Safety Limits ensure that this requirement is satisfied. The proper functioning of the RPS and the main steam safety valves prevent violation of the Safety Limits.

Satisfying the Core Safety Limits prevents damage to the fuel and/or cladding during normal operation and AOOs but does not ensure the unacceptable damage is avoided during accidents. Operating within the Power Distribution Limits establishes the operating envelope that defines the initial conditions assumed in accident analyses. If the plant is operated within the Power Distribution Limits, then fuel and/or cladding damage should be limited to an acceptable extent during an accident.

The primary parameters used to monitor and control the core power distribution are the regulating rod position, APSR position, API, and QPT. These parameters are normally

used to monitor and control the core power distribution because their measurements are continuously observable. Limits are placed on these parameters to ensure that the limits on core power peaking factors (heat flux hot channel factor and enthalpy rise hot channel factor) are met at the onset of an accident.

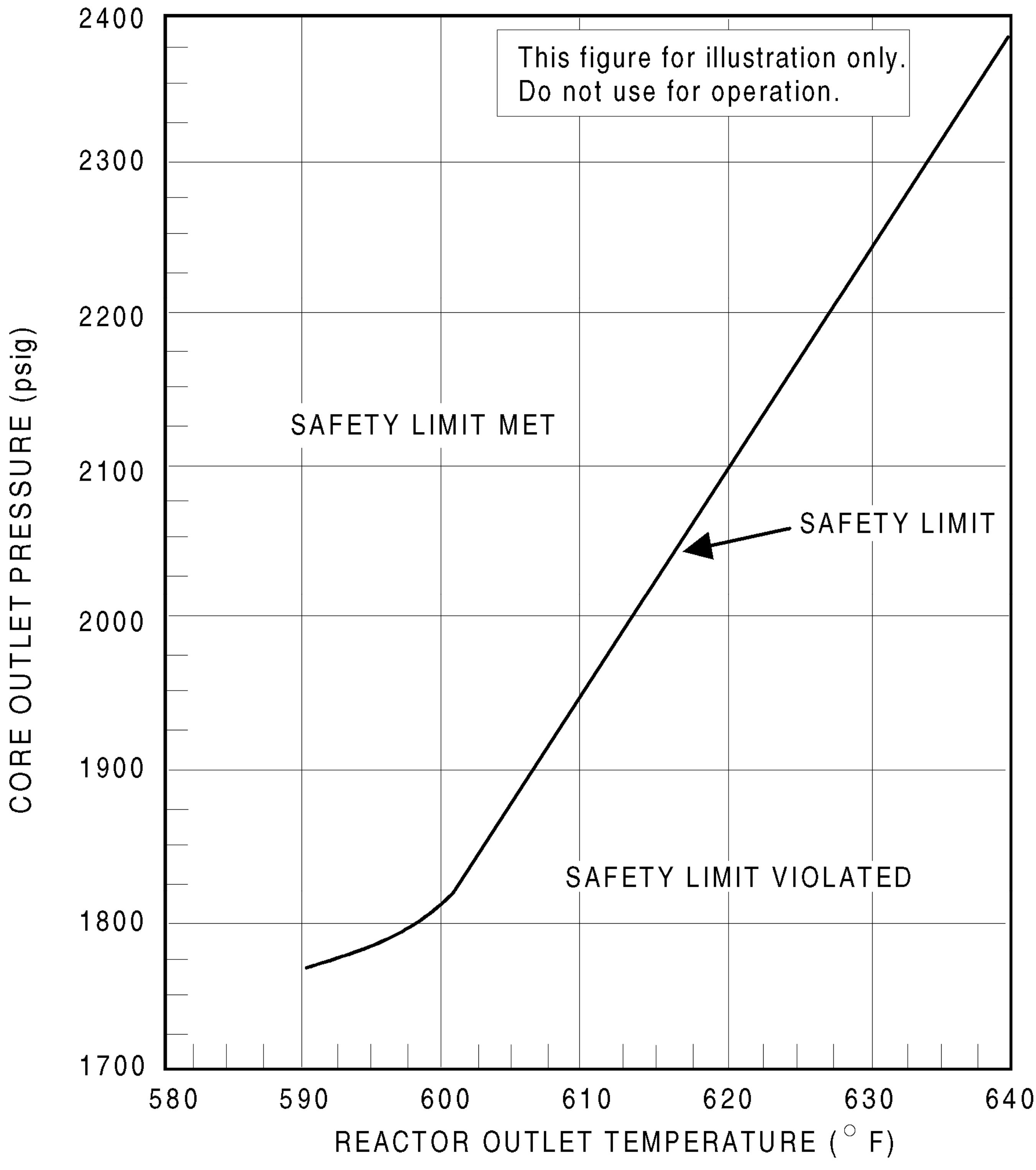


Figure 22-1 RCS Temperature/Pressure Safety Limits

This page intentionally blank

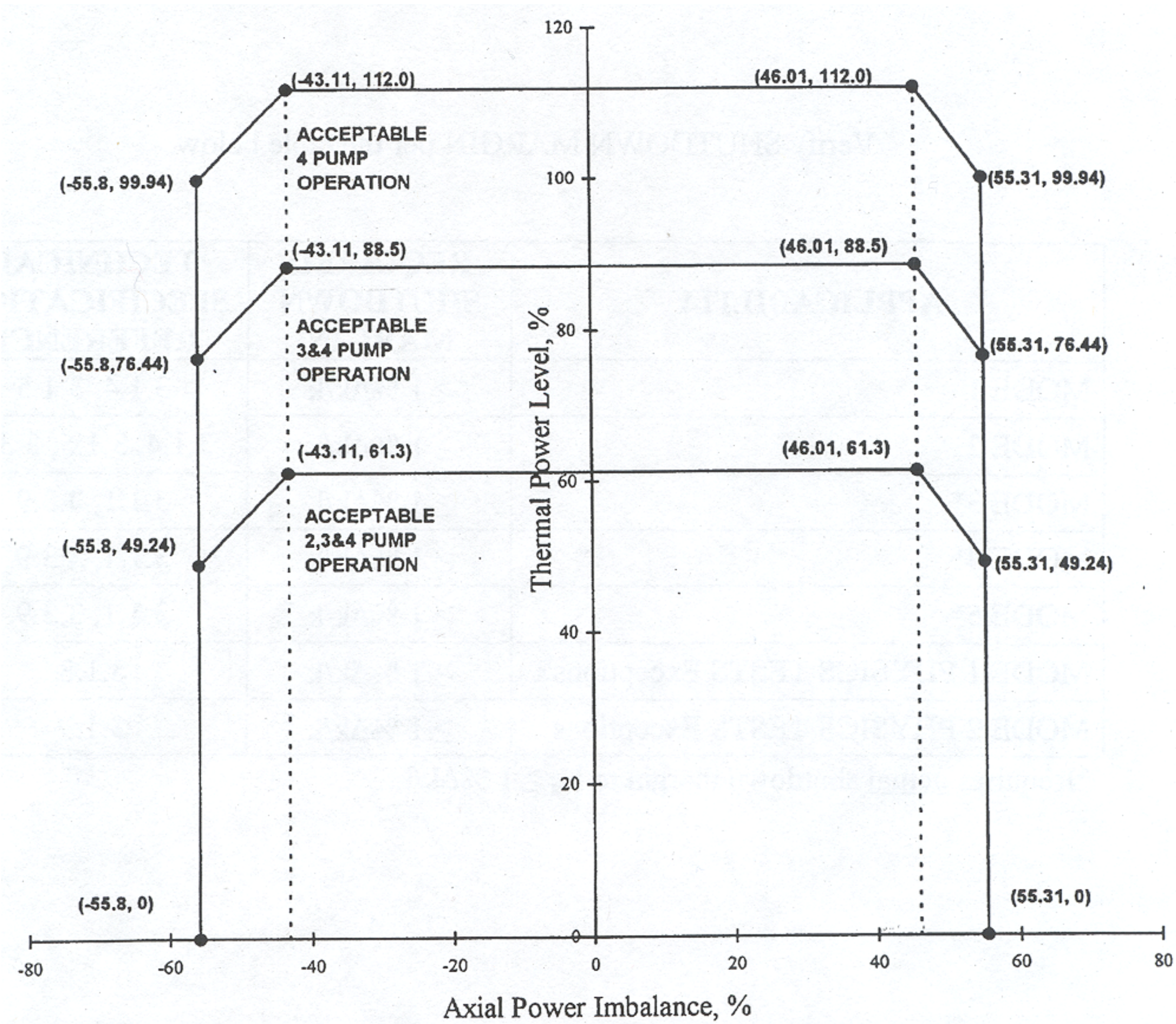


Figure 22-2 Typical API Protective Limits (Measurement System Independent)

This page intentionally blank

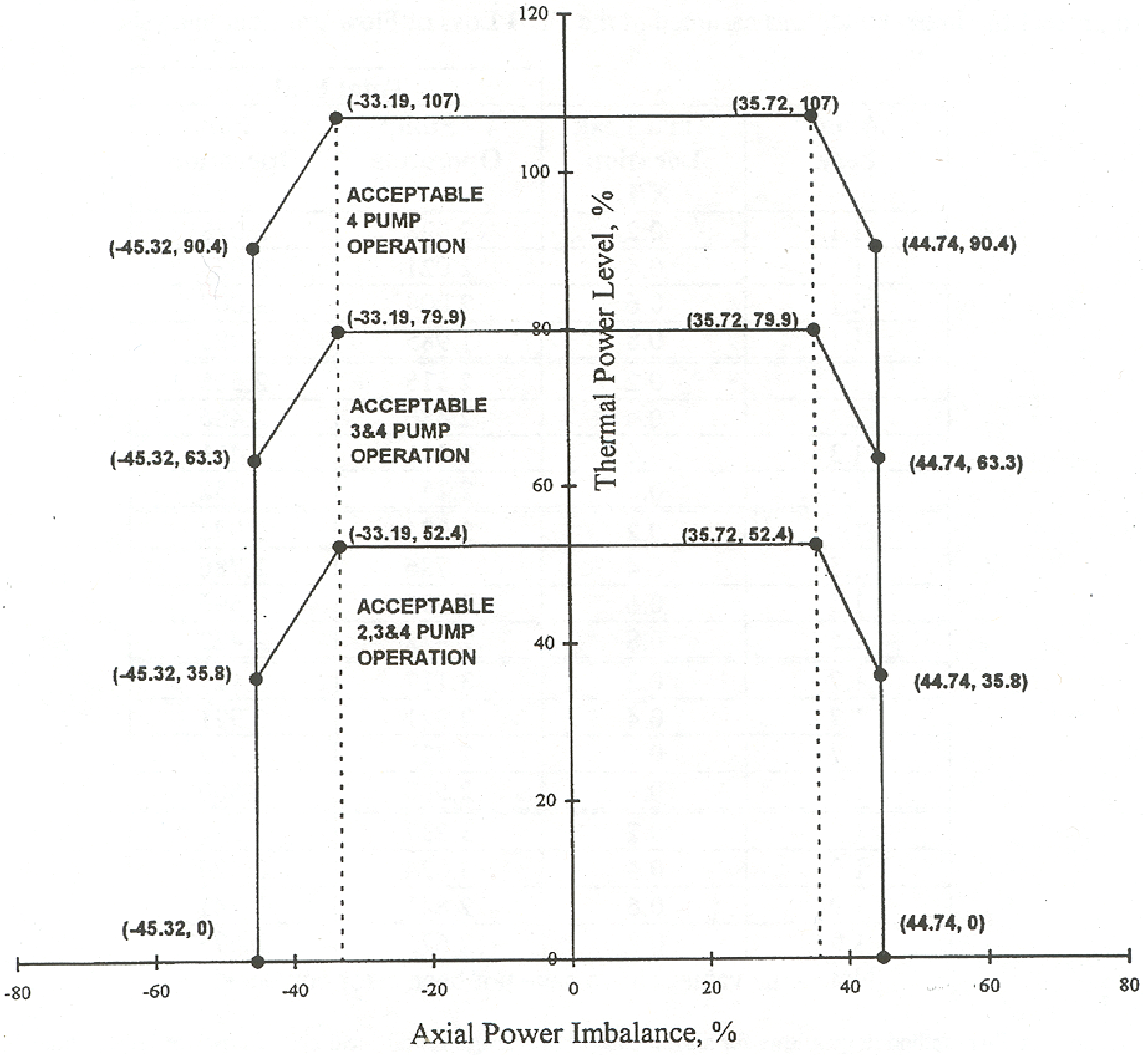


Figure 22-3 Typical API RPS Trip Setpoints

This page intentionally blank

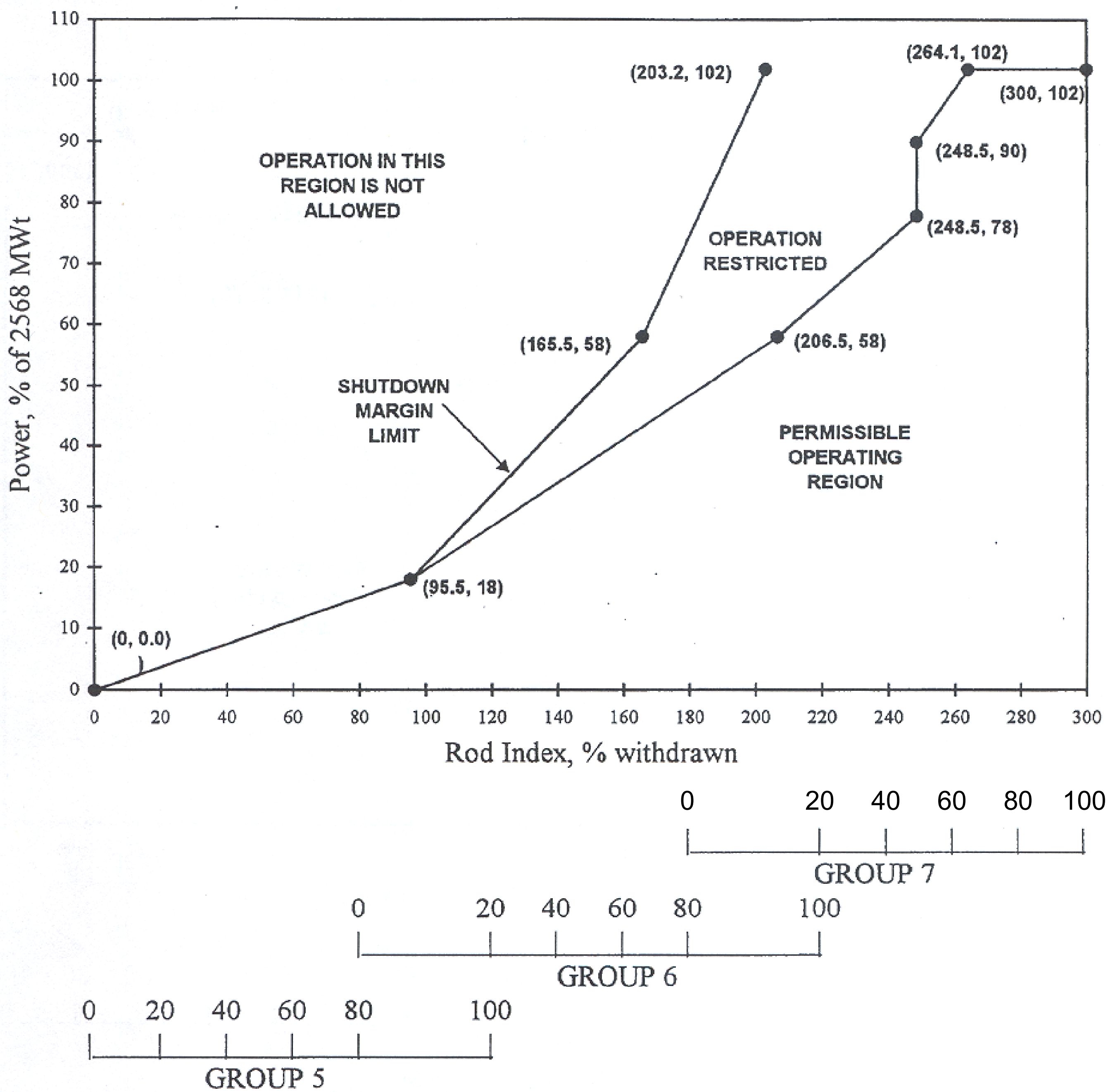


Figure 22-4 Typical Regulating Rod Insertion Limits (4 RCPs)

This page intentionally blank

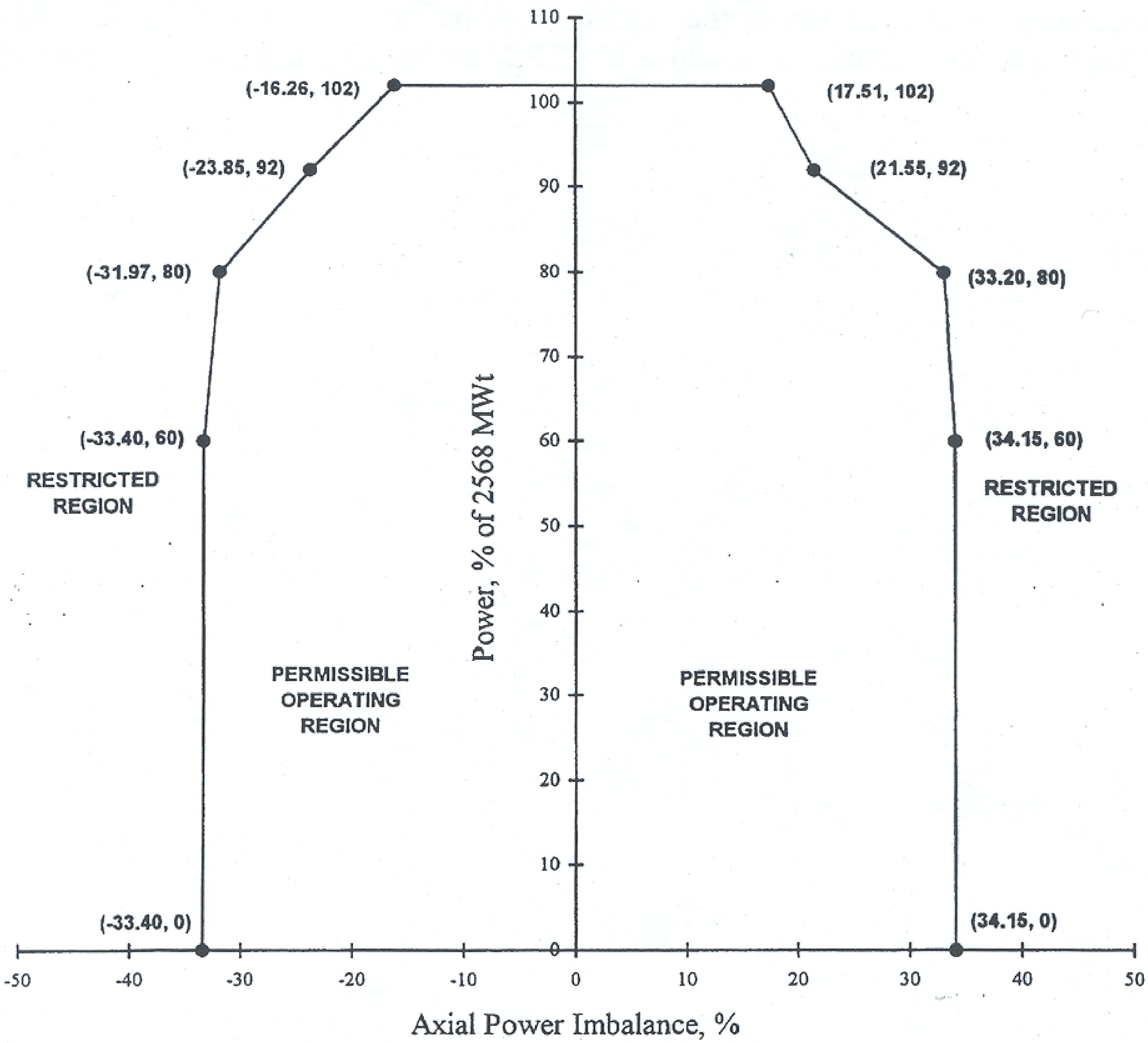


Figure 22-5 Typical API Operating Limits - Full Incore Conditions (4 RCPs)

This page intentionally blank

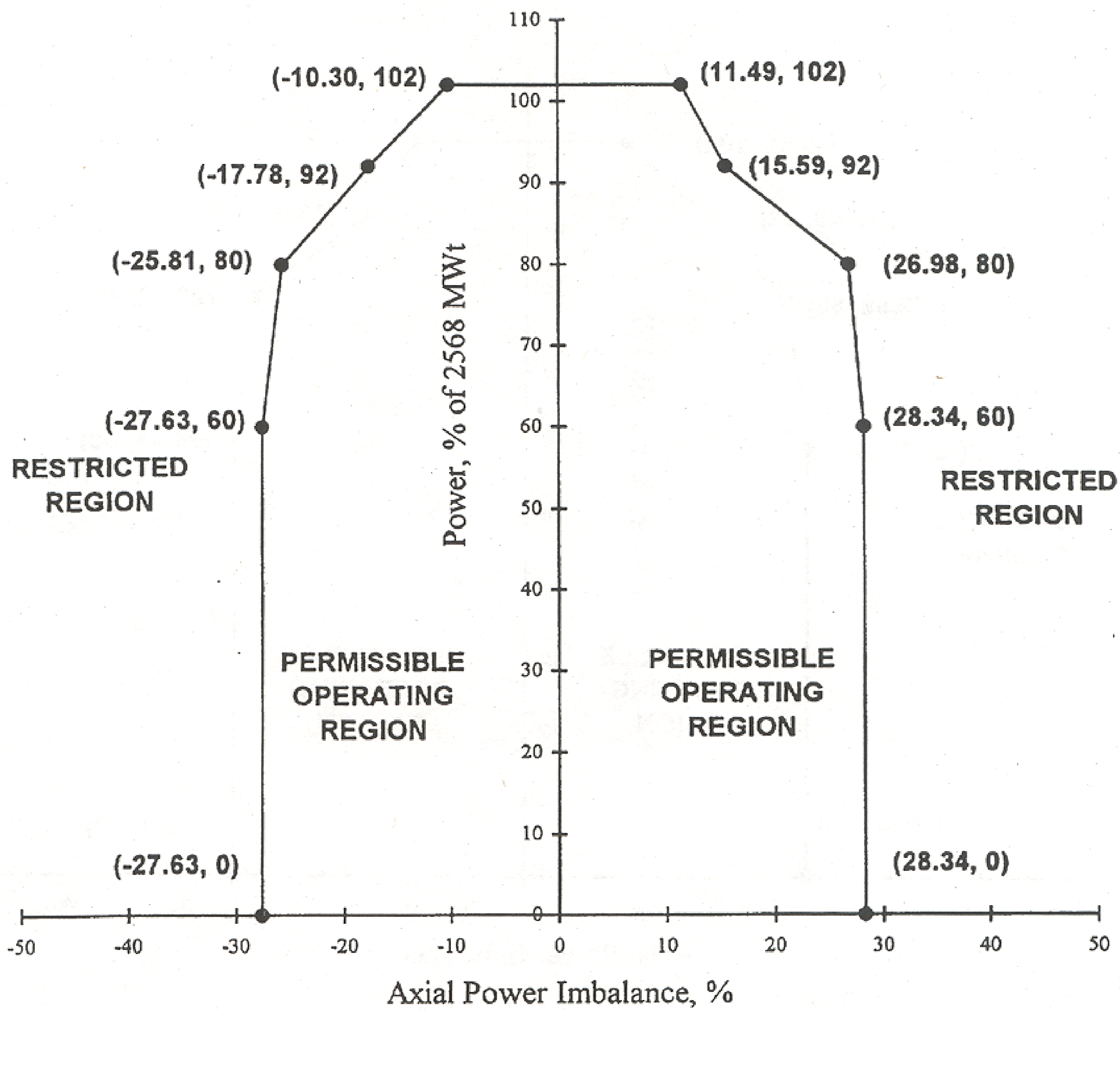


Figure 22-6 Typical API Operating Limits - Excore Conditions (4 RCPs)

This page intentionally blank

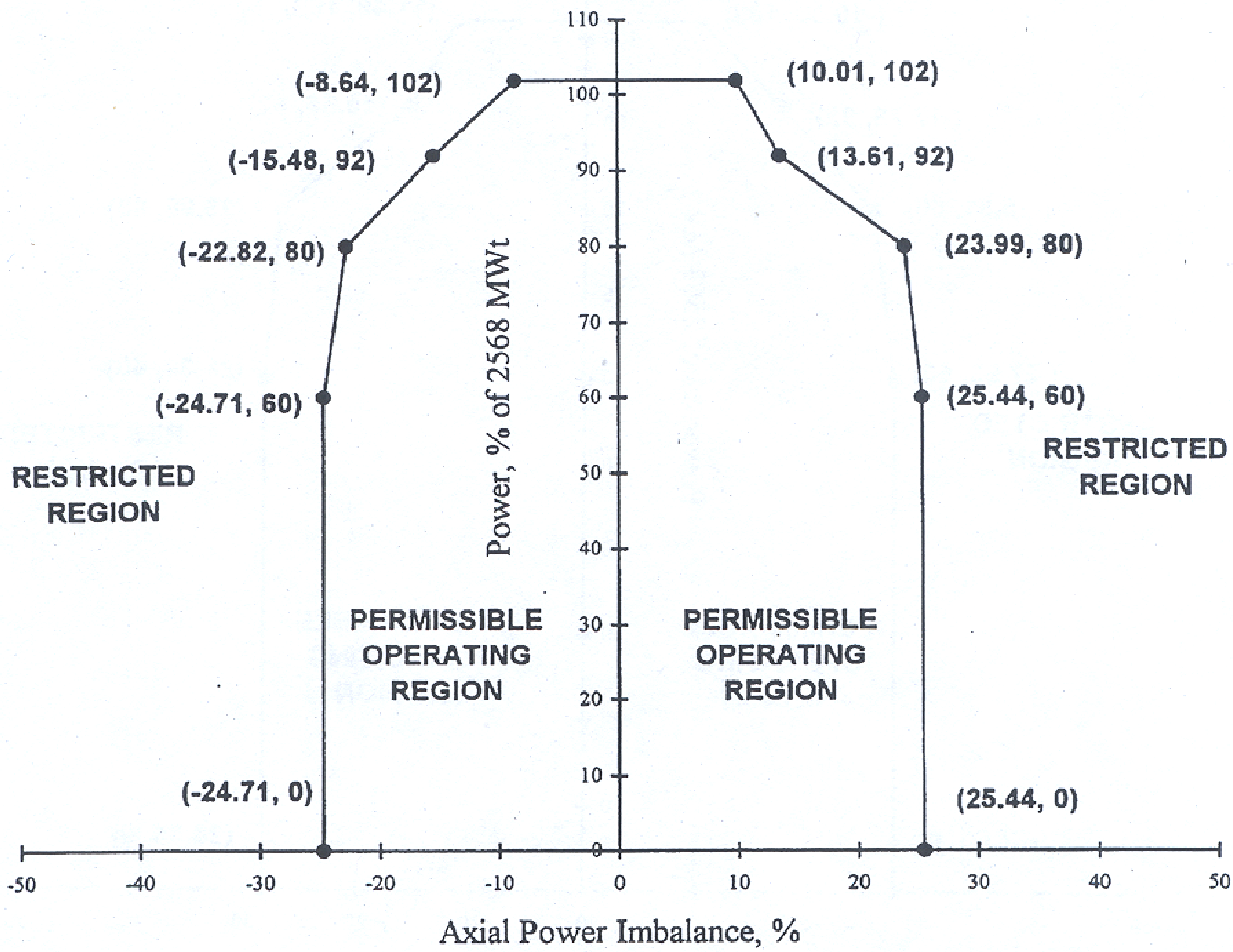


Figure 22-7 Typical API Operating Limits - Minimum Incore Conditions (4 RCPs)

This page intentionally blank

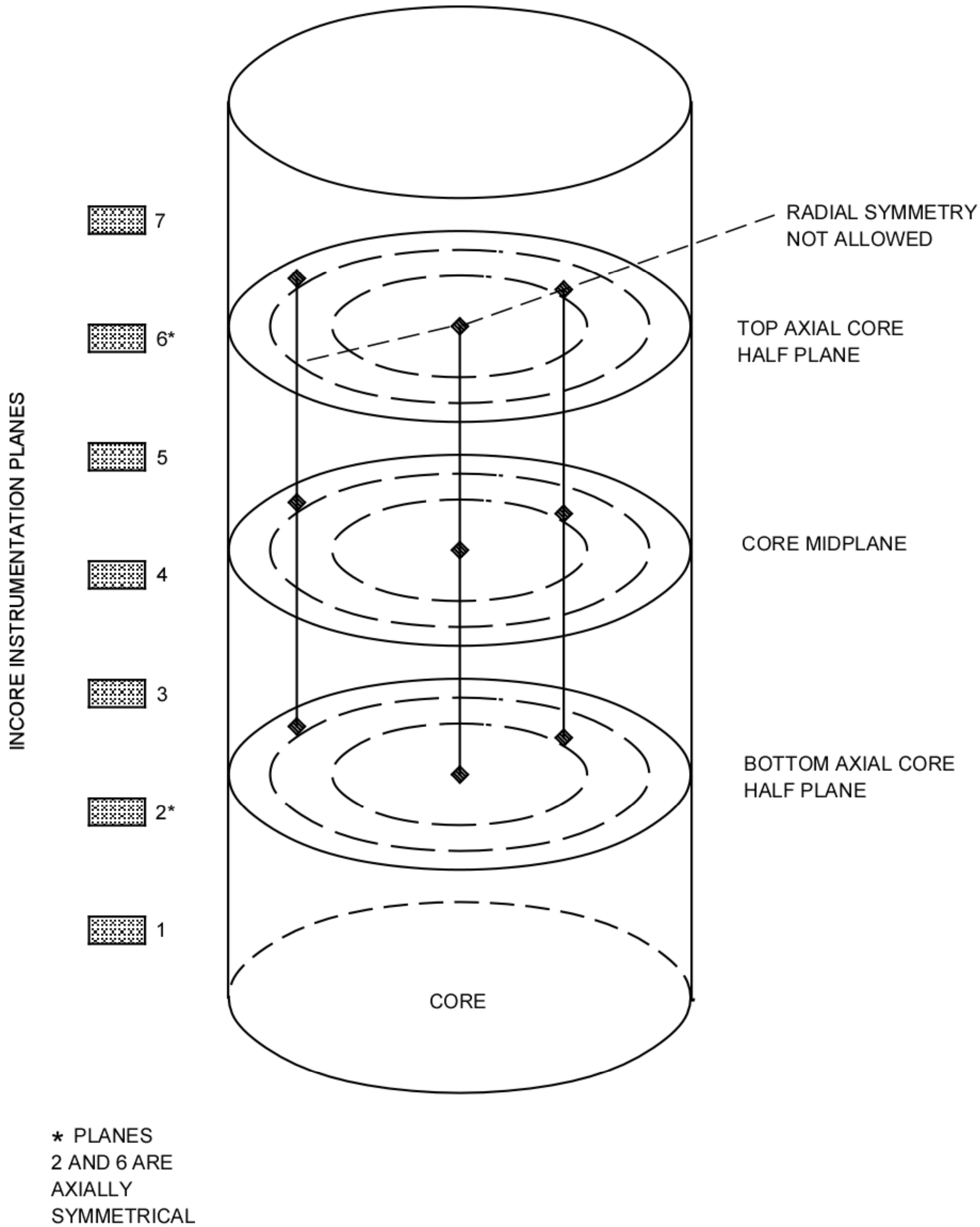


Figure 22-8 Minimum Incore System Conditions for API Measurement

This page intentionally blank

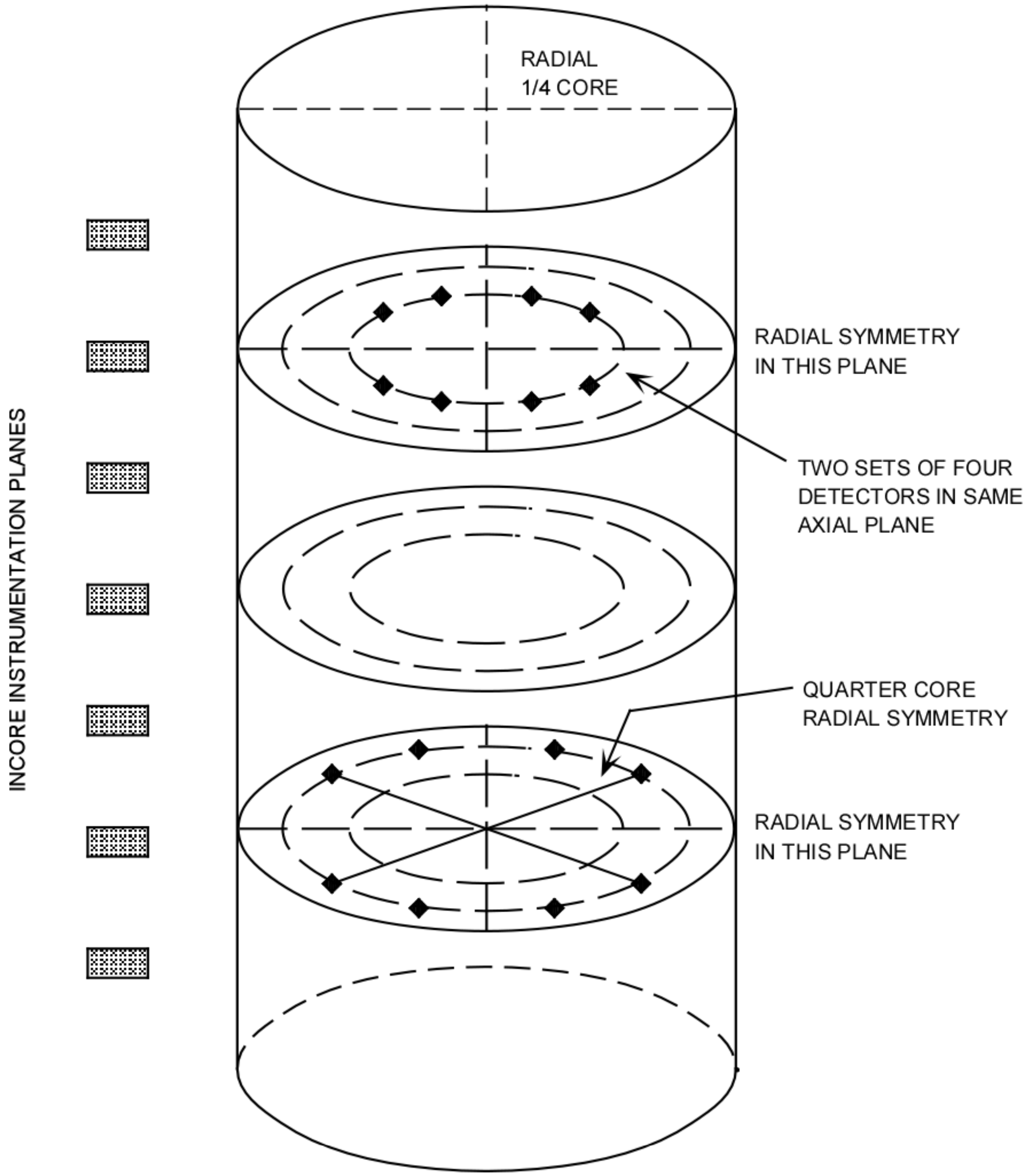
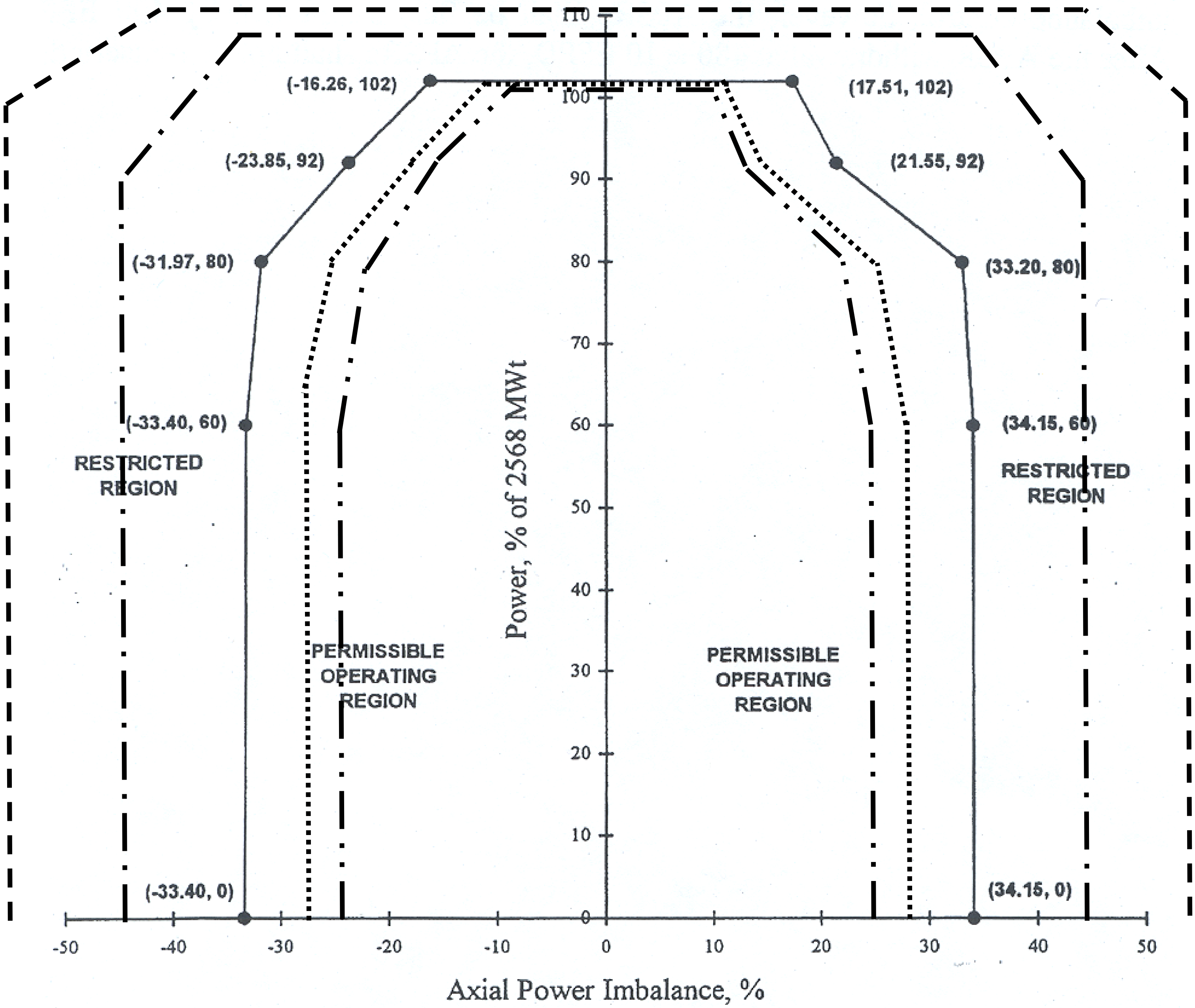


Figure 22-9 Minimum Incore Detector System for QPT Measurement

This page intentionally blank



API Protective Limits (Measurement System Independent)
API RPS Trip Setpoints
API Operating Limits - Full Incore Conditions
API Operating Limits - Excore Conditions
API Operating Limits - Minimum Incore Conditions

Figure 22-10 Composite Family of Curves for Typical API Limits (4 RCPs)

This page intentionally blank