5.0 PHYSICS ANALYSIS AND TESTS RELATED TO COMMISSIONING

5.1 General

An important phase of the commissioning program of a reactor is that during which tests are done to determine the nuclear characteristics of the reactor at very low power levels. In general terms, the test program for CANDU reactors is quite similar to that used for other reactor types. However, there are differences in detail because of the differences in nuclear characteristics of the reactor and in the design of the control and shutdown systems. In this section we will summarize the tests which are typically carried out during commissioning of the reactor and discuss some of the simulation work done with reactor physics codes both before and after the tests.

5.2 Physics Tests

5.2.1 Approach To Critical

The first major low power physics test is the initial approach to criticality of the reactor. In all reactors subsequent to the Pickering 'A' design there are no provisions for rapidly dumping the moderator as a means of shutting down the reactor and hence the capability to raise the level of the moderator in a reasonably rapid and controlled manner is not available. Therefore, the procedure used to prepare for the initial critical test is to put a highly conservative quantity of boron and/or gadolinium in the moderator, fill the calandria with moderator, and load the fuel channels with the appropriate initial fuel load. Criticality is then reached by removing the poison from the moderator by use of the ion exchange system. This is part of the reactor design as there is need to alter the poison concentration in the moderator during normal operation from time to time. Also, when the poison injection shutdown system is employed, the gadolinium poison must be removed by ion exchange before the reactor can be restarted.

An important aspect of the first approach to critical is providing the capability to reliably monitor the behaviour of the neutron population in the reactor core. Since the neutron flux levels in the core are very much lower than normal during this period of time, special instrumentation is provided for this purpose. A unique feature of the heavy water reactor which bears on the type of instrumentation needed is the photoneutron reaction which occurs when heavy water is exposed to a source of gamma rays. This means that the "natural" source of neutrons arising from spontaneous fission of the fuel in the reactor is augmented by photoneutrons produced from the gamma radiation from the ^{238}U in the fuel, as well as from cosmic rays. The result is that there exists a significant source of neutrons in the reactor even when the multiplication factor is quite small. It gives a flux of about one n/cm^2 s which is sufficient to measure with BF_3 type neutron counters if they are placed in the core. Consequently, it is not necessary to have an independent neutron source in the reactor in order to put the nuclear instrumentation on scale during the early part of the approach to critical.

This does not mean that portable neutron sources are not used at all at CANDU stations. These sources (e.g. radium beryllium sources) are available at the station during the startup program and are used merely to verify that the instrumentation is functioning properly in situ, but are removed from the core prior to beginning the process of approaching critical. (The strong source of neutrons from the photoneutron reactions also means that once the reactor has been operating even at low power for a short period and then a reactor trip occurs, the normal out-of-core neutron measuring instrumentation used by the reactor regulating system does not generally go off scale. Therefore, it is not required to employ special startup instrumentation except during the first approach to critical.)

Figure 5.2-1 shows the typical variation of the inverse of the neutron count rate from an incore BF_3 counter during the approach to critical at one of the Bruce reactors. This reactor was brought to

criticality by removal of poison from the moderator by ion exchange as will be the case for the 600 MWe reactors. This is a straight-forward process since the ion exchange process does not remove poison at a very rapid rate. This gives plenty of time to observe the rate at which the neutron population is changing and to measure the rate at which poison is being removed during the stage when the reactor is still subcritical. By the time criticality is approached the ion exchange system performance is quite predictable and can be controlled such that the rate at which criticality is reached is well controlled. Since the variation of reactivity with boron concentration in the moderator is a very linear function, the inverse count rate plotted against poison concentration is expected to be a straight line.

The special neutron counters used for the first startup are normally inserted in a tube which is inserted through the calandria inspection port at the top of the calandria. This permits locating the instruments well within the core. Three BF_3 counters are inserted to afford two-out-of-three trip protection.

In addition to the incore instruments there are special counters inserted in the cavities provided in the side shielding of the reactor for the normal regulating system instrumentation. They are designed to measure the flux in these cavities at levels lower than the normal regulating system instrumentation would detect. Therefore, as criticality is approached and as power is subsequently raised the incore counters are removed in stages but are not completely removed from the core until the signal on the special out-of-core counters is clearly reliable. The power rise is then monitored on those counters and protection is transferred to them until such time as the normal regulating system ion chambers come on scale. Prior to this time the reactor flux level is being controlled manually either by adjustment of the ion exchange flow, during the period that the reactor is sub-critical, or by adjustment of the position of a control absorber to raise power once

criticality is reached. When the normal regulating system instrumentation comes on scale (at approximately 10^6 full power) the reactor regulating system will automatically take over control of the liquid zone control level and will control reactor power level through the control computers from that point on.

Figure 5.2-1.1 shows a schematic of the start-up instrumentation arrangement typically employed. The range of sensitivity of this instrumentation is shown in Figure 5.2-1.2.

During the approach to critical and when criticality is reached the concentration of poison in the moderator is carefully measured and the results are compared with calculations that were done to predict the poison concentration at criticality. Also by observing the variation of the neutron population with poison concentration prior to criticality and making extrapolations, any unexpected results pertaining to the reactivity state of the core at critical can be revealed well before criticality.

5.2.2 Calibration Of Zone Control System

After intial criticality is reached and power is raised to about 10^4 of full power, the tests related to checking the nuclear characteristics of the reactivity control and shutdown mechanisms begin. The system normally tested first is the liquid zone control system.

Since the cross section of ^{10}B is proportional to the inverse of the neutron velocity over a significant energy range, the effect on the reactivity of the reactor when boron is added to the moderator can be accurately calculated. Therefore it is the practice in the commissioning of CANDU reactors to use boron in the natural form as the reactivity "scale". It is considered that the most accurate way of knowing the concentration of boron in the moderator is to weight accurately the quantity <u>added</u> in the form of B_2O_3 and calculate the concentration, knowing the volume of moderator. This means that when

the reactivity devices are calibrated against boron they have to be put in a configuration such that boron can be always added to the moderator.

To calibrate the liquid zone control system, poison is removed from the moderator and the zone control system is allowed to fill to maintain criticality. Calibration would not begin until all the compartments in the system are filled with H_2O. At this point, carefully measured quantities of B_2O_3 is added to the system in increments. When the poison ia added the automatic regulating system would reduce the level of H_2O in all compartments uniformly such that the reactor is maintained critical. When it is clear that the level of H_2O in the compartments has stabilized following addition of an increment of poison, the value of the level is recorded. Another increment of poison is then added to the moderator and the process repeated until the water level in the compartments have been reduced to near zero. A lower limit would be set based on the need to maintain control of the reactivity. This means that the compartments would not be allowed to empty completely.

5.2.3 Reactivity Calibration Of Individual Shutoff Rods

During the approach to critical and the calibration of the liquid zone control system the shutoff rods are, of course fully withdrawn from the reactor. To verify that these rods are mechanically functional and that the absorber element has the expected reactivty effect, each of the shutoff rods are driven into the reactor in turn and then withdrawn. Before this process is initiated the boron level is adjusted in the moderator such that the liquid zone control system is at its nearly full configuration. This is because, having measured the reactivity worth of the zone control system, it is now much more convenient from a time and cost point of view to use it as the reactivity scale rather than adjustment of the poison level in the moderator. Since the reactivity effect of any one shutoff rod is worth less than the reactivity effect of draining all compartments in the H_2O zone control system, it is possible to measure the reactivity worth of each

shutoff rod by driving them in one at a time and allowing the zone control system to reduce level automatically. The level change is noted and the shutoff rod is then removed again. The process is repeated for each shutoff rod.

5.2.4 Calibration Of Mechanical Control Absorbers

These four devices, which are physically the same as shutoff rods, are also measured one at a time against liquid zone level changes following the same procedures used for the shutoff rods.

5.2.5 Calibration Of Individual Adjuster Rods

The initial approach to critical and the other tests which have been described would all be done with the adjuster rods all fully inserted in the core. There are two reasons for this. Firstly, this is normal operating state of the reactor so it is preferable to check the reactivity worth of the other devices in this core configuration. Secondly, the reactivity effect of completely withdrawing all of the adjuster rods is one of the tests to be done. Since the combined worth of all adjuster rods exceeds the reactivity worth of the zone control system, this determination is done by adding poison to the moderator. Since addition of poison can be done more accurately than removal, it is necessary to begin the measurement with all adjuster rods inserted.

The calibration of the individual adjusters is done by withdrawing each rod individually and compensating by raising the level of H_2O in the zone control system. This means that the initial level in the zone control system before this series of measurement begins would be adjusted by boron addition to the moderator such that it is in the near empty condition. After each rod is withdrawn the change in liquid zone control level would be recorded and then the rod would be reinserted. The process is repeated for each individual adjuster rod.

It might be argued that because of symmetry considerations it is not necessary to measure all the rods. However, this is normally done to verify that all of the rods are functional and that the quantity of absorbing material specified in the design is present. Manufacturing tolerances can also introduce small variations amongst symmetrically placed rods.

5.2.6 Flux Mapping Measurements And Reactivity Calibrations Of Groups Of Reactivity Devices

It is desirable to perform measurements of the outputs of the vandium flux mapping detectors during the low power commissioning phase. Although the normal instrumentation used to measure the current from these devices would not be on scale at these flux levels in the reactor, it is possible to get quite good readings using special picoammeters. These measurements verify that all the flux detectors are functioning and are useful to compare the relative readings from these detectors with corresponding predictions from simulation of the flux distribution in the reactor, with a 3-dimensional diffusion code.

In addition to recording the output from the vanadium self-powered detectors, some independent flux measurements are generally made as well. In the Pickering commissioning tests flux distributions were measured by a copper wire activation as reported by Critoph[1]. In Bruce both copper wire activation and use of a small fission chamber which could be transversed across the core where employed. The results from the "travelling" fission chamber were shown to be reliable in comparison with copper wire activation measurements so it is anticipated that the fission chamber scans will be used in future reactors. Typically measurements will be made by the fission chamber in at least two different directions. The exact location would depend on the availability of a guide tube through which the fission chamber can be moved. The use of the special tube provided for incore approach-to-critical instrumentation would probably be used for the vertical measurement and one of the sites which would normally contain incore flux

monitors in the horizontal direction would be used to obtain data across a horizontal diametral line. The location of these sites is not critical since the intent is to compare the measurements with calculation and with data obtained from the flux mapping detectors.

These special measurements of the flux distribution are normally combined with measurement of the adjuster rod reactivity worth and the mechanical control absorber system reactivity worth when the devices are ganged as they are normally operated by the automatic regulating system. As mentioned previously, adjuster rods are driven out in groups or "banks" when excess reactivity is required by the regulating system to compensate for xenon buildup or fuel burn-up during periods of extended fuelling machine unavailability. Therefore, their reactivity worth is measured by adding boron to the moderator in measured increments and allowing the regulating system to withdraw the adjuster rods in their normal bank sequence to compensate for this poison addition (the zone control system compensates during each bank withdrawal as described in section 3). This permits comparison of the adjuster rod system reactivity with the calculation done during the design of the core. Flux data from the flux mapping detectors and a scan with the fission chamber would be done perhaps after each bank of adjuster rods have been withdrawn until all rods are out.

Similarly, measurements are made of the reactivity worth of the mechanial absorbers when driven according to the sequence in which the regulating system would drive them in when negative reactivity is required beyond the range of the zone control system. They are normally driven in banks of two. Flux data would be measured also during that operation. In the case of the mechanical control absorbers the starting configuration for the reactor would be with all adjusters rods in and all mechanical control absorbers in. This would be accomplished by removing boron by ion exchange. Then the reactivity worth of the mechanical control absorbers would be measured by adding boron and allowing the regulating system to withdraw the rods in their normal

sequence* to compensate. Two or three sets of flux data would be obtained during this process as well.

5.2.7 Dynamic Tests

There are two types of dynamic tests of the regulating shutdown systems that are typically performed during the low power commissioning program. One is to check the performance of the fast power setback feature of the reactor regulating system. As previously described, the reactor regulating system will release the clutches of the four mechanical absorbers and allow them to fall into the core under gravity in the case where rapid power reduction is called for but conditions are not severe enough to initiate shutdown system action through a reactor trip. To test this feature a stepback condition is intentionally initiated and the outputs from the normal regulating system or protective system ion chambers are monitored to verify that the flux level in the reactor is decreasing as expected.

The other type of dynamic test done is to activate each of the two shutdown systems in turn and monitor the consequent transient change in flux in the reactor. In these cases, because of the very large changes in flux shape that occur and because of the importance of the delayed neutron source distribution on that transient shape, the flux rundown is measured by placing about three special fission chambers in the core at different positions as well as monitoring the signal from the special BF_3 counters placed in the out-of-core ion chamber cavity. With this test fast brush recorders are required to measure the rapid changes in the flux at the detectors following a shutdown system activation.

5.2.8 Heat Transport System Temperature

A reactivity change associated with uniformly heating the coolant and fuel is measured by raising the coolant temperature with pump heat i.e. by appropriate adjustment of the flow on the secondary

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*This sequence would be the reverse of the insertion sequence.

side of the primary heat transport system heat exchangers. Since this reactivity effect is negative the test is usually initiated with adjuster rods all fully inserted. As the coolant (and fuel) is heated the regulating system would tend to drive out the adjuster rods in the same manner as would occur during compensation for xenon transients at high power (see section 3). Since the adjuster rod reactivity worth was measured previously, the number of adjuster rods which have to be withdrawn can be converted to the reactivity worth of heating the coolant and the fuel. No special instrumentation is required for this measurement.

5.2.9 Moderator Temperature Coefficient Measurement

Although this temperature coefficient is not very important from an operating point-of-view, it is usually calculated because of interest from the reactor physics point-of-view. As in the case of the heavy water coolant of the heat transport system, the temperature of the moderator is changed by use of pump heat since nuclear heating is very small in magnitude. However, it is not possible to cause very large changes in moderator temperature this way so there may be problems getting good precision from this type of measurement.

5.2.10 Some Typical Results From Power Physics Tests

Critoph in his 1978 lectures at the Winter College[1], presented some data from commissioning tests at Pickering and Bruce. Therefore, the following will tend to focus on those areas which were not covered in his lectures.

5.2.10.1 Approach To Critical For Bruce A

Criticality was reached in the Bruce reactors in a manner very similar to that described in section 5.2.1. The reactor was completely loaded with the initial fuel load and the calandria was filled with moderator containing a conservatively high poison concentration. Criticality was reached by extraction of the poison using the ion exchange columns in the moderator purification system. In this case the moderator contained some gadolinium as well as boron as the poison injection system had been tested with gadolinium.

Six ion exchange columns were prepared for the first approach to critical. They contained resins which were capable of extracting both gadolinium and boron although four of the columns had a mixture which had a higher affinity for boron. Because of the concentrations of gadolinium and boron initially in the moderator some of the resins had to be changed because of becoming saturated prior to criticality being reached. For this reason the inverse count rate from the incore BF_3 counters plotted versus time is not a smooth exponential curve as one would expect if it was simply one ion exchange column operating on constant flow and not saturating. This is shown in Figures 5.2-2 and 5.2-3. However, the poison concentrations were measured at various times and converted to an equivalent reactivity rate. The plot of the inverse count rate versus this inferred reactivity load is shown in Figure 5.2-1. Note the curve is linear over quite a wide range of count rates. Extrapolation to the zero inverse count rate axis indicates that the poison concentration at critical was equivalent to about 70 mk excess reactivity. This agreed quite well with predictions.

5.2.10.2 Shutdown System Dynamic Tests

Considerable attention was given at Bruce A to the measurements of flux change in the reactor at various points following activation for the shutdown systems. This was because of the desire to obtain good experimental verification of the IQS method used to calculate the transient behaviour of these systems in accident analysis.

Tests were done following insertion of all 30 shutoff rods; insertion of 28 injection shutoff rods (2 most effective missing); 6 poison injection nozzles injecting gadolinium poison; a single poison injection nozzle injecting poison; and both the shutoff rod system and the poison injection system being activated together.

Figures 5.2-4, 5.2-5, 5.2-6 and 5.2-7 shows some of the results obtained for the 28 shutoff rod tests. Figure 5.2-4 and 5.2-5 are from incore detectors at two different radial positions in the core. Both of these detectors were positioned below the core centre-line. Figure 5.2-6 is from an ion chamber in the ex-core cavity at the top of the calandria which houses the normal regulating and protective system ion chambers. Comparison of these three figures show the spatial dependence of the power rundown transient. Figure 5.2-7 shows the longer term characteristic of the power rundown. The good agreement with calculation indicates that the total reactivity worth of the shutoff rod system was incorrectly predicted. Further information on these tests is given by Dastur et al[17].

Figures 5.2-8 and 5.2-9 show two in-core measurements when the poison injection shutdown system is activated. One of the nozzles was intentionally placed out of the service to test the condition assumed for purposes of safety analysis. Figure 5.2-8 is data measured in the outer region of the core at the side closest to the point of injection. Figure 5.2-9 is about 4 m away on the opposite side of the core. The difference between these arise from the fact that the jets are longer at the end of the nozzle closest to the poison injection tanks. This "gradation" along the nozzle is not simulated in the modelling of the system. This is probably the reason for the larger discrepancy with calculation in Figure 5.2-8. Figures 5.2-10 and 11 show the longer term power history for the poison injection system. Comparison with Figure 5.2-7 shows that the short term behaviour (1→3s) is quite similar to the shutoff rods. However, the reactivity worth of the poison continues to decrease beyond that point as the poison disperses. As discussed in Section 3, no attempt is made to simulate the dispersion in the analysis so we do not have calculated data to compare with Figure 5.2-11.

Figure 3.2-20 shows the kind of modelling used to simulate the poison injection system at two points in the time during the injection.

Figures 5.2-12 and 5.2-13 show results obtained from loading gadolinium poison into only one of the poison injection tanks. This was done as a more definitive check of the modelling methodolgoy since the complication associated with interaction of jets from more than one nozzle is eliminated. The good agreement with calculation indicates that the methods used were good. The difference between the two detectors is quite pronounced because of their position relative to the nozzle. This is a good demonstration that the spatial effects are well predicted by the CERBERUS code using the IQS method.

Figure 5.2-14 shows the result of a test in which both shutdown systems were simultaneously activated. The numerical modelling of this situation in the CERBERUS code is very complex since there are many regions having different nuclear properties and in some cells the effects of threee devices (adjuster, shutoff rods and poison injection) must be simultaneously accounted for. We have a computer program which performs the data preparation task directly from the geometric definition of the various devices. This minimizes errors and greatly reduces manpower effort in preparing input. The agreement between experiment and calculation in this case substantiates the approximations that necessarily must be made in the modelling.

5.2.10.3 Flux Distribution Measurements

Figures 5.2-15 and 5.2-16 illustrate the kind of data obtained from performing detailed measurement of the flux distribution across a diameter of the core. These results are from Bruce A commissioning also. Measurements of the same flux distribution were made two ways. One method was to insert a straight copper wire in a carrier tube and measure the activation of the copper after an irradiation of about 20 minutes. This method was also used in the Pickering and Gentilly-1 commissioning programs. The other method was to traverse the core with a small fission chamber by moving it in small increments and stopping

long enough to record the data. Figure 5.2-15 shows that the two methods agree very well. Consequently, it is anticipated that the "fission chamber scan" approach will be used in future commissioning programs because of its simplicity and potential for automation (by putting it on a drive mechanism and continuously recording the output).

Figure 5.2-16 shows that the measurements agreed very well with calculations using the two group diffusion code methods discussed in section 3.

5.2.10.4 Zone Control System Calibration

The core design of each of the four units at the Bruce A station is identical. This means that the measurements of the zone control system reactivity worth should be the same for the four units. Comparing the actual data from the four units provides an indication of the precision of the experimental method employed. This data is shown in Figure 5.2-17. The small scatter in the experimental data indicates that the technique of measuring the boron poison added to the moderator system as the reactivity "scale" is adequately precise.

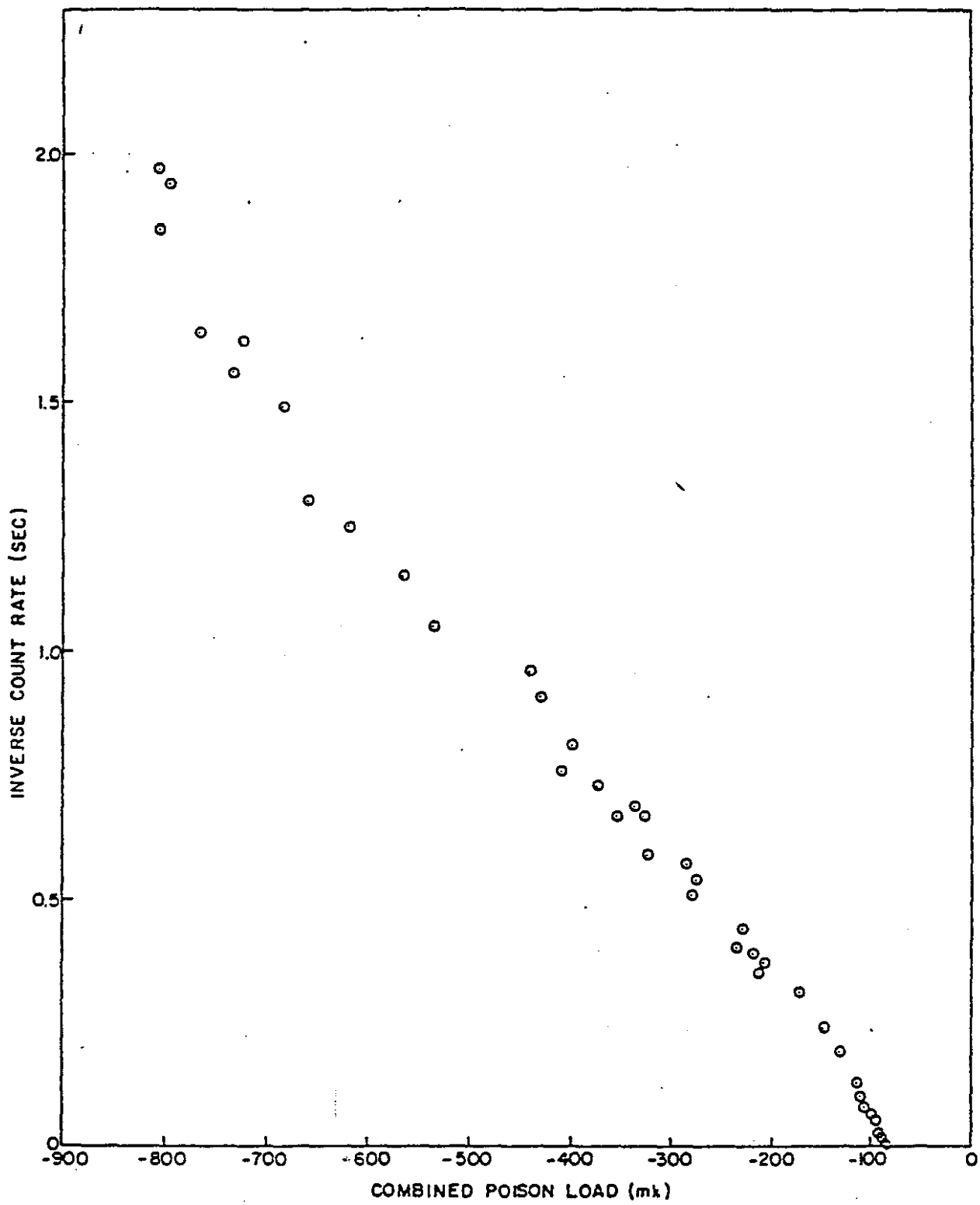

FIGURE 5.2-1 POISON LOAD VS INVERSE COUNT RATE CHANNEL E INCORE BF_3 COUNTER

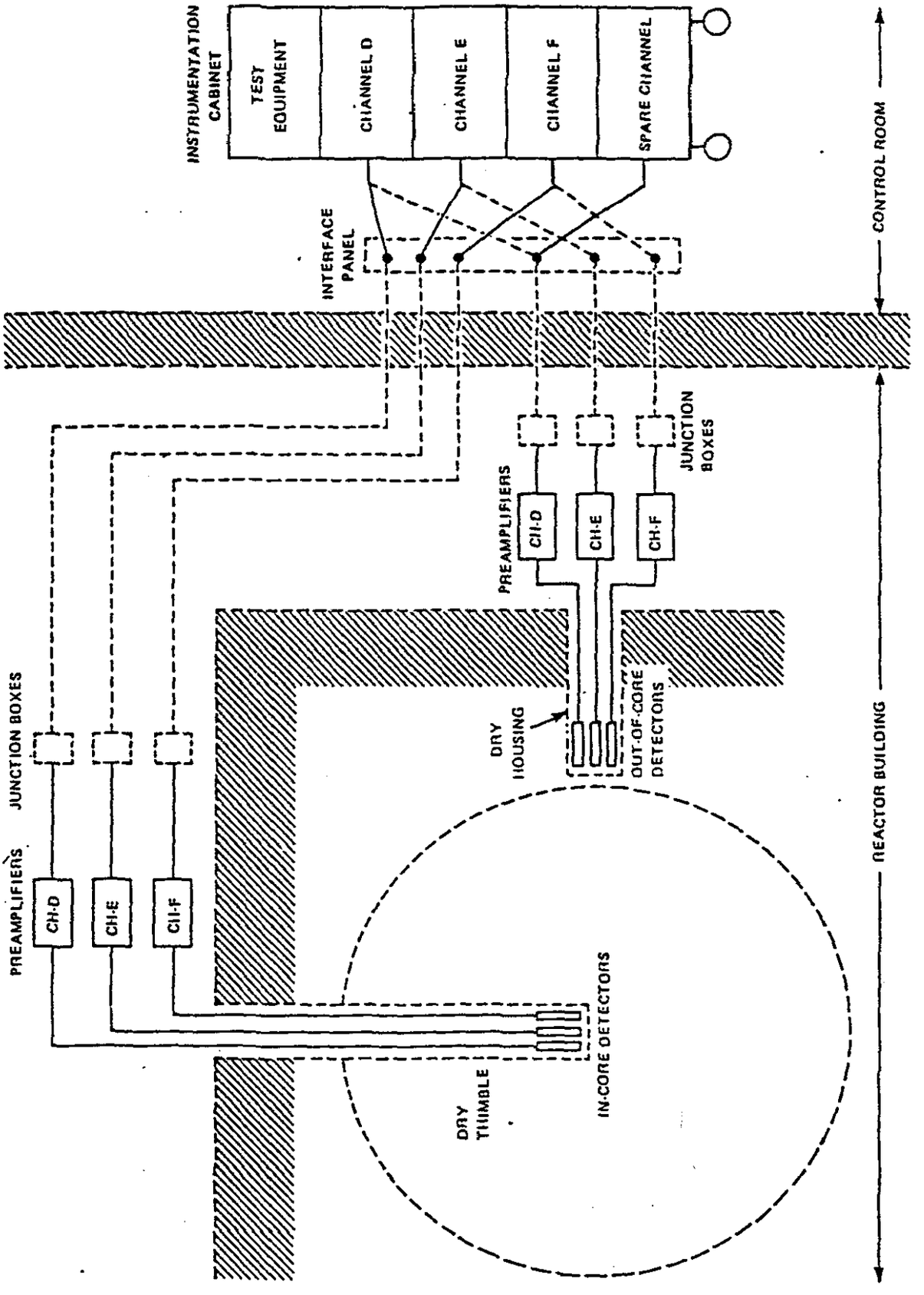

FIGURE 5.2-1.1 ARRANGEMENT OF START-UP INSTRUMENTATION

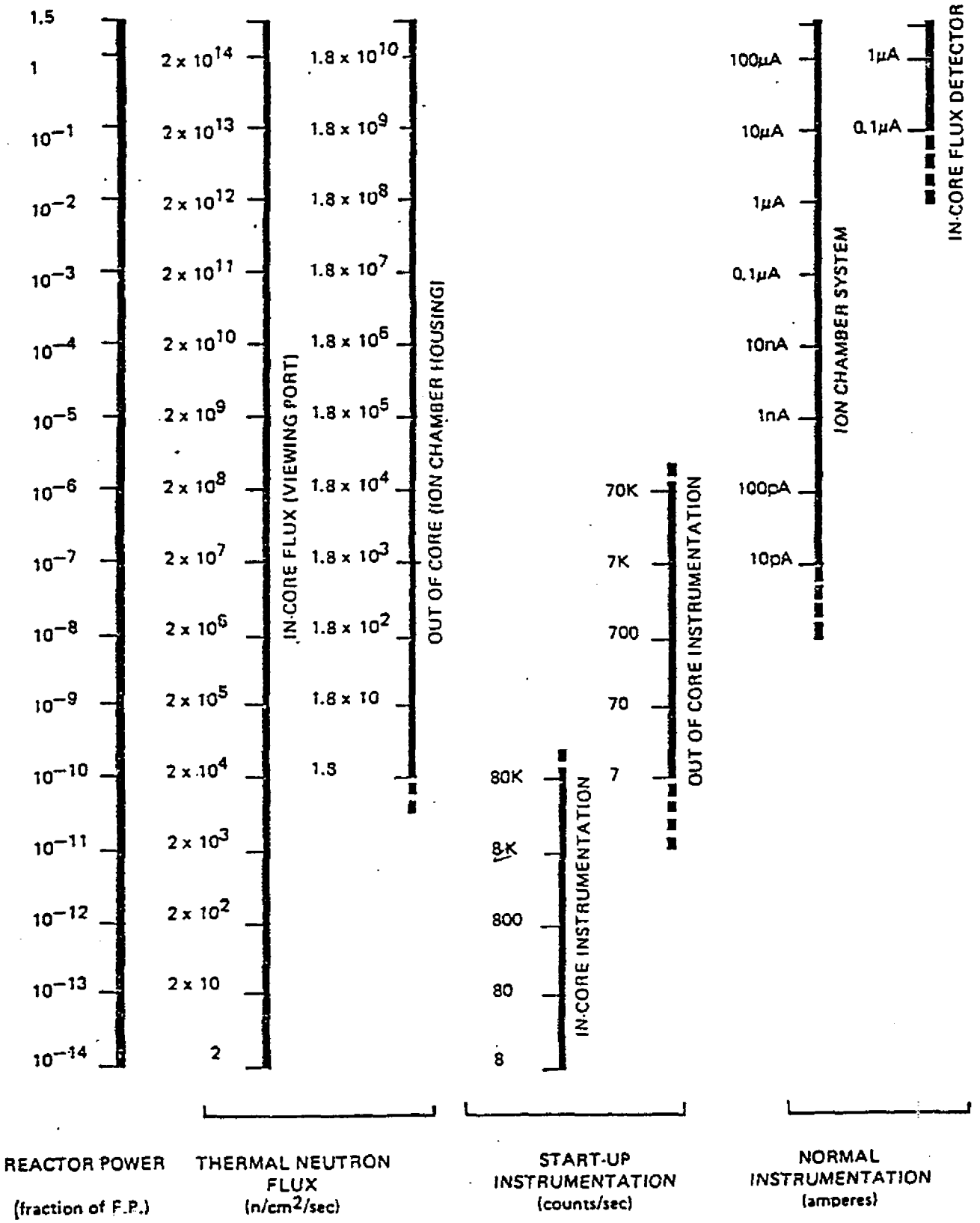

FIGURE 5.2-1.2 RANGE OF SENSITIVITY OF NUCLEAR INSTRUMENTATION FOR REACTOR POWER MEASUREMENT

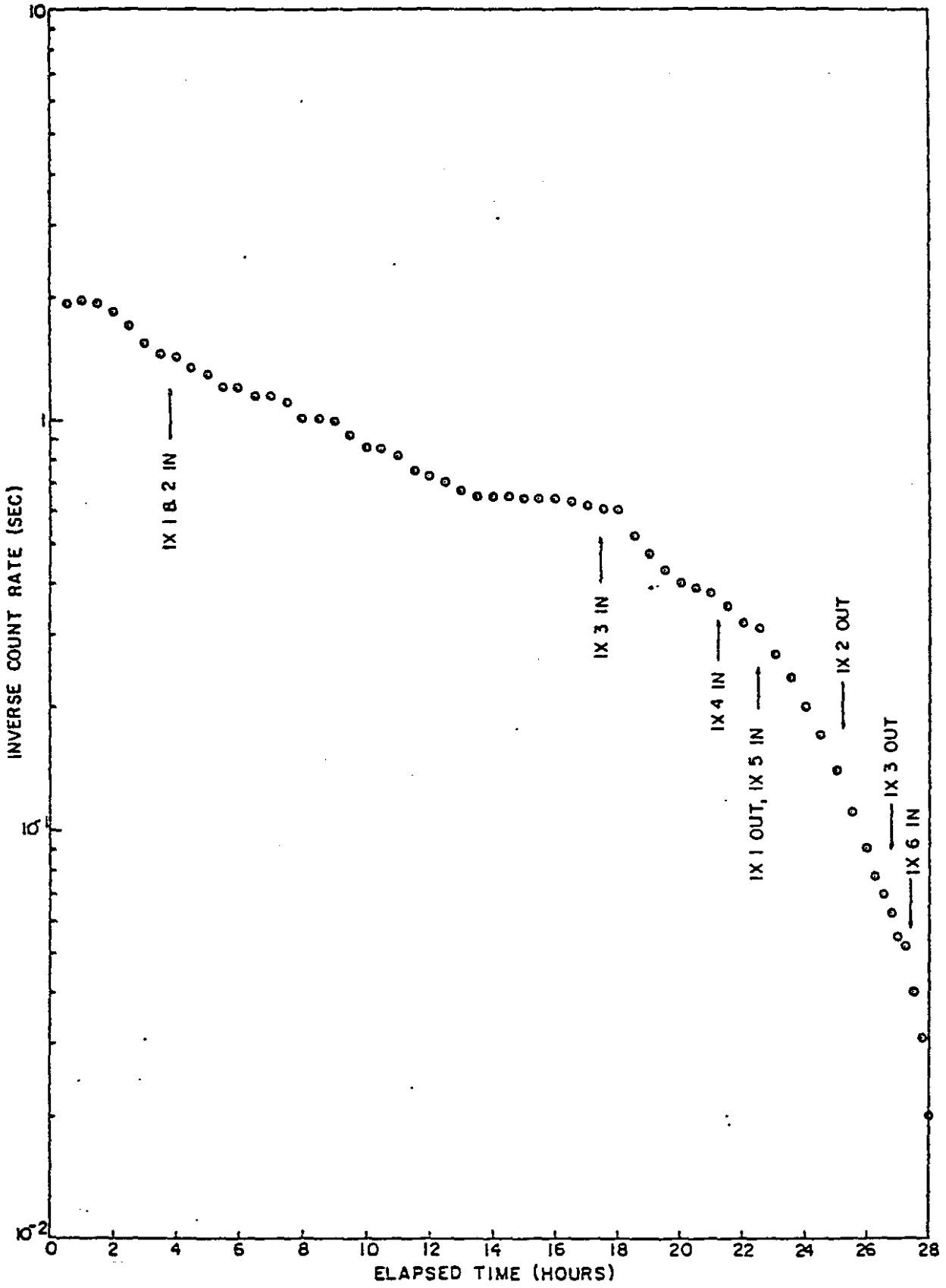

FIGURE 5.2-2 FIRST APPROACH TO CRITICAL CHANNEL D INCORE BF_3 COUNTER

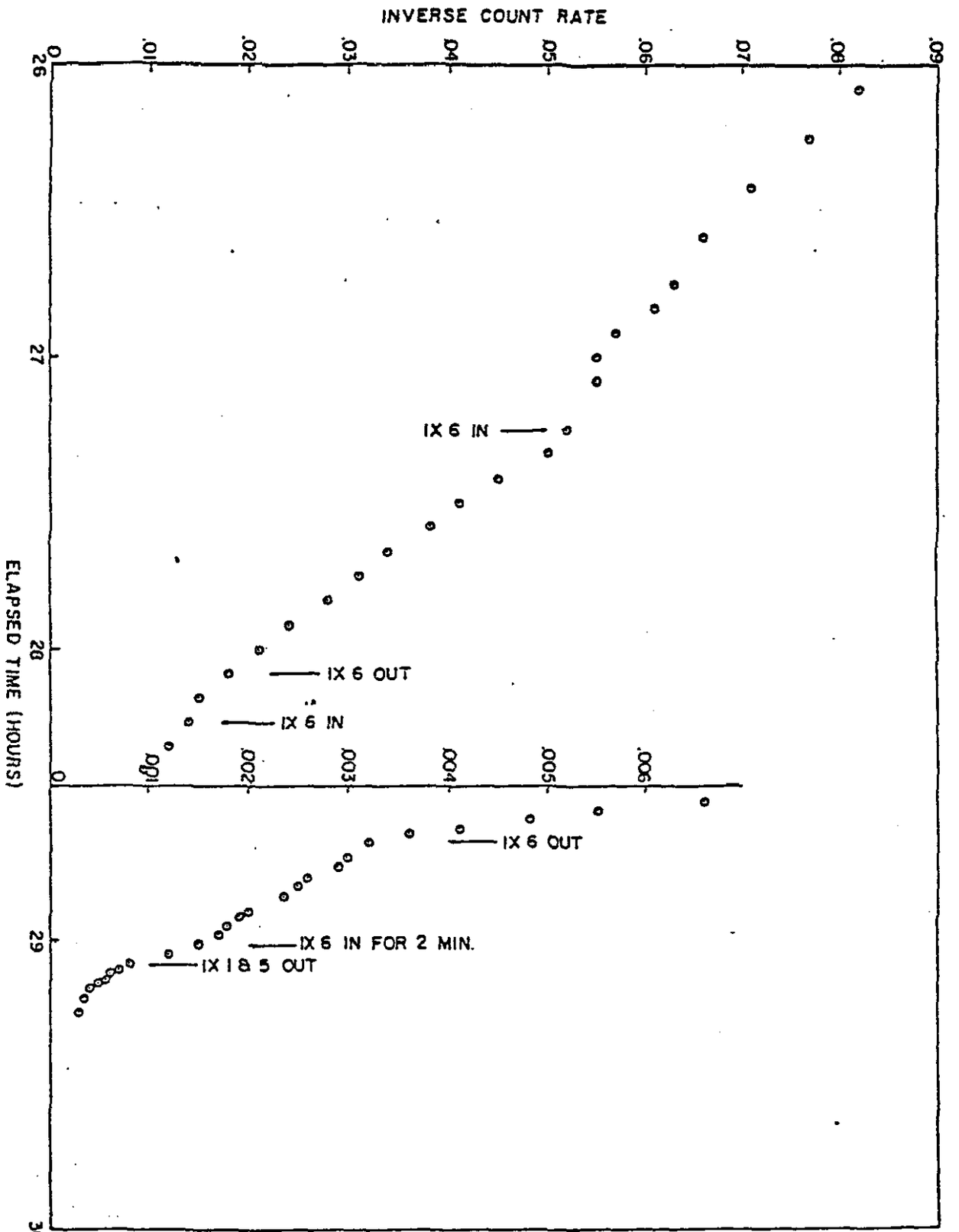

FIGURE 5.2-3 CHANNEL D INCORE BF_3

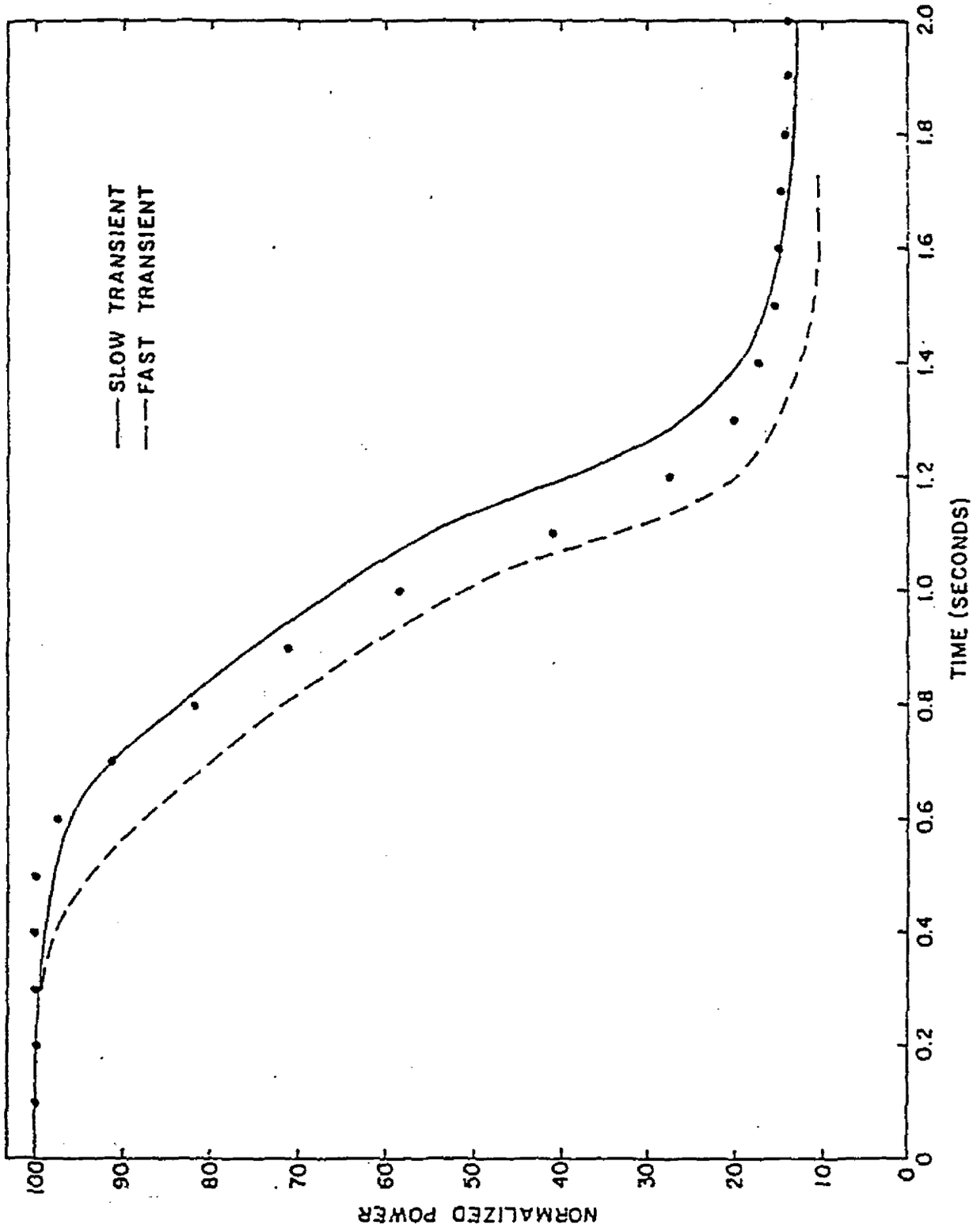

FIGURE 5.2.4 S.I.C. NFM 2-N
SDS1 TEST — 28 RODS

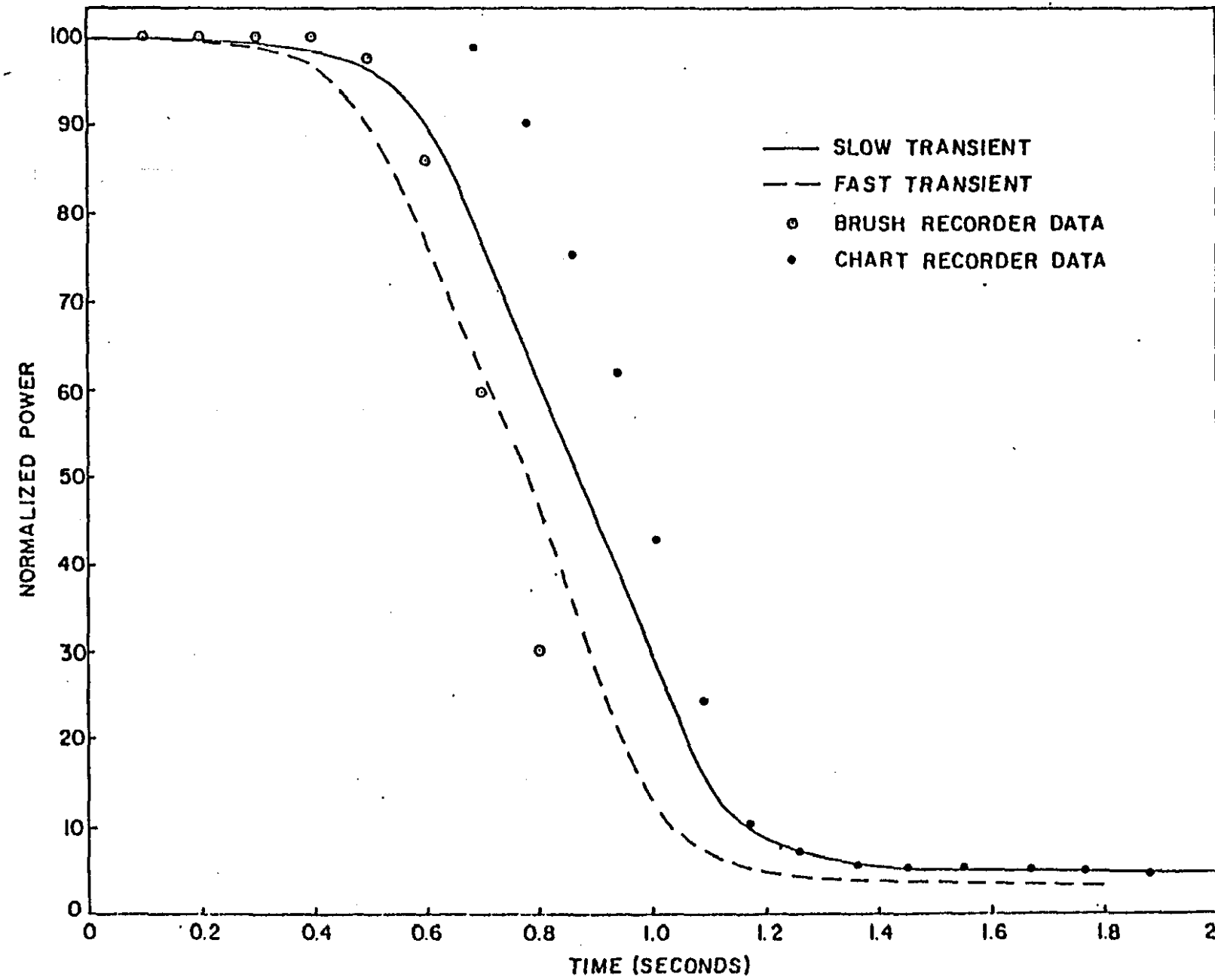

FIGURE 5.2-5 S.I.C. NFM 1 - C
SDS1 TEST — 28 RODS

TDAI-244

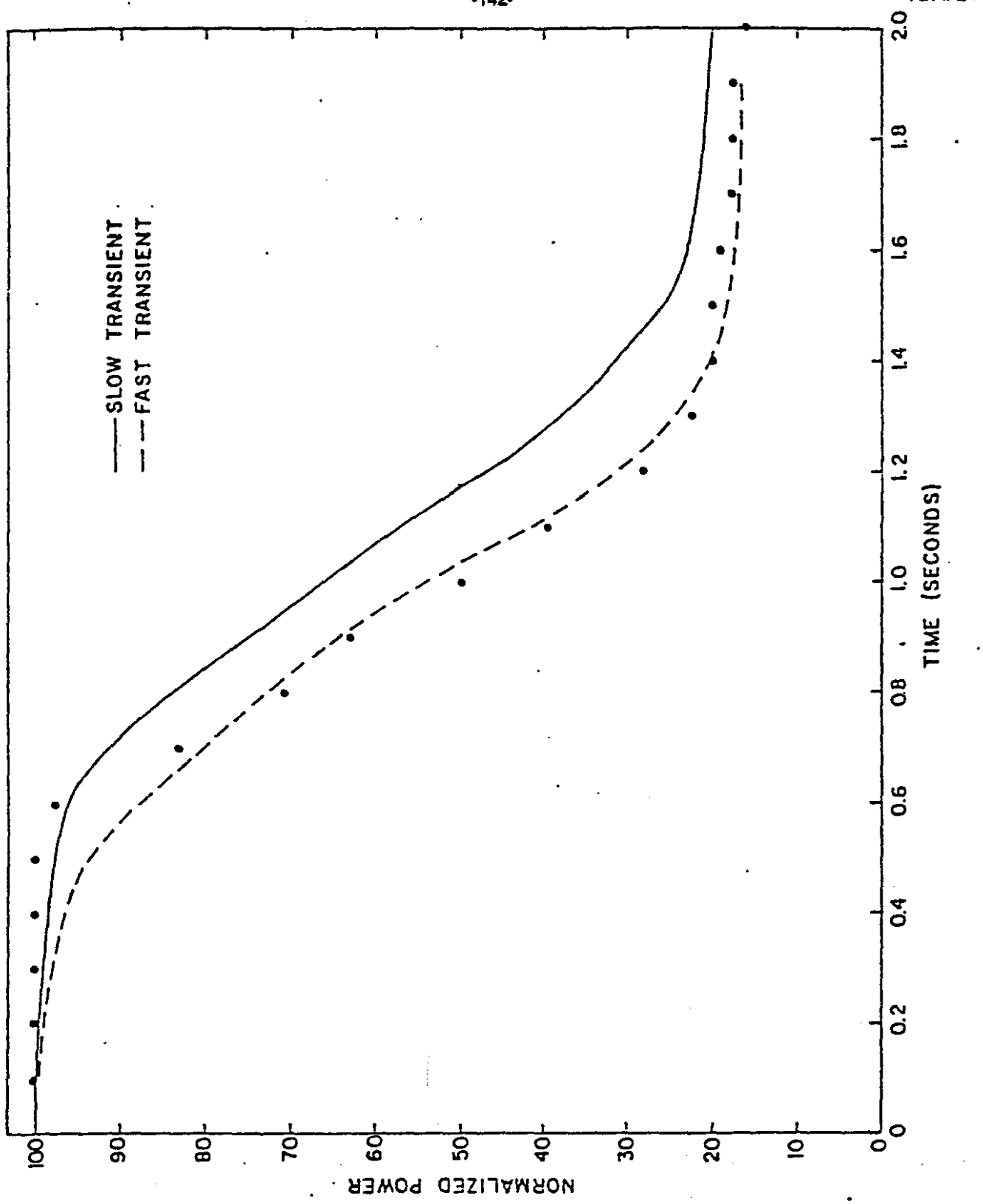

FIGURE 5.2-6 CHANNEL J SDS 2 ION CHAMBER
SDS1 TEST — 28 RODS

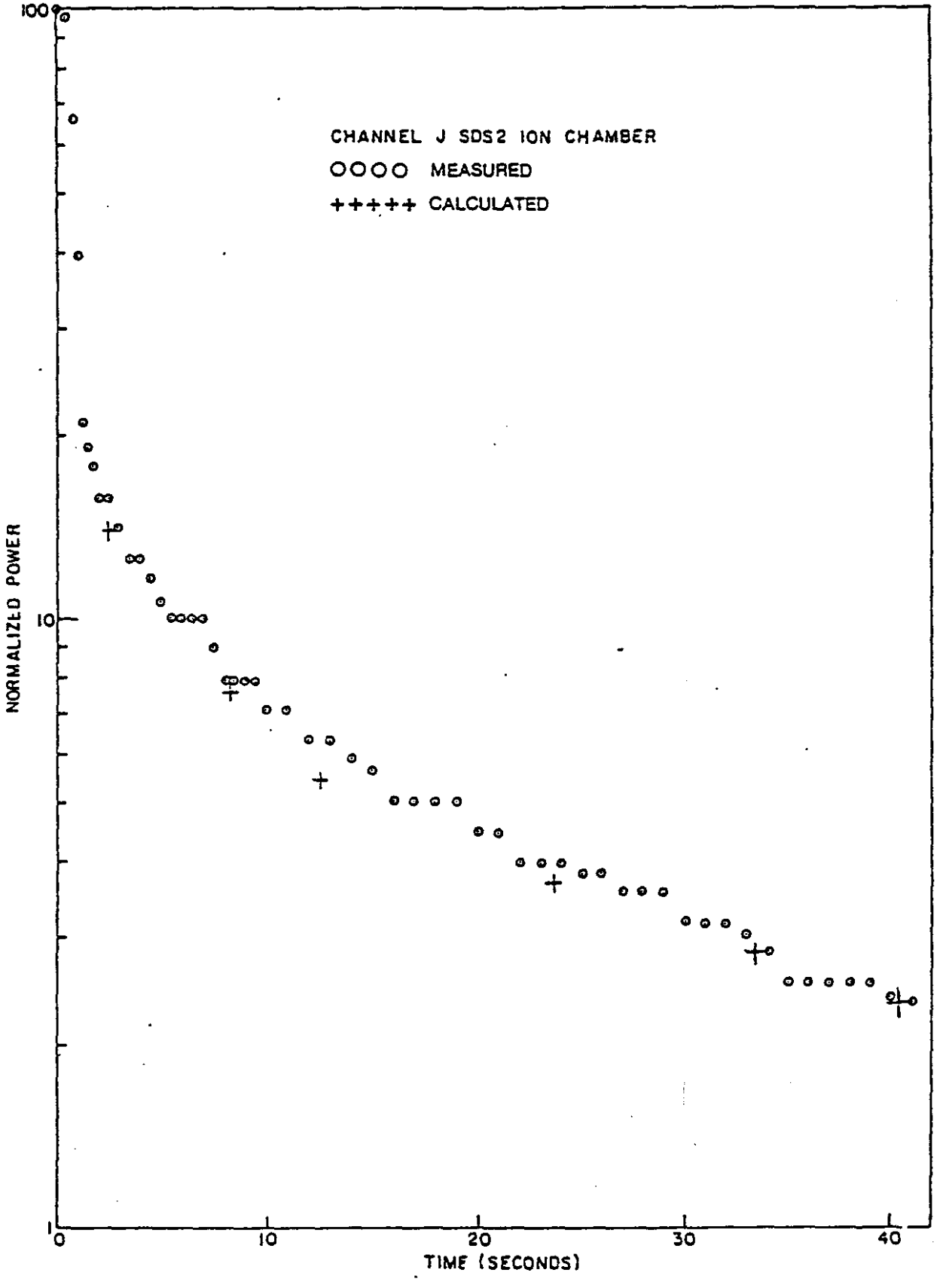

FIGURE 5.2-7 SDS 1 TEST - 28 RODS

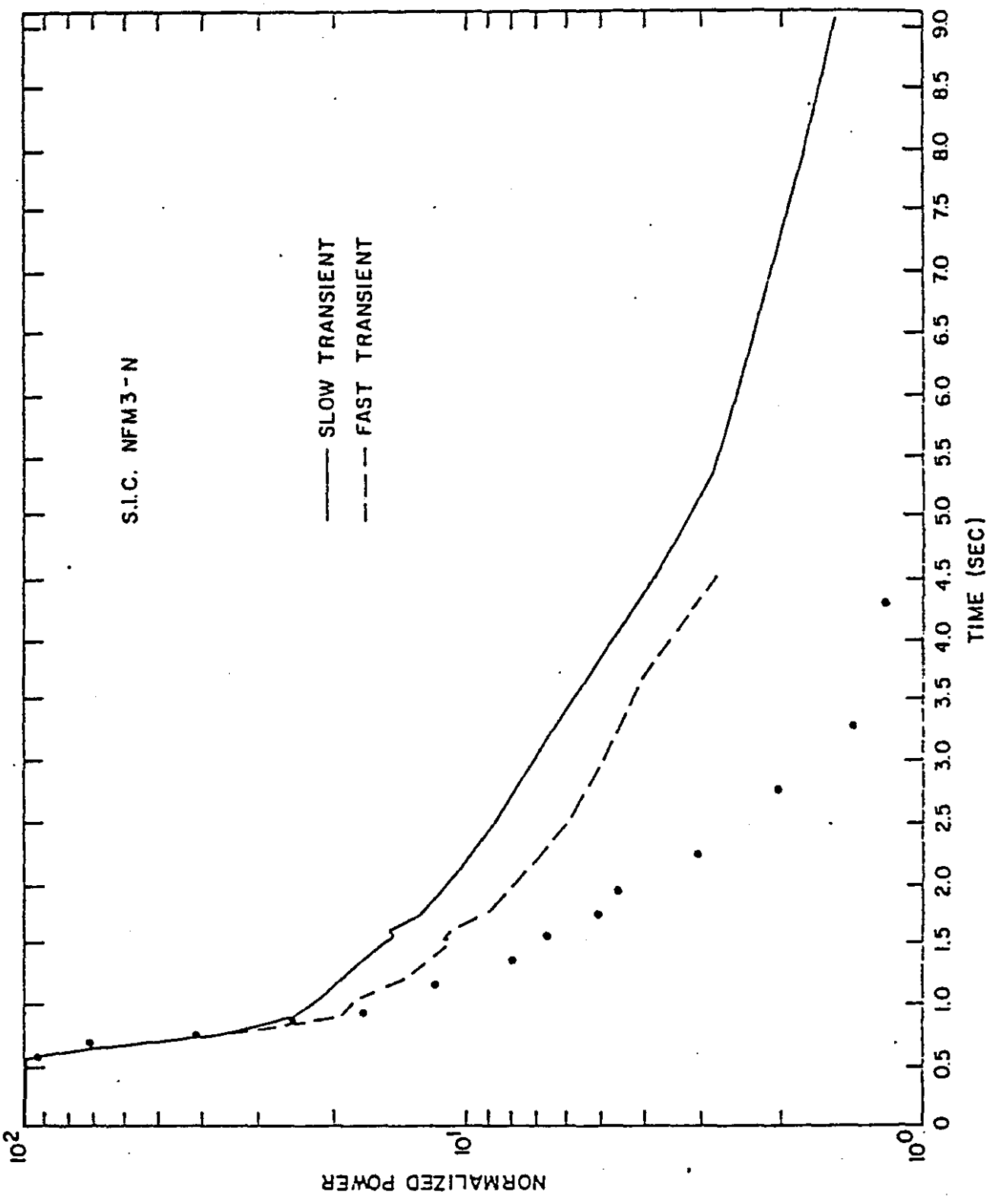

FIGURE 5.2-8 SDS2 TEST - 6 TANKS

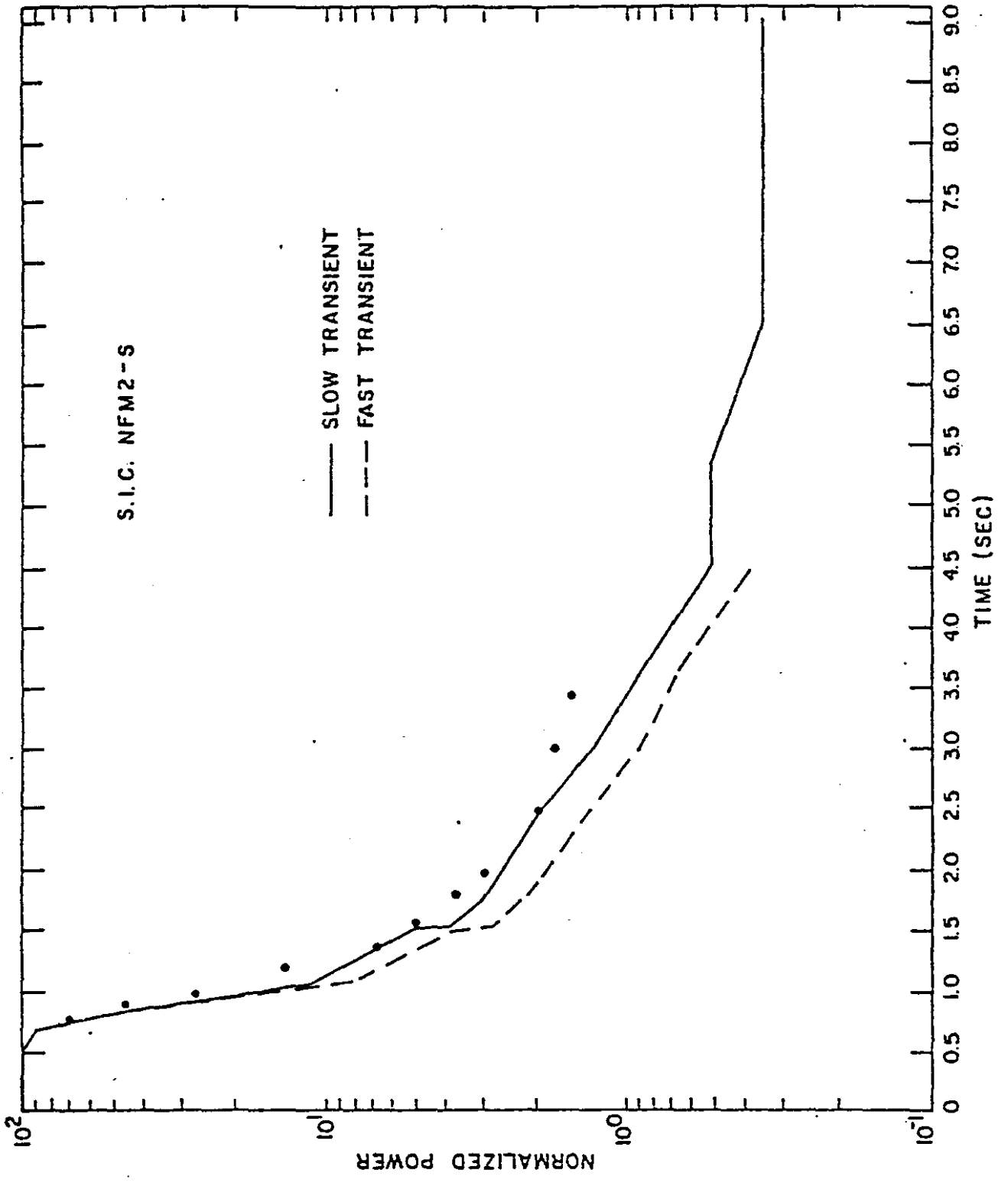

FIGURE 5.2-9 SDS 2 TEST - 6 TANKS

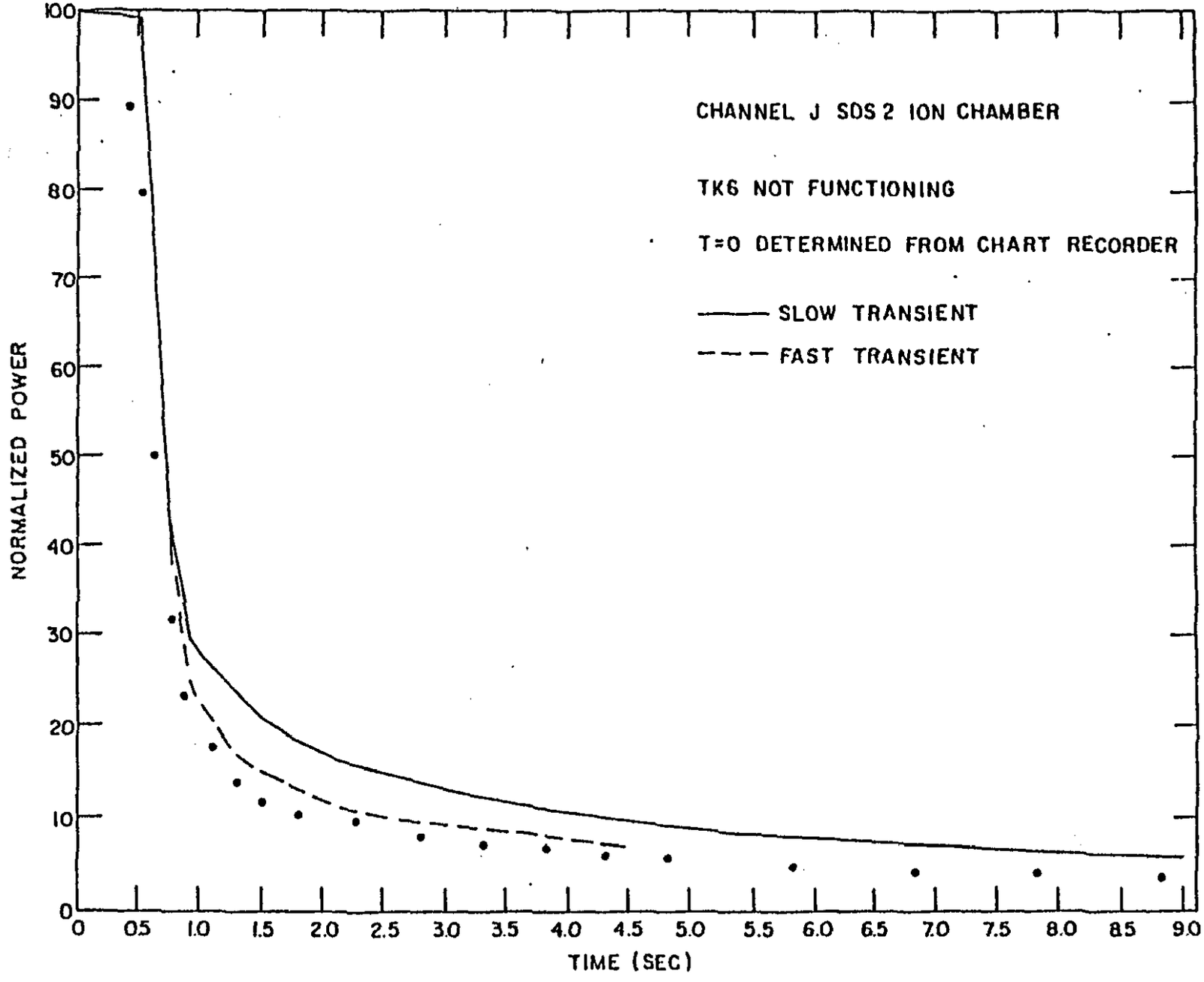

FIGURE 5.2-10 SDS 2 TEST - 6 TANKS

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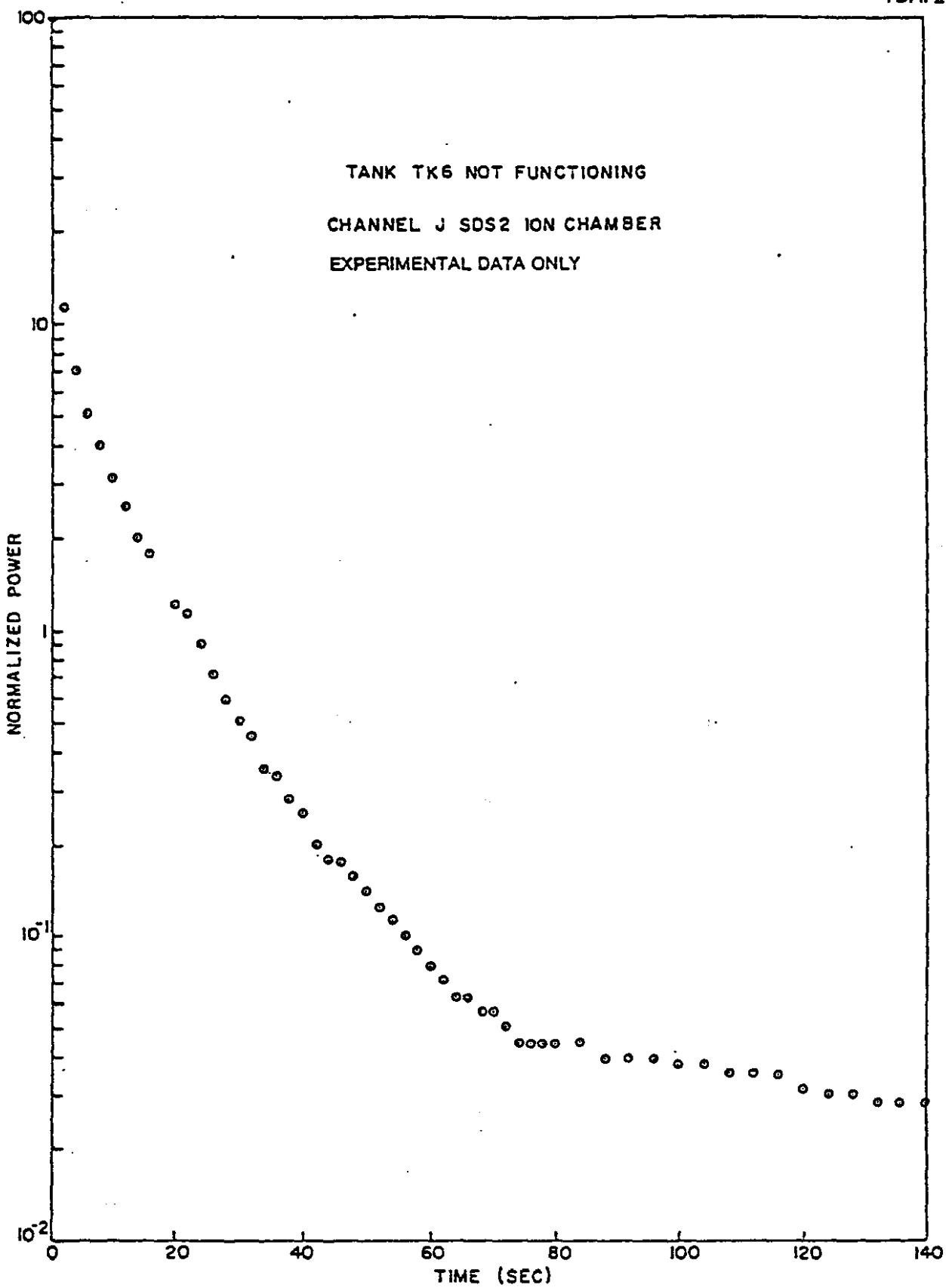

FIGURE 5.2-11 SDS 2 TEST - 6 TANKS

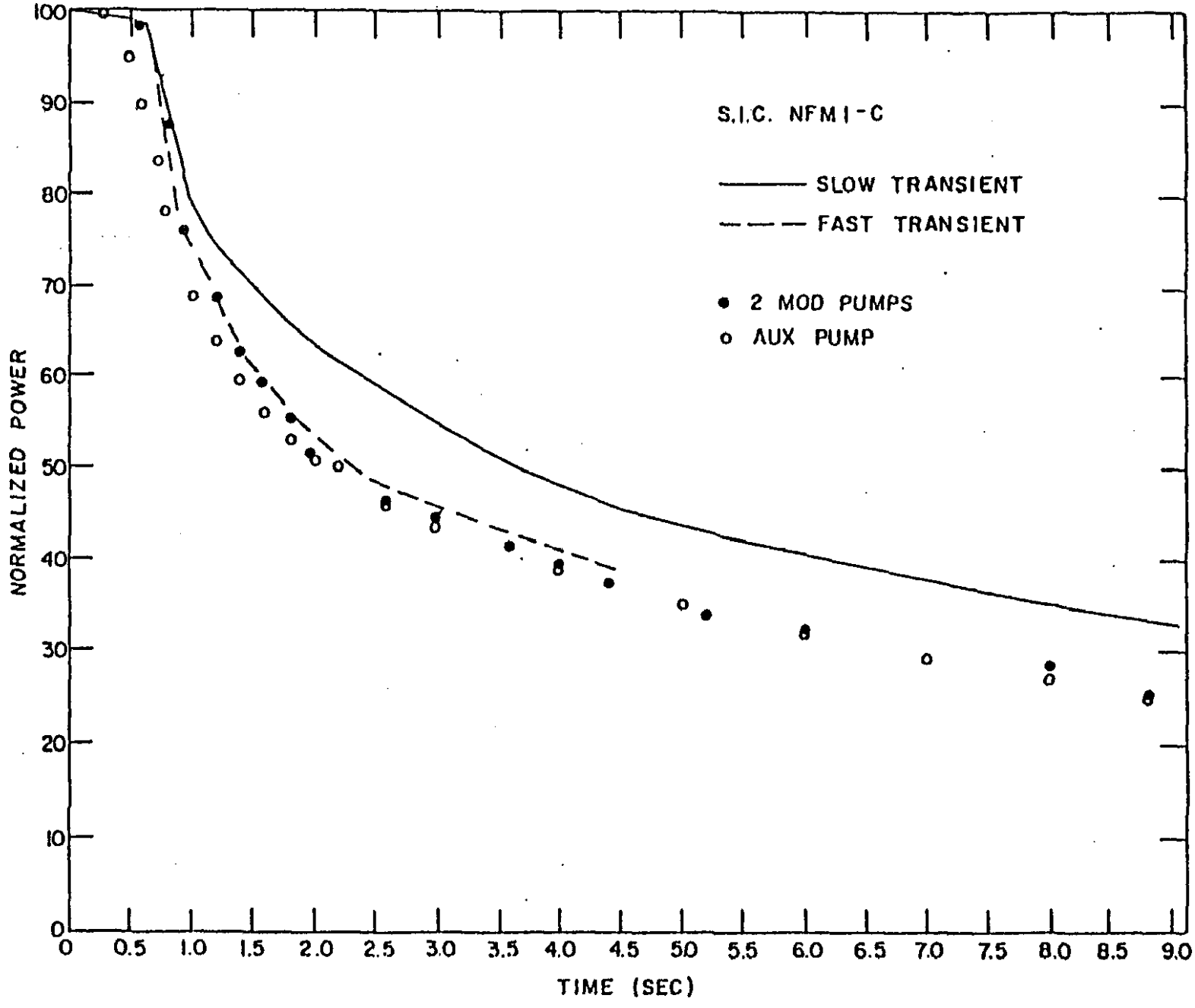

FIGURE 5.2-12 SDS 2 TEST - TANK 7 ONLY

TDAI-244

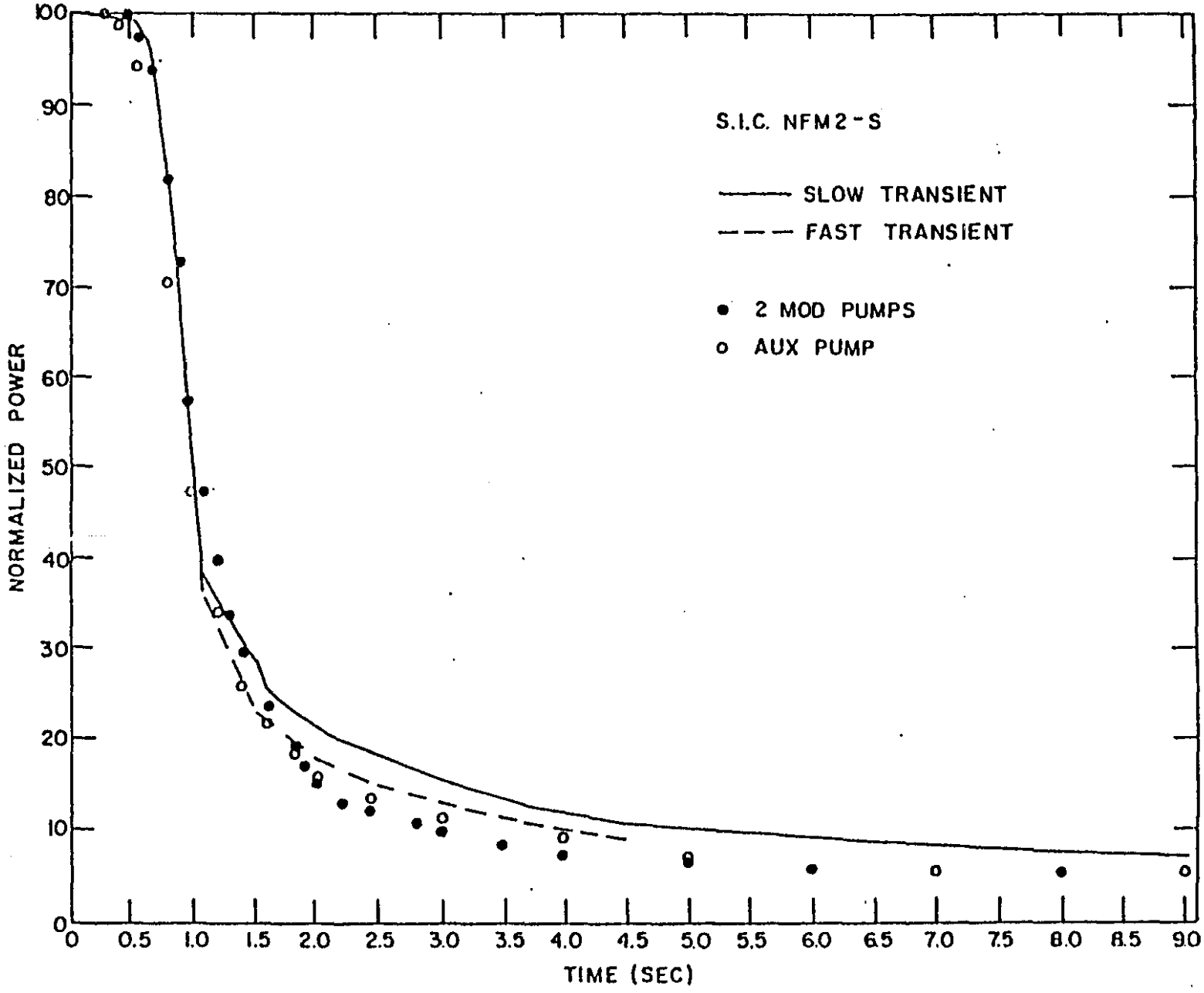

FIGURE 5.2-13 SDS 2 TEST - TANK 7 ONLY

TDAI-244

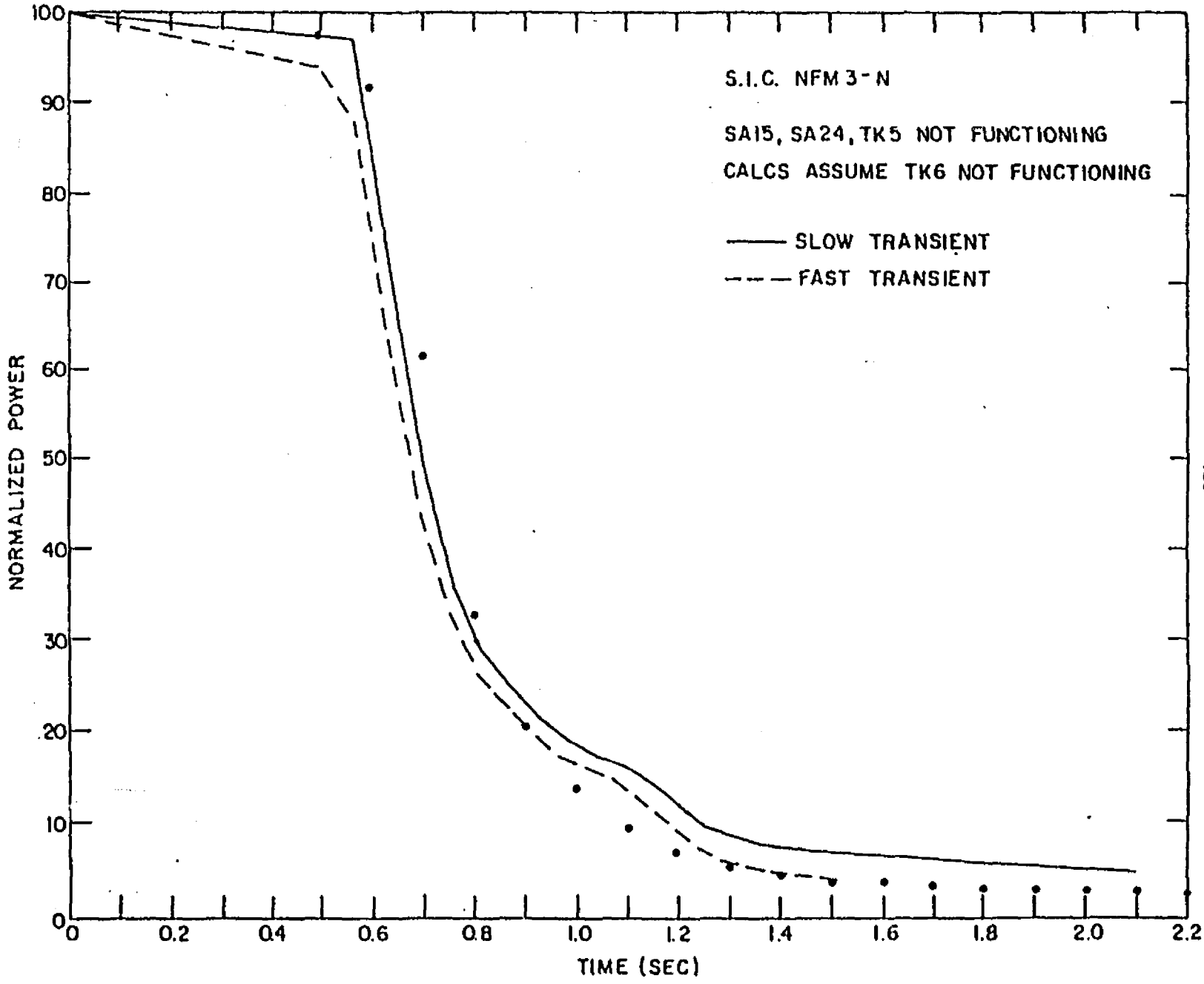

FIGURE 5.2-14 COMBINED SDS 1 + SDS 2 TEST

TDAI-244

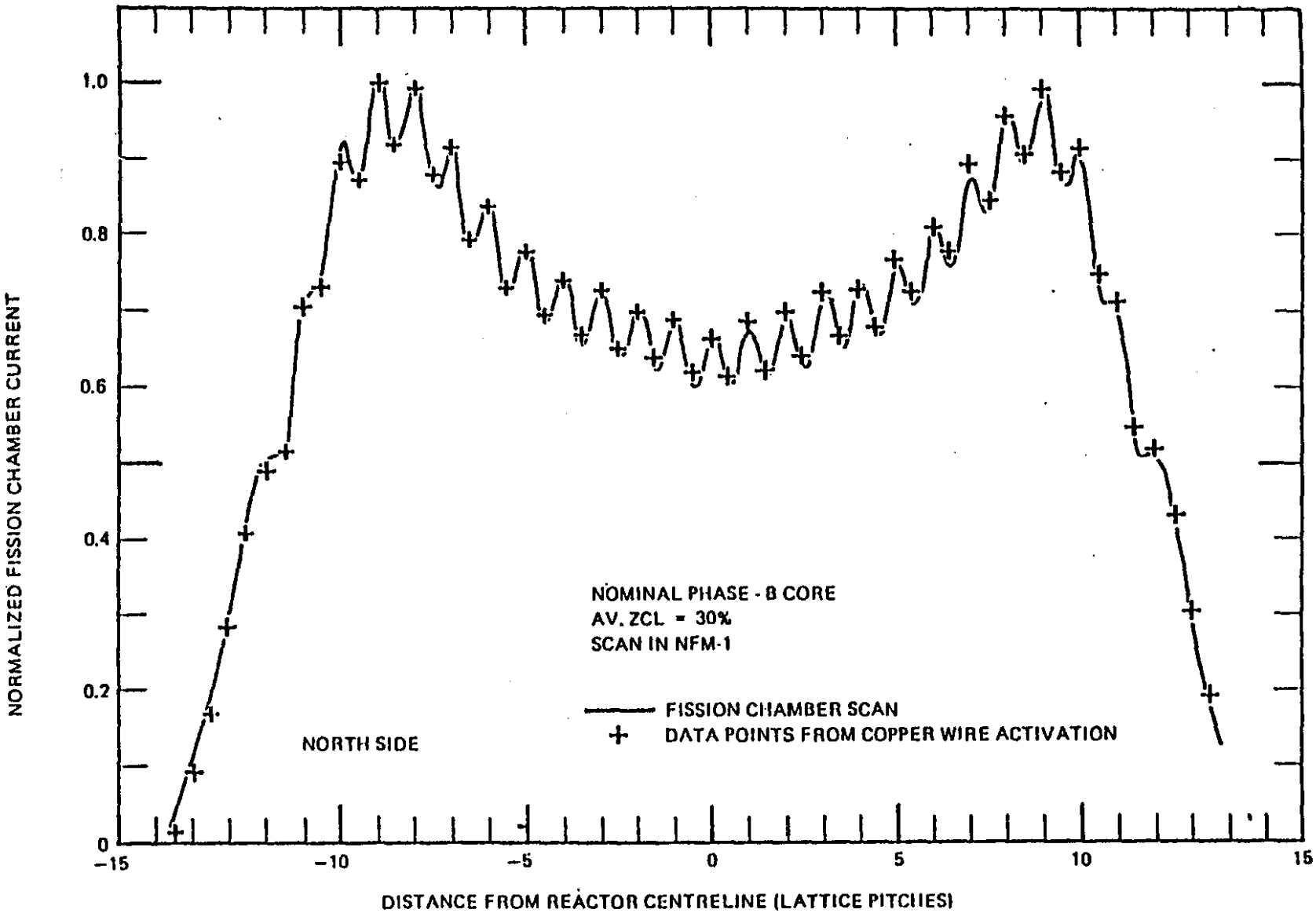

FIGURE 5.2-15 COMPARISON WITH COPPER WIRE ACTIVATION DATA

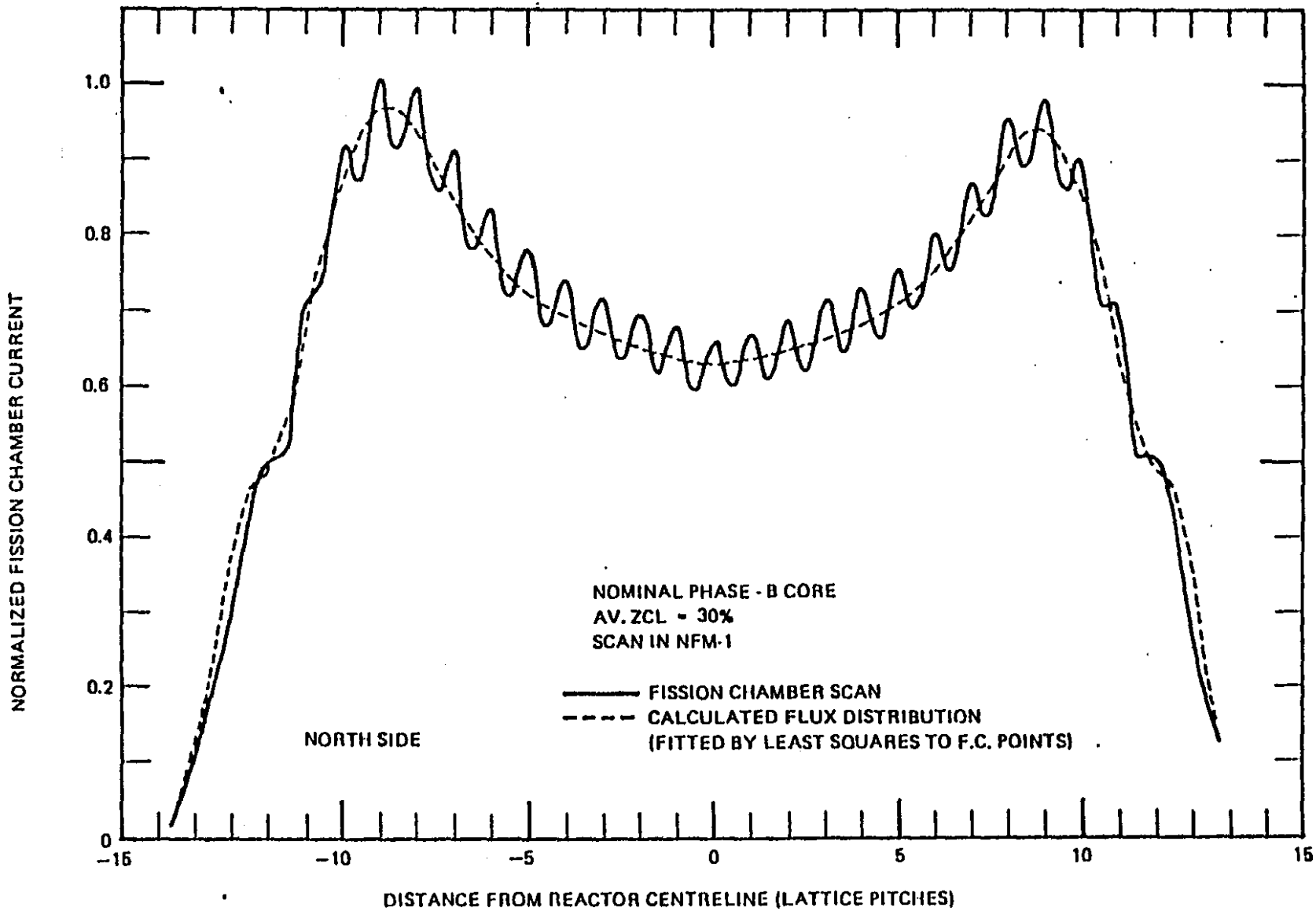

FIGURE 5.2-16 COMPARISON WITH CALCULATED FLUX DISTRIBUTION

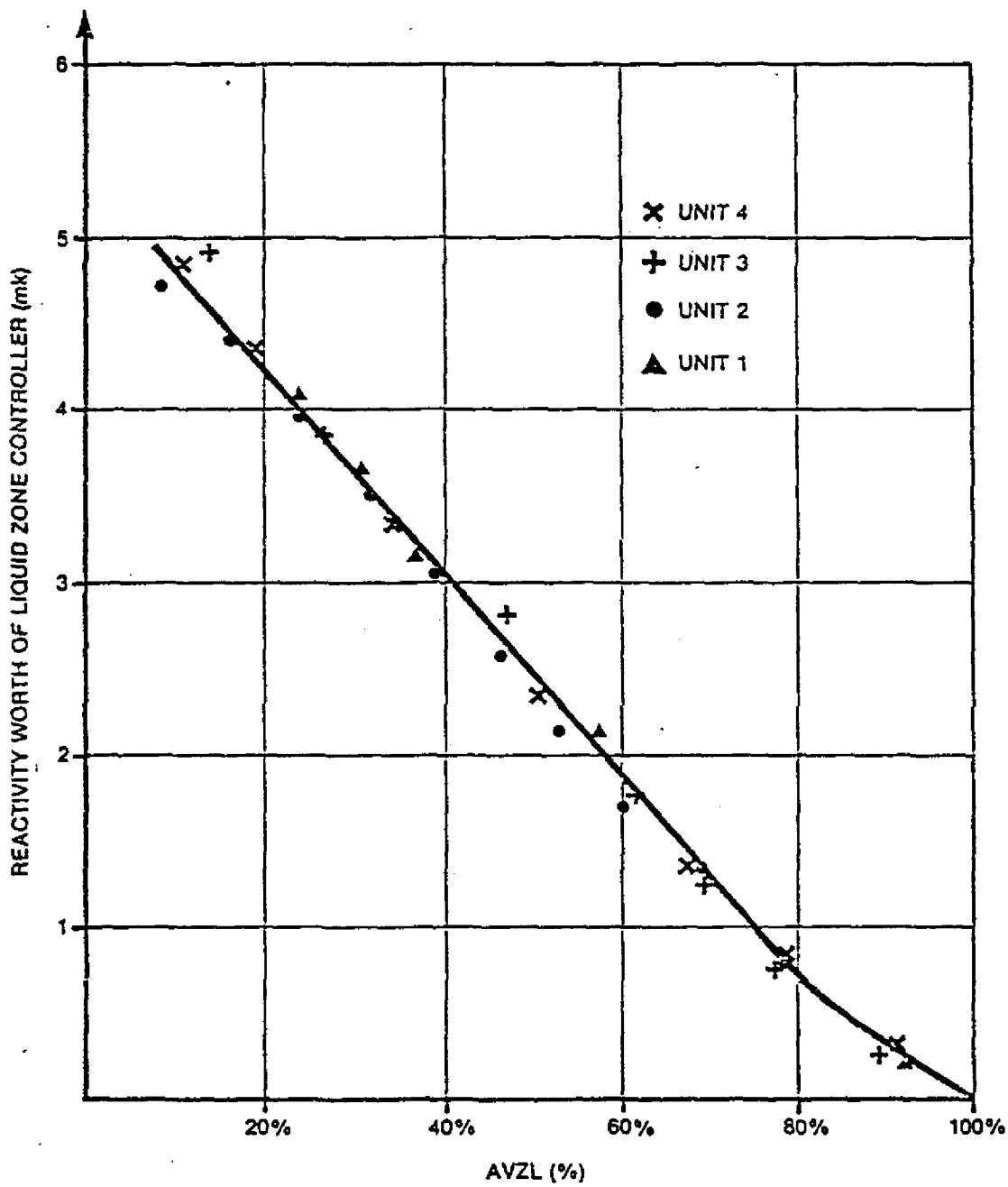

FIGURE 5.2-17 ZONE CONTROLLER CALIBRATIONS