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WANL-TME-1431
June 1, 1966
Subcontract NP-1

Westinghouse Astronuclear Laboratory

Evaluation Of Thermal Response Of Three Proposed Reactor Designs To Post-Operational Heating Conditions

(Title Unclassified)

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Mr. J. L. Dooling
NERVA Subcontract Manager
Rocket Engine Operations - Nuclear
Department 7140
Aerojet-General Corporation
Post Office Box 15847
Sacramento, California 95813

JUN 14 1966

Subject: WANL-TME-1431, "Evaluation of Thermal Response of Three Proposed Reactor Designs to Post-Operational Heating Conditions," (U) dated June 1, 1966

Dear Mr. Dooling:

Transmitted herewith for your information are ten (10) copies of the subject report.

Respectfully,
H. F. FAUGHT/RLS

H. F. Faught
Program Manager
NERVA Nuclear Subsystem

MRT:km

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AGC Resident Office at WANL, w/o enclosures
H. S. McCreary, WANL Resident at AGC, w/o enclosures
E. W. Bosse, SNPO-C, w/1 enclosure
L. C. Corrington, SNPO-C, w/1 enclosure
L. R. Nichols, SNPO-C, w/1 enclosure
P. M. Ordin, SNPO-C, w/1 enclosure
R. S. Decker, SNPO-W, w/1 enclosure
J. Helms, SNPO-W, w/1 enclosure
P. Johnson, SNPO-W, w/1 enclosure
C. Schwenk, SNPO-W, w/1 enclosure
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EVALUATION OF THE THERMAL RESPONSE OF THREE PROPOSED REACTOR DESIGNS TO POST-OPERATIONAL HEATING CONDITIONS

(Title Unclassified)

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Date 4-15-83

Prepared By:

M. R. Trammell

M. R. Trammell, Fellow Scientist
Physical Sciences Analysis
Nuclear Systems Applications

W. C. McCune

W. C. McCune, Analyst
Reactor Physics and Math

Approved By:

G. R. Thomas, Manager
Nuclear Systems Engineering

J. M. Bridges, Supervisor
Physical Sciences Analysis
Nuclear Systems Applications

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ACKNOWLEDGMENT

The authors wish to gratefully acknowledge the assistance rendered by Mr. W. S. Brown in the preparation of the material in Chapter I on gamma dose considerations.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF TABLES

[redacted]

INTRODUCTION

Analyses of the radiological consequences attendant on the possible failure of a nuclear rocket engine during an assigned mission have indicated, for a variety of reasons, that it is desirable that the reactor engine be maintained in an intact configuration for an extended period of time following such a failure. A resume of the reasons leading to this conclusion is given in Chapter I of this document.

The remainder of the document is given over to a description of a comparative study of the response of three proposed NERVA reactor designs to a severe reactor accident condition-- a loss of coolant accident. The advanced designs, i.e., the Beryllium Ring, the Graphite Stave Barrel, and the PHOEBUS-II Designs, are evaluated in terms of the capability, in this situation, of each to maintain core bundling forces throughout an extended period following failure. It has been found that the Graphite Barrel Design is the one which maintains integrity best under severe accident conditions; the Be-Ring Design next best; and the PHOEBUS-II Design not at all.

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CHAPTER I RADIOLOGICAL SAFETY CONSIDERATIONS IN THE DESIGN OF FLIGHT-TYPE NUCLEAR ROCKET ENGINES

A. Mission Characteristics

The missions for which the following data have been computed are lunar transfer missions from a nominal 100 nautical mile orbit. In the first one, the nuclear engine is also used suborbitally to serve as the final boost stage to the parking orbit. Subsequently, it is to be used to accomplish transfer from the parking orbit to the moon. In a second mission, the nuclear stage and payload are boosted into a 100 NM orbit using conventional chemical rockets. The nuclear engine undergoes startup in orbit and is used to accomplish transfer to the moon.

If it is assumed that the reactor is separated from the remainder of the stage immediately after failure is detected during suborbit operation, then the impact location of the reactor re-entry vehicle, consisting of reactor, pressure vessel, and nozzle, can be predicted as a function of failure time. Failure during the range of times after launch indicated in Table I-1 yields land impact in the area specified in the table. The elapsed time from failure to impact is also given for each of the land impact cases.

TABLE I-1 IMPACT LOCATION OF INTACT NERVA REACTOR FOLLOWING FAILURE DURING SUBORBITAL OPERATION

Area	Failure Time (Sec after Launch)	Failure to Impact (Min)
(SN Stage Startup)	(502)	
Africa and Madagascar	998-1008	18-25
Australia	1015	46
Pacific Ocean and Indeterminate*	1016-1020	≥ 65

---

* Impact locations are not well defined for this period. The launch vehicle is approaching an unstable orbit at failure and the re-entry vehicle may go through anywhere from 1/2 to 10 orbital passes before terminal re-entry begins.

[redacted]

B. Gamma Dose Considerations

The following paragraphs consider the external gamma dose delivered by the reactor fuel elements in the event of flight failure subsequent to nuclear engine startup. Dose calculations are based on the activity of the fuel elements at the instant when they impact the Earth. Radioactive decay during the four-day dose exposure period is taken into account.

1. Suborbit Start Missions

Failures from suborbit start of the nuclear stage result in prompt re-entry (18-25 minutes) with the debris localized over a relatively small ground area. (Approximately one square mile.) The four-day gamma doses at one meter distance from a NERVA fuel element are shown in Figure I-1. This figure also shows the failure times which result in land impaction. Use of a mobile receptor dose model and the appropriate population densities of African countries, yields the results of Table I-2.

TABLE I-2 MAXIMUM POPULATION EXPOSURE TO FOUR-DAY GAMMA DOSE FOR NERVA FAILURES FROM SUBORBIT START

Expected Numbers of Persons Receiving Indicated Dosage (Rems)					
0.5-5	5-10	10-50	50-100	100-500	500
9640	130	208	66	63	5.4

2. Orbit Start Missions

The gamma dose on Earth impact following failure from orbit will depend on:

(1) Decay time (orbit lifetime) of reactor or debris.
(2) Loss of fission product inventory by diffusion of fission products out of the fuel.

[redacted]

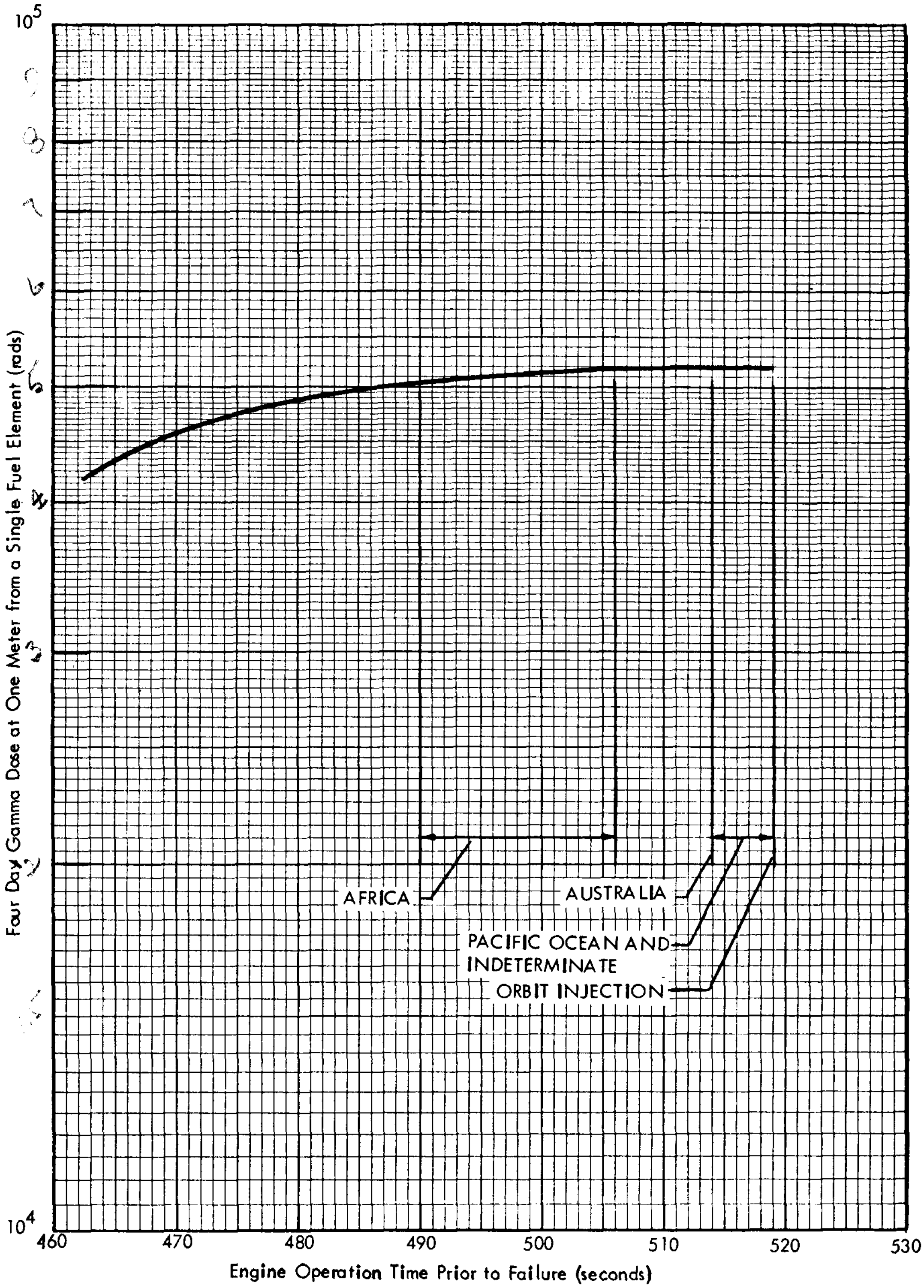

FIGURE I-1 GAMMA DOSE FROM A NERVA FUEL ELEMENT ON EARTH'S SURFACE FOLLOWING FAILURE FROM SUBORBIT START

[redacted]

[redacted]

Also, the orbit lifetime at failure point depends on:

(1) Altitude, velocity, and other flight trajectory parameters.
(2) Ballistic parameter (W/C_DA) - the ratio of weight to cross-sectional area of the re-entering body. Orbit lifetime is directly proportional to W/C_DA.

Orbit lifetimes of the intact NERVA reactor and of a fuel element (released due to reactor disassembly) are shown in Figure I-2. A fuel element has approximately 1/25 the lifetime of the intact reactor due to the difference in their ballistic parameters.

The four day gamma doses (at one meter distance) resulting from flight failures (100 NM initial orbit start) are shown in Figure I-3. The following comments apply:

(1) Curve 1 represents potential doses for the advanced design subjected to a loss of coolant accident followed by rapid disassembly.
(2) Curve 2 represents potential doses for an advanced design reactor subjected to normal cooldown following in-flight failure, thus assuring that the reactor remains intact for its full orbit lifetime.
(3) Curve 3 represents an improved NERVA design which can withstand a loss of coolant accident and maintain its integrity without disassembly. The reduction in dose from Curve 2 to Curve 3 is due to loss of fission products by diffusion.

Those doses consider the receptor is stationary for four days at a distance of one meter from the element. The alternative dose model, considering the probability of exposure of a person to a fuel element and considering that the person is mobile in his normal daily routine, leads to the data of Table I-3. This model assumes the debris will re-enter randomly and impact on the Earth's surface between 40°N - 40°S latitudes.

TABLE I-3 MAXIMUM POPULATION EXPOSURE TO FOUR-DAY GAMMA DOSE
Failures from 100 NM Initial Orbit Start

Expected Numbers of Persons Receiving Indicated Dosage (Rems)*						
0.1-0.5	0.5-5	5-10	10-50	50-100	100-500	>500
3072	117	2.4	8.0	0.10	<0.03	<0.03

* These values are for failure of the NERVA engine at approximately 30 seconds after SN startup. For failures occurring prior or subsequent to these times, the dose would be less.

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[redacted]

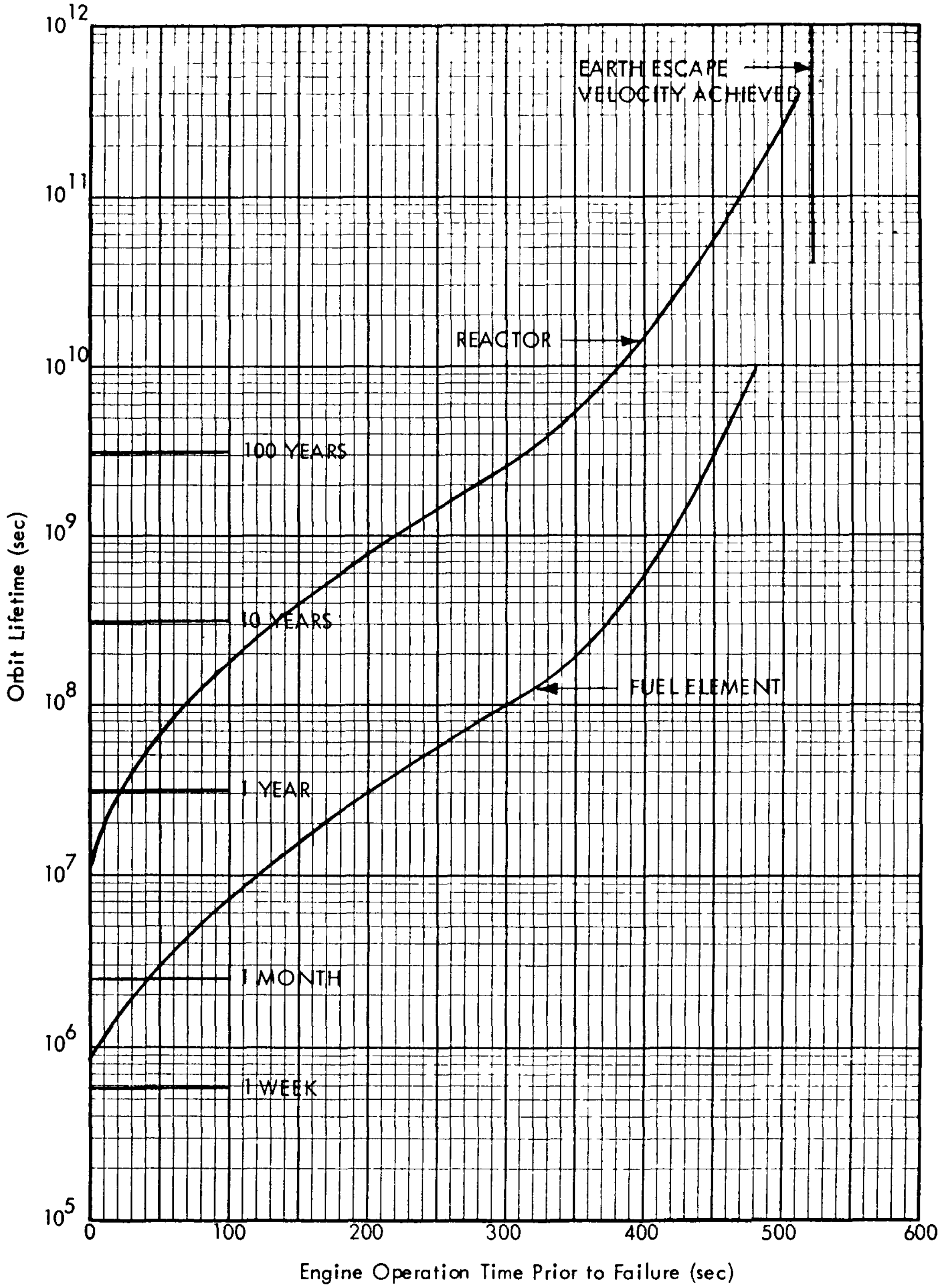

FIGURE I-2 ORBIT LIFETIME FOR A NERVA REACTOR AND FUEL ELEMENT FOLLOWING FAILURE FROM 100 NM ORBIT START

[redacted]

[redacted]

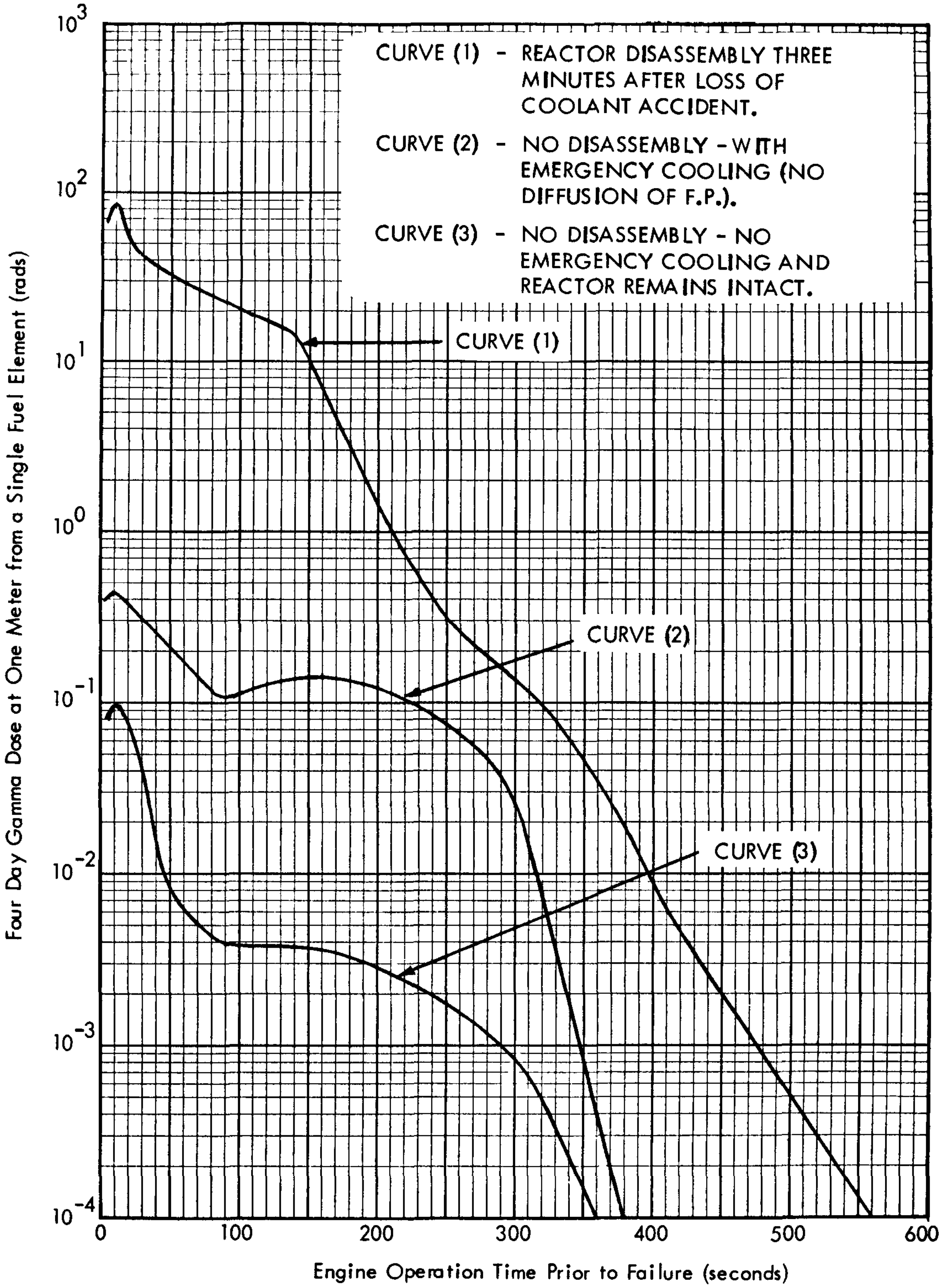

FIGURE I-3 GAMMA DOSE FROM NERVA FUEL ELEMENT ON EARTH'S SURFACE FOLLOWING FAILURE FROM 100 NM ORBIT START

[redacted]

C. Possible Countermeasure Systems

1. Suborbit Start Missions

If a countermeasure such as an auxiliary thrust system, (ATS), is used to insure deep ocean disposal of the reactor system following failure at anytime prior to orbit injection, then the elapsed time from failure to impact should be approximately 18-25 minutes.

The proposed ATS countermeasure system[1.] consists of either six or eight Be-384 solid rocket "strap on" motors. Each motor generates 5,770 pounds of thrust for a burning period of 9.15 seconds. The total applied thrust may range from about 35,000 to 45,000 pounds. This thrust subjects the engine system to approximately 2 "g's" acceleration and imparts a ΔV of 200 to 225 feet/second.

The time required to initiate and complete ATS action is the sum of the following steps:

Identify failure	5-6 seconds
Choose disposal mode (retro or boost)	4-5 seconds
Orient vehicle	20-100 seconds
Jettison payload	$\geq$10 seconds
Dump propellant	10-180 seconds
Solid rocket burn time	10-30 seconds
Total: Suborbital failure	2-6 minutes

Therefore, the total time during which the reactor must be able to withstand an axial acceleration of as much as 2 g's is perhaps as long as six minutes for suborbital failures.

2. Orbit Start Missions

Should failure occur during the orbital operating portion of a mission, a delay period of 35-60 minutes will be required (to reach orbit apogee) before an ATS system could be used to circularize the orbit of the failed engine system and, thus, prolong its orbital lifetime. Therefore, the reactor must be in a condition to withstand small loads (~ 2 g's) for as much as 60 minutes after failure to make use of such a countermeasure system.

The safety of reactor operation could also be enhanced by specifying that the parking orbit altitude be greater than 100 NM, which, of course, involves some payload penalty. The parking orbit altitude required to reduce the predicted gamma dose arising from reactor failure and immediate (i.e., within minutes) disassembly of the core to the value predicted for a reactor which starts from a lower orbit and remains intact after failure is shown in Figure I-4.

D. Importance of Condition of the Reactor Following Failure

The preceeding discussion has shown that evaluation of the radiological consequences arising from failure of a nuclear rocket engine during its mission requires a detailed knowledge of the physical condition of the reactor and its components subsequent to that failure. Further, it is clear that if the reactor core can be maintained in an intact condition, the possibility of failure resulting in any serious hazard may be greatly reduced and, perhaps, eliminated altogether.

The remainder of this document is devoted to an examination of the thermal response of the components of three proposed flight reactor designs to a severe accident--loss of coolant. On the basis of such information, an analysis can be made to determine whether or not the core, in each design, may be maintained in an intact configureation:

(1) for the length of time required to exercise some countermeasure, and/or
(2) for an extended period following system failure leading to loss of coolant.

Thus, the design features which provide the least possibility of radiological hazard arising from its use to the Earth's population may be considered.

The consequences of failure following two different engine operating periods have been examined. The first, a 500 second full power operating period, is representative of the

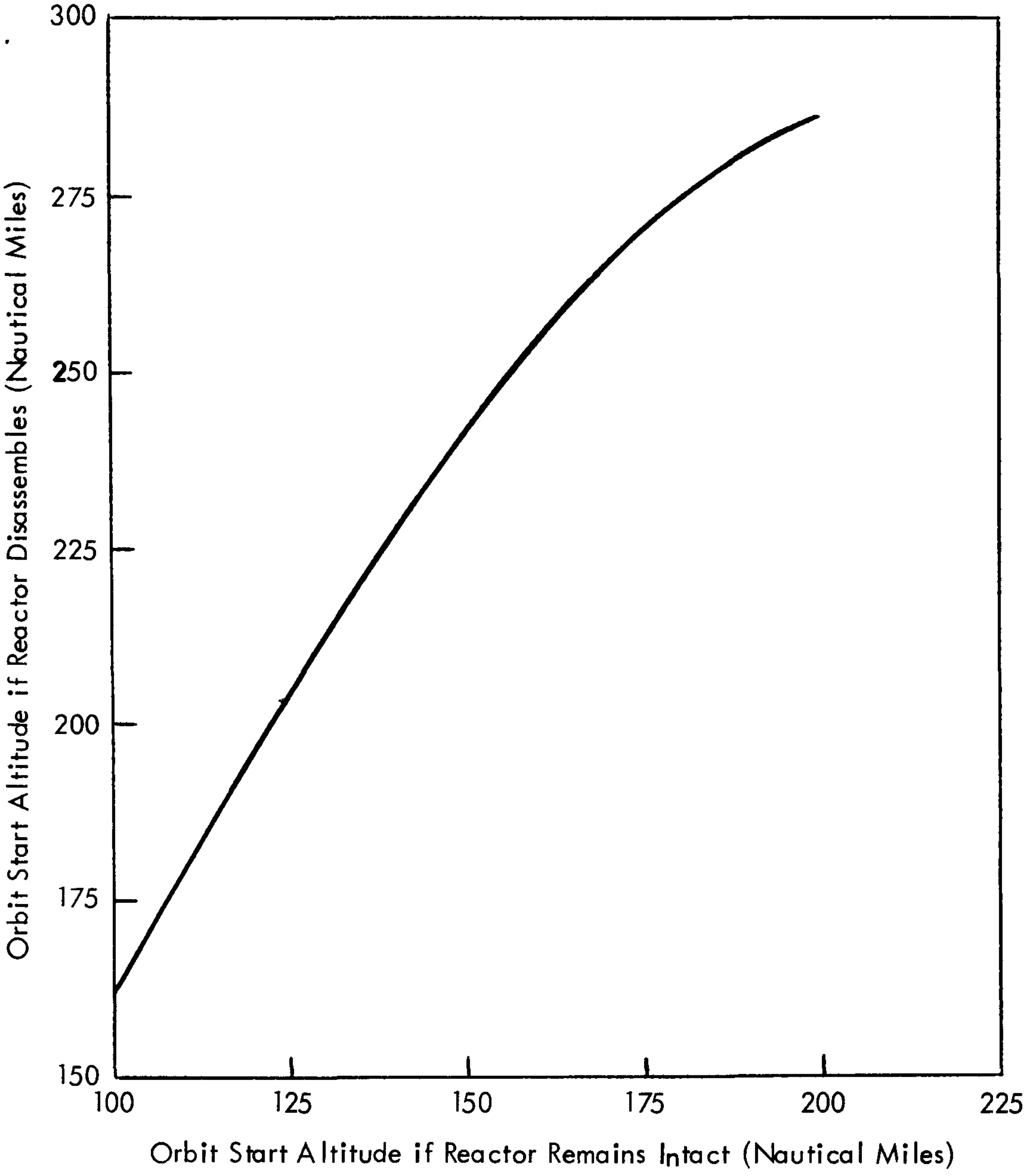

FIGURE I-4 EFFECT OF REACTOR INTEGRITY ON ORBIT START ALTITUDE FOR NO VARIATION IN GROUND GAMMA DOSE

[redacted]

failure times (1002 seconds after launch) which might yield land impact of the debris resulting from such a failure during a suborbital startup mission (see Table I-1).

The second, an "equivalent" 30 second full power operating period, typifies failures that would occur early in a mission requiring orbital startup of the nuclear engine. Failures of this type (see Figure I-3) yield the maximum dose possibilities for such a mission.

[redacted]

CHAPTER II THE THREE DESIGN MODELS

A. Basic Features Common to All Models

Heat transfer calculations to determine the thermal response of the reactor components to post-operational heating conditions are based on the reactor model shown in Figure II-1. The basic components are:

(1) The Core with Surrounding Pyrographite Tiles and Filler Strips
(2) Support Blocks
(3) Aluminum Core Support Plate
(4) Aluminum Top Shield
(5) A Lateral Support Region
(6) A Beryllium Reflector Region
(7) An Aluminum Buffle or Heat Shield
(8) A Pressure Vessel

The lateral support region contains those components, such as the seal system and graphite or aluminum inner reflector, which provide, at least in part, bundling forces which act on the core. The beryllium reflector region contains the reflector structure, central drums or cans, and all associated hardware. For those designs in which the lateral support springs have been recessed into the beryllium reflector region, they have been assumed to be a part of the homogenized reflector structure and to be at the temperature computed for that structure at all times. A highly simplified model representing the poison plate and drum has been used to represent the poison central system.

The heat transfer paths considered for the model as a whole are indicated according to the legend which appears in the figure. In addition, nuclear heat arising from the decaying fissioning rate after shutdown and from radioactive decay of the fission product inventory generated during the normal operating period are included at each location in each component. A temperature history for each of the axial sections, or locations, indicated by dotted lines in the figure is computed.

[redacted]

[redacted]

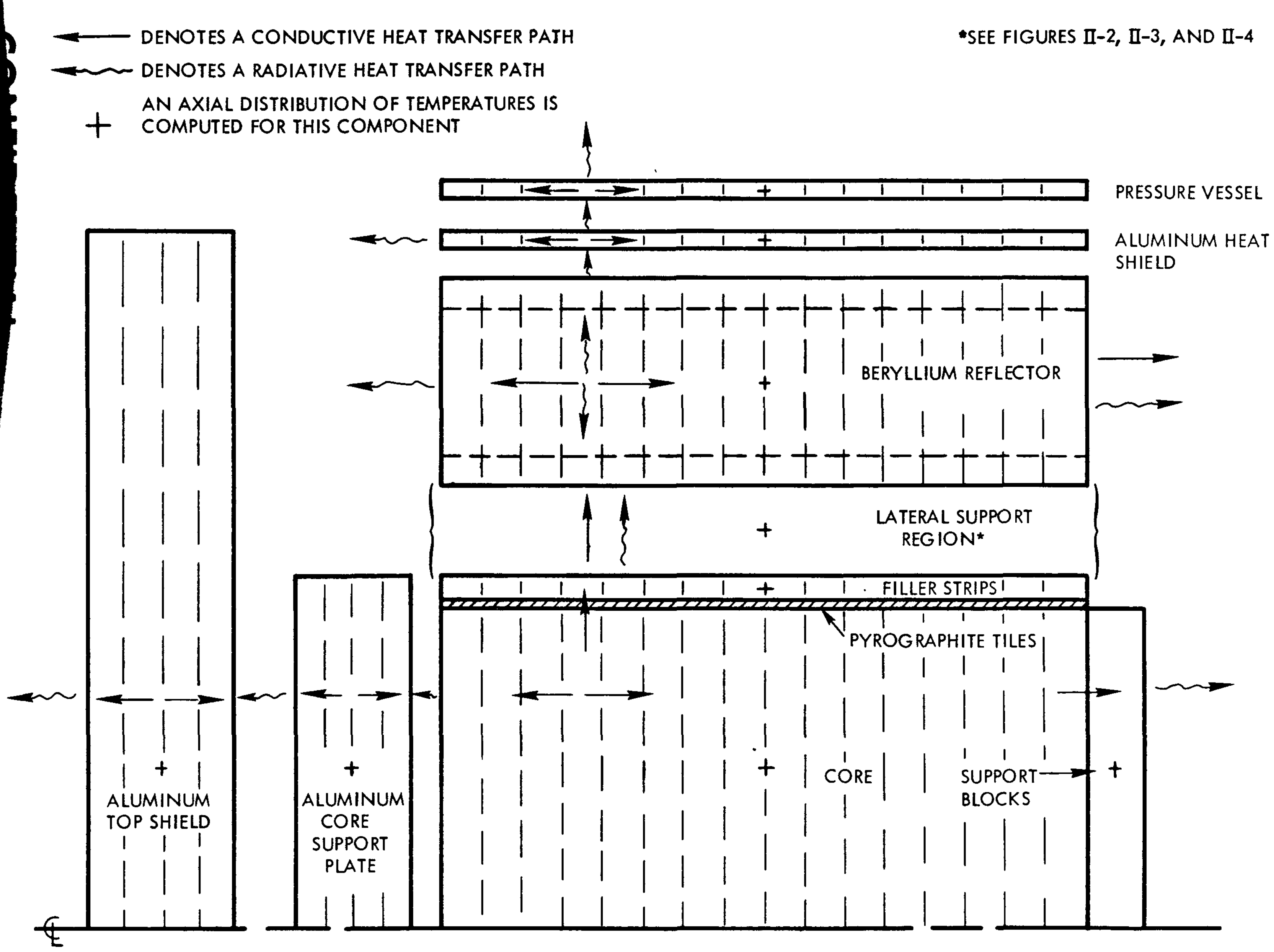

FIGURE II-1 BASIC REACTOR MODEL - SCHEMATIC DRAWING

[redacted]

Graphite sublimation from the core represents a major mechanism of heat loss from the system. At present, no precise estimate of the rate at which graphite can sublime from the core coolant channels and flow out of the core is available. However, this effect can be "bracketed" by assuming that the maximum heat removal due to this phenomena would occur if the fuel material sublimes and is removed as though the vapor pressure above the surface was essentially zero, i.e., by the use of vacuum sublimation rates. The minimum heat removal by graphite phase change must occur if no sublimation were observed. Since core temperature affects heat transfer rates to outer reactor components, then computations, similar in other respects but utilizing these two extreme assumptions, must yield a range of times after loss of coolant during which other events of interest, e.g., beryllium reflector failure, must occur. Such ranges, for the components and events of interest, are presented later in this report.

One further qualification should be made at this time. The section of the reactor pressure vessel considered in this model is that section which extends the length of the core only. Therefore, in the detailed specifications which appear just after this section for each model, only that portion of the vessel weight has been included.

The melting temperatures and heats of fusion that have been used in phase change calculations for all metallic components are given in Table II-1.

B. The Beryllium Ring Design[2.,3.,4.]

The three designs studied differ principally in the nature of the lateral support system proposed for each. Minor differences in the dimensions of each major component also have been noted.

A schematic representation of the lateral support region in the Be-Ring design appears in Figure II-2. Lateral support forces are transmitted to the core by segmented graphite seals acted on by graphite plungers which are in turn supported by Inconel springs recessed into the beryllium reflector structure. Axial motion of the seals is restricted by graphite

[redacted]

TABLE II-1 MELTING TEMPERATURES AND HEATS OF FUSION FOR METALLIC REACTOR COMPONENTS

	Melting Point		Heat of Fusion	
Material	°K	°R	BTU/lb	Joules/gm
Aluminum	933	1680	167.4	389.3
Beryllium	1550	2790	559.3	1300.4
Titanium	1953	3515	187.2	435.3
Stainless Steel	1723	3101	117.0	272.1
Inconel	1713	3083	122.4	284.6
Copper	1356	2441	88.1	204.9

[redacted]

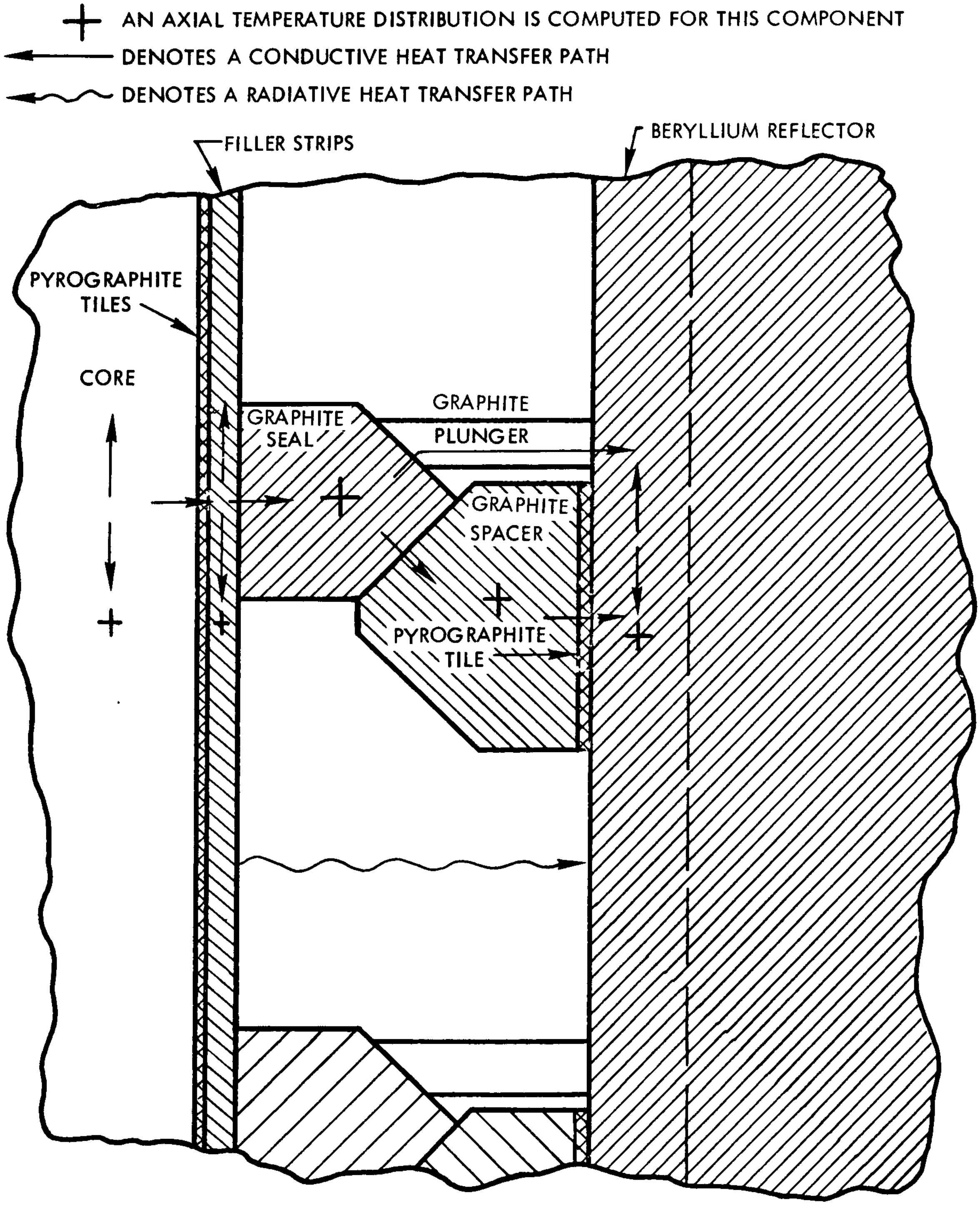

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FIGURE II-2 LATERAL SUPPORT REGION FOR BE-RING DESIGN - SCHEMATIC DRAWING

[redacted]

[redacted]

spacers inset into the inner surface of the beryllium reflector (this inset is not shown in the schematic). Heat transfer from the spacers to the reflector is retarded by a layer of pyrographite tile or cloth resting between the surfaces. The heat transfer paths from core to filler strips to reflector are indicated in the diagram.

The detailed dimensions used in the Be-Ring design model are given in Table II-2. The fission and gamma heating fractions for each component, i.e., the fractions of the energy deposited in each component which is directly proportional to fission power and the fractions of the energy deposited in each component which is proportional to decay of fission products, for this design are given in Table II-3.

The initial temperature profiles for each component[2.,6.] are shown in Figure II-3. The curves shown correspond to the following initial profiles:

(1) - Core
(2) - Seals
(3) - Filler Strips
(4) - Spacers
(5) - Beryllium Reflector, Control Drums, Aluminum Heat Shield, and Pressure Vessel

The aluminum core support plate and top shield were assumed to be at a uniform temperature of 540°R.

C. The Graphite Barrel Design

The details of the lateral support region in the Graphite Barrel design are shown schematically in Figure II-4. Here, as in the Be-Ring design, Inconel springs act on graphite plungers which in turn transmit the lateral support forces, through a segmented graphite seal system, to the core. Axial restraint on the seals is provided by the graphite barrel which also serves to position the plungers. The heat transfer paths considered in the computational scheme are indicated in the figure.

Details of the model used for this design are given in Table II-4 and its fission and gamma heating fractions appear in Table II-3.

[redacted]

[redacted]

TABLE II-2 BERYLLIUM RING DESIGN MODEL SPECIFICATIONS

		English	Metric
Core:	Weight	8165 lb	3.704×10^6 gms
	Outer Radius	28.3 in	71.88 cm
	Pyro Wrapper Thickness	0.1 in	0.254 cm
	Number of Coolant Channels	94,801	
	Diameter of Coolant Channels: Coated	0.112 in	0.284 cm
	Diameter of Coolant Channels: Uncoated	0.115 in	0.292 cm
	Length	52 in	132.1 cm
Support Blocks:	Weight	414.7 lb	1.881×10^5 gms
	Length	2.25 in	5.72 cm
Filler Strips:	Weight	271.4 lb	1.231×10^5 gms
	Inner Radius	28.40 in	72.13 cm
	Outer Radius	28.75 in	73.03 cm
	Radiation Area to Beryllium Reflector	3956 in^2	2.552×10^4 cm^2
	Conduction Area to Seals	2873 in^2	3.499×10^4 cm^2
Lateral Support Region:	Total Weight	470.2 lb	2.133×10^5 gms
a) Seals:	Weight (Total)*	243.6 lb	1.105×10^5 gms
	Number	24	
	Axial Dimension	1.25 in	3.18 cm
	Radial Dimension (max)	0.875 in	2.22 cm
	Conduction Area to Spacer	2761 in^2	1.781×10^4 cm^2
	Conduction Area through Plunger	226.3 in^2	1460 cm^2
	Effective Conduction Length:		
	Filler Strips to Seal	0.750 in	1.9 cm

---

* Includes plunger weight

[redacted]

[redacted]

TABLE II-2 (Continued)

	English	Metric
Seal, through Plunger, to Beryllium Reflector	0.875 in	2.22 cm
Seal to Spacer	0.75 in	1.9 cm
b) Spacers: Weight (Total)	226.6 lb	1.028×10^5 gms
Number	24	
Axial Dimension	1.25 in	3.18 cm
Radial Dimension (max.)	1.00 in	2.54 cm
Conduction Area to Beryllium Reflector	5676 in^2	3.662×10^4 cm^2
Pyrographite Tile Thickness	0.05 in	0.127 cm
Beryllium Reflector Region: Total Weight	5230 lb	2.372×10^6 gms
a) Reflector Structure: Weight	2793 lb	1.267×10^6 gms
Inner Radius	30.05 in	76.35 cm
Outer Radius	36.80 in	93.47 cm
Drum Centerline Radius	30.75 in	78.11 cm
Radius of Drum Hole	2.875 in	7.303 cm
Axial Conduction Area	1047 in^2	6755 cm^2
b) Control Can: Weight (24 Cans)	638 lb	2.141×10^5 gms
Outer Radius	2.815 in	7.150 cm
Inner Radius	2.435 in	6.185 cm
Axial Conduction Area	47.38 in^2	305.7 cm^2
c) Stationary Drum: Weight (24 Drums)	1799 lb	6.028×10^5 gms
Drum Radius	2.375 in	6.033 cm
Axial Conduction Area	425.3 in^2	2744 cm^2
Aluminum Heat Shield: Weight	85 lb	3.856×10^4 gms
Inner Radius	36.863 in	93.63 cm
Outer Radius	36.926 in	93.79 cm

[redacted]

[redacted]

TABLE II-2 (Continued)

		English	Metric
Pressure Vessel:	Weight (Titanium)	606 lb	2.749×10^5 gms
	Inner Radius	37.114 in	94.36 cm
	Outer Radius	37.414 in	95.12 cm
Support Plate:	Weight	1965 lb	8.913×10^5 gms
	Thickness	8.5 in	21.59 cm
Top Shield:	Weight (includes shield extension)	4136 lb	1.876×10^6 gms
	Thickness	9.0 in	22.86 cm

[redacted]

[redacted]

[redacted]

TABLE II-3 FISSION AND GAMMA HEATING FRACTIONS FOR THE THREE DESIGNS

Component	Be-Ring Design[2].		Graphite Barrel Design[2].		PHOEBUS-II Design[5].	
	Fission	Gamma*	Fission	Gamma*	Fission	Gamma
1. Core	0.9892	0.8815	0.9892	0.8748	0.9892	0.8676
2. Suppprt Blocks	0.00019	0.0035	0.00019	0.0035	0.00019	0.0035
3. Lateral Support Region	(0.00156)	(0.0244)	(0.00156)	(0.0311)	(0.00156)	(0.0456)
a. Filler Strips	0.000571	0.00893	0.000132	0.002625	0.000158	0.004624
b. Seal	0.000513	0.00802	0.000154	0.003063	0.000055	0.001601
c. Spacer	0.000477	0.00745	-----	-----	-----	-----
d. Plunger	-----	-----	0.000005	0.000109	0.000007	0.000207
e. Graphite Barrel	-----	-----	0.001269	0.025303	-----	-----
f. Aluminum Barrel	-----	-----	-----	-----	0.001340	0.039170
4. Beryllium Reflector Region	(0.00666)	(0.04945)	(0.00454)	(0.04943)	(0.00661)	(0.05914)
a. Reflector Structure	0.00242	0.0264	0.00293	0.03188	0.001935	0.02549
b. Control Can	0.00267**	0.00605	0.00042**	0.00460	0.002470**	0.00461
c. Stationary Drum	0.00156	0.0170	0.00119	0.01295	0.002205	0.02904
5. Aluminum Heat Shield	0.00007	0.00075	0.00007	0.00078	0.000119	0.00156
6. Pressure Vessel	0.000468	0.00802	0.000468	0.0080	0.000468	0.0071
7. Support Plate	0.00044	0.0233	0.00044	0.0233	0.00044	0.0121
8. Top Shield	0.000858	0.0035	0.000858	0.0035	0.000858	0.0035
Total	0.99945	0.99442	0.99733	0.99441	0.99945	1.0001

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* Adjusted for β-heating.

** Includes a heating rate fraction of 0.00212 for (n-α) heating.

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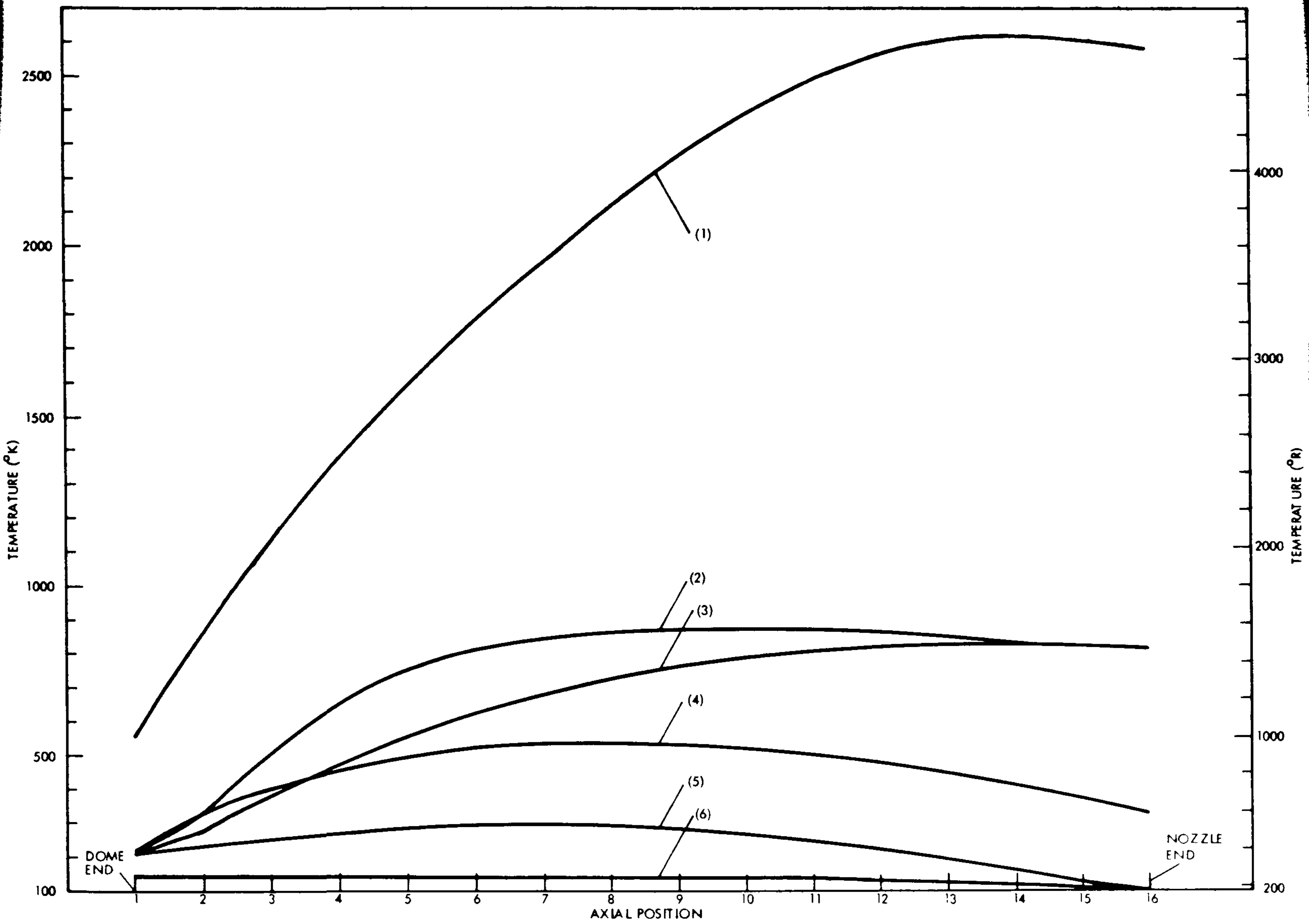

FIGURE II-3 INITIAL COMPONENT TEMPERATURE PROFILES

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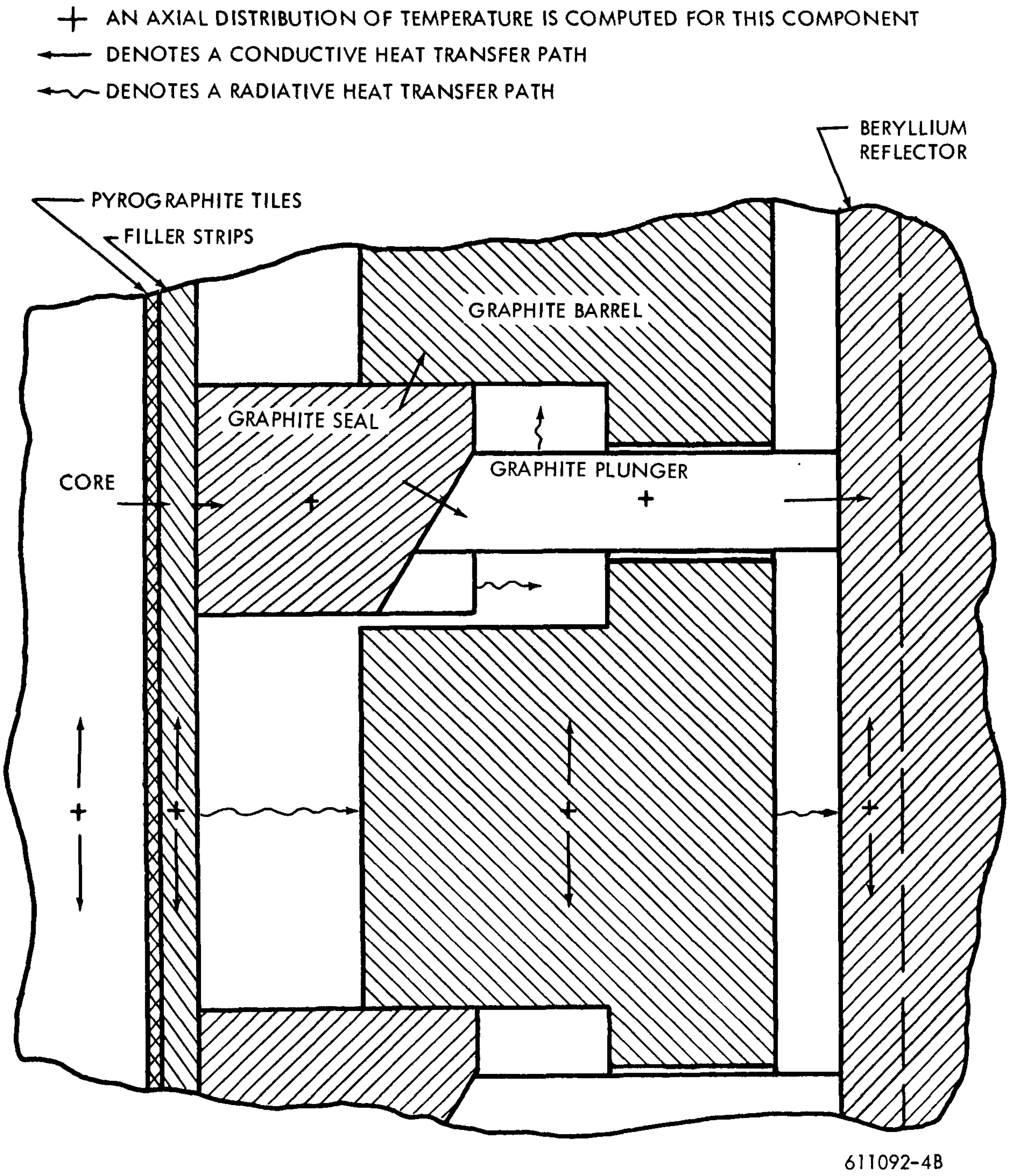

FIGURE II-4 LATERAL SUPPORT REGION FOR GRAPHITE BARREL DESIGN - SCHEMATIC DRAWING

[redacted]

[redacted]

TABLE II-4 GRAPHITE BARREL DESIGN MODEL SPECIFICATIONS

	English	Metric
Core: Weight	8596 lb	3.899×10^6 gms
Outer Radius	28.94 in	73.51 cm
Pyro Wrapper Thickness	0.1 in	0.254 cm
Number of Coolant Channels	94,801	
Diameter of Coolant Channels: Coated	0.112 in	0.284 cm
Diameter of Coolant Channels: Uncoated	0.115 in	0.292 cm
Length	52 in	132.1 cm
Support Blocks: Weight	403 lb	1.829×10^5 gms
Length	2.56 in	6.502 cm
Filler Strips: Weight	214.8 lb	9.743×10^4 gms
Inner Radius	29.04 in	73.76 cm
Outer Radius	29.39 in	74.65 cm
Radiation Area to Graphite Reflector	6280 in^2	40,510 cm^2
Conduction Area to Seals	3323 in^2	21,440 cm^2
Lateral Support Region: Total Weight	2330 lb	1.057×10^6 gms
a) Seals: Weight (Total)	250.6 lb	1.137×10^5 gms
Number	18	
Axial Dimension	1.00 in	2.54 cm
Radial Dimension	1.15 in	2.92 cm
Conduction Area to Graphite Reflector	3490 in^2	22,510 cm^2
Conduction Area to Plungers	84.8 in^2	547.2 cm^2
Radiation Area to Graphite Reflector	6394 in^2	41,250 cm^2
Effective Conduction Length:		
Filler Strips to Seal	0.683 in	1.735 cm

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[redacted]

TABLE II-4 (Continued)

	English	Metric
Seal to Plunger	1.38 in	3.51 cm
Seal to Graphite Reflector	1.0 in	2.54 cm
b) Plungers: Weight (Total)	8.78 lb	3.983×10^3 gms
Number	432	(24 per row)
Length	1.61 in	4.09 cm
Radius	0.25 in	0.635 cm
Conduction Area to Be Reflector	84.8 in^2	547.2 cm^2
Radiation Area to Graphite Reflector	271 in^2	1752 cm^2
Effective Conduction Length:		
Plunger to Be Reflector	1.38 in	3.51 cm
c) Graphite Barrel: Weight	2071 lb	9.394×10^5 gms
Inner Radius	29.485 in	74.89 cm
Outer Radius	32.025 in	81.34 cm
Beryllium Reflector Region: Total Weight	5072 lb	2.301×10^6 gms
a) Reflector Structure: Weight	3271 lb	1.484×10^6 gms
Inner Radius	32.15 in	81.66 cm
Outer Radius	39.565 in	100.50 cm
Drum Centerline Radius	35.86 in	91.08 cm
Radius of Drum Hole	2.875 in	7.303 cm
Axial Conduction Area	1047 in^2	6755 cm^2
b) Control Can: Weight (24 Cans)	472 lb	2.141×10^5 gms
Outer Radius	2.815 in	7.150 cm
Inner Radius	2.435 in	6.185 cm
Axial Conduction Area	47.38 in^2	305.7 cm^2

[redacted]

TABLE II-4 (Continued)

		English	Metric
c) Stationary Drum:	Weight (24 Drums)	1329 lb	6.028×10^5 gms
	Drum Radius	2.375 in	6.033 cm
	Axial Conduction Area	425.3 in^2	2744 cm^2
Aluminum Heat Shield:	Weight	85 lb	3.86×10^4 gms
	Inner Radius	39.628 in	100.66 cm
	Outer Radius	39.691 in	100.82 cm
Pressure Vessel:	Weight (Titanium)	650.4 lb	2.950×10^5 gms
	Inner Radius	39.879 in	101.29 cm
	Outer Radius	40.179 in	102.05 cm
Support Plate:	Weight	2149 lb	9.748×10^5 gms
	Thickness	8.5 in	21.6 cm
Top Shield:	Weight (includes shield extension)	4136 lb	1.876×10^6 gms
	Thickness	9.0 in	22.9 cm

[redacted]

The initial temperature profiles are as follows: (Refer to Figure II-3.)

Curve (1) - Core
Curve (2) - Seals
Curve (3) - Filler Strips
Curve (4) - Graphite Reflector
Curve (5) - Beryllium Reflector, Control Drums, Aluminum Heat Shield, and Pressure Vessel

As in the Be-Ring Design, the aluminum top shield and core support plate are assumed to have a uniform initial temperature of 540°R.

D. The PHOEBUS-II Design[6.,7.]

The lateral support region model used as a basis for PHOEBUS-II calculations is illustrated in Figure II-5. Here, "H-blocks" serve to support aluminum leaf springs which bear on graphite plunger pins. The plunger pins act on segmented graphite seal systems which transmit lateral support forces to the core. Axial restraint on the seals is provided by the aluminum reflector structure. The heat transfer paths considered are indicated in the diagram.

The dimensions incorporated into the PHOEBUS-II model are given in Table II-5 and component fission and gamma heating fractions are summarized in Table II-3.

The initial temperature profiles used for PHOEBUS-II Design components are also represented by the curves in Figure II-3 as follows:

Curve (1) - Core
Curve (3) - Filler Strips
Curve (4) - Seals
Curve (5) - Aluminum Reflector
Curve (6) - Beryllium Reflector, Control Drums, Aluminum Heat Shield, and Pressure Vessel

Initially, the aluminum top shield and core support plate are assumed to have a uniform temperature of 540°R.

[redacted]

+ AN AXIAL DISTRIBUTION OF TEMPERATURE IS COMPUTED FOR THIS COMPONENT

← DENOTES A CONDUCTIVE HEAT TRANSFER PATH

←∿ DENOTES A RADIATIVE HEAT TRANSFER PATH

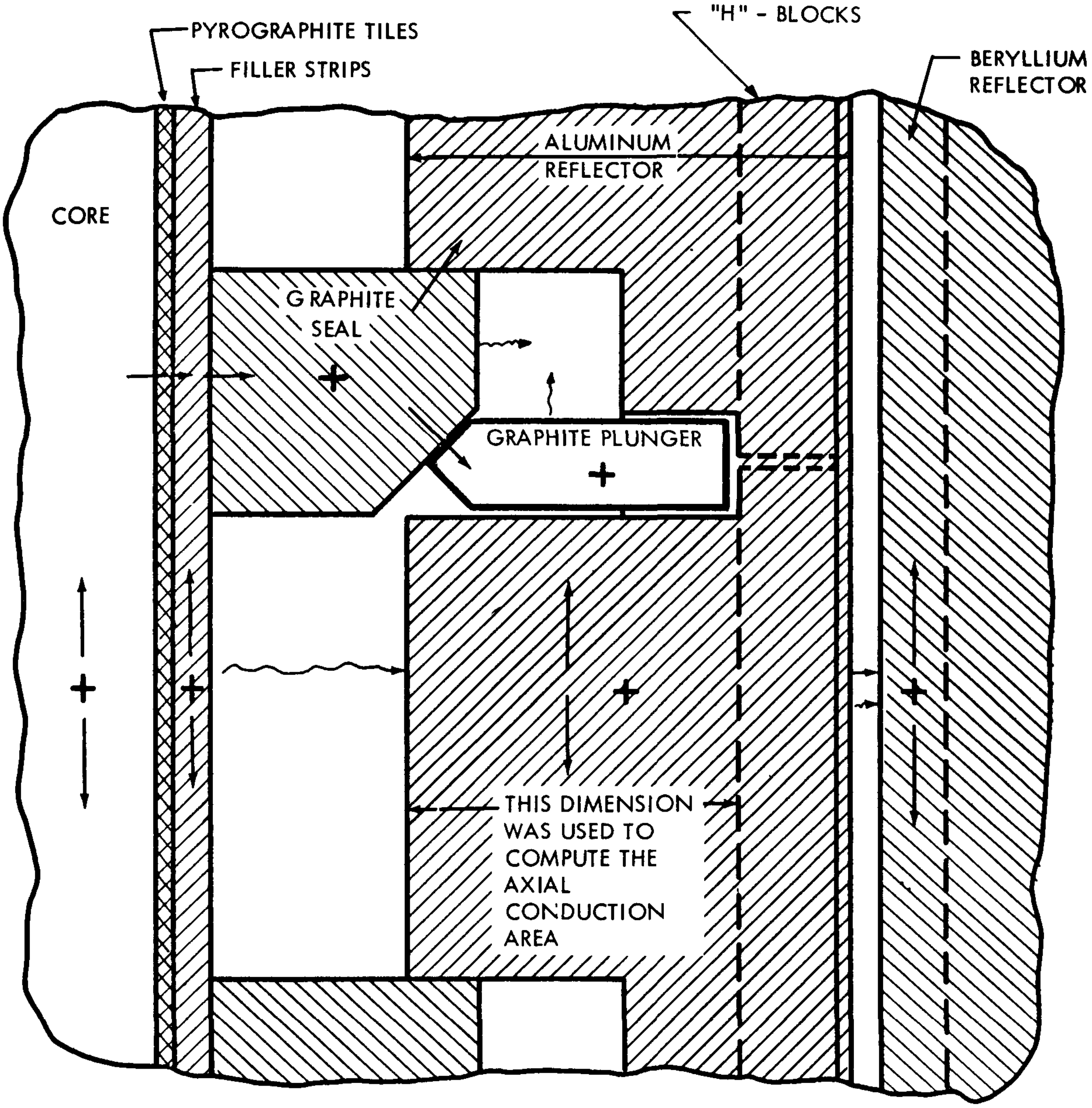

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FIGURE II-5 LATERAL SUPPORT REGION FOR PHOEBUS-II DESIGN - SCHEMATIC DRAWING

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TABLE II-5 PHOEBUS-II DESIGN MODEL SPECIFICATIONS

	English	Metric
Core: Weight	8165 lb	3.704×10^6 gms
Outer Radius	27.89 in	70.84 cm
Pyro Wrapper Thickness	0.1 in	0.254 cm
Number of Coolant Channels	94,801	
Diameter of Coolant Channels: Coated	0.107 in	0.272 cm
Diameter of Coolant Channels: Uncoated	0.110 in	0.279 cm
Length	52 in	132.1 cm
Support Blocks: Weight	346 lb	1.569×10^5 gms
Length	2.3 in	5.84 cm
Filler Strips: Weight	201.2 lb	9.124×10^4 gms
Inner Radius	27.99 in	71.09 cm
Outer Radius	28.33 in	71.96 cm
Radiation Area to Aluminum Reflector	7476 in^2	48,230 cm^2
Conduction Area to Seals	1780 in^2	11,480 cm^2
Lateral Support Region: Total Weight	2092 lb	9.489×10^5 gms
a) Seals: Weight (Total)	81.1 lb	3.679×10^4 gms
Number	8	
Axial Dimension	1.25 in	3.18 cm
Radial Dimension (max.)	0.875 in	2.22 cm
Conduction Area to Aluminum Reflector	544.7 in^2	3514 cm^2
Conduction Area to Plungers	19.95 in^2	128.7 cm^2
Radiation Area to Aluminum Reflector	917.6 in^2	5920 cm^2
Effective Conduction Length:		
Filler Strips to Seal	0.607 in	1.54 cm

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TABLE II-5 (Continued)

	English	Metric
Seal to Plunger	1.20 in	3.05 cm
Seal to Aluminum Reflector	1.25 in	3.18 cm
b) Plungers: Weight (Total)	10.6 lb	4.808×10^3 gms
Number	532	
Length	1.625 in	4.13 cm
Radius	0.25 in	0.635 cm
Radiation Area to Aluminum Reflector	1362 in^2	8784 cm^2
c) Aluminum Reflector: Weight	2000 lb	9.072×10^5 gms
Inner Radius	28.83 in	73.23 cm
Outer Radius	31.08 in	78.94 cm
Axial Conduction Area	296.0 in^2	1910 cm^2
Beryllium Reflector Region: Total Weight	7518 lb	3.410×10^6 gms
a) Reflector Structure: Weight	3240 lb	1.470×10^6 gms
Inner Radius	31.18 in	79.20 cm
Outer Radius	39.18 in	99.52 cm
Drum Centerline Radius	35.17 in	89.33 cm
Radius of Drum Hole	3.72 in	9.45 cm
Axial Conduction Area	725 in^2	4680 cm^2
b) Control Can: Weight (24 Cans)*	547 lb	2.663×10^5 gms
Outer Radius	3.63 in	9.22 cm
Inner Radius	3.38 in	8.59 cm
Axial Conduction Area	32.7 in^2	211 cm^2
c) Stationary Drum: Weight (24 Drums)*	3691 lb	1.674×10^6 gms
Drum Radius	3.31 in	8.41 cm
Axial Conduction Area	826 in^2	5330 cm^2

---

* A model which contains 18 cans and drums is also available.

[redacted]

TABLE II-5 (Continued)

		English	Metric
Aluminum Heat Shield:	Weight	198.3 lb	8.995×10^4 gms
	Inner Radius	39.43 in	100.15 cm
	Outer Radius	39.586 in	100.55 cm
Pressure Vessel:	Weight (Titanium)	648.8 lb	2.943×10^5 gms
	Inner Radius	39.68 in	100.79 cm
	Outer Radius	39.98 in	101.55 cm
Support Plate:	Weight	1965 lb	8.913×10^5 gms
	Thickness	8.5 in	21.59 cm
Top Shield:	Weight (includes shield extension)	4136 lb	1.876×10^6 gms
	Thickness	9.0 in	22.86 cm

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CHAPTER III TEMPERATURE DATA

The nuclear heat source in each of the designs is essentially identical, since each has a very similar core and identical full power operating levels. This heat source can be characterized by the "fission power" (i.e., all the sources of energy deposition in the reactor, the magnitudes of which are directly proportional to the instantaneous fission rate), and the "decay power" (the sources of energy deposition in the reactor which depend on the rate of decay of fission products). The power history corresponding to each of the chosen full power operating periods at 5000 MW, 30 seconds and 500 seconds, is given in Figures III-1 and III-2, respectively. In each case a shutdown reactivity insertion of -3.05 per cent, which corresponds to the hydrogen worth in the core, has been assumed immediately upon loss of coolant.

Beryllium Ring Design - The component of critical interest in determining the possibility of maintaining bundling pressure on the core in this design is the beryllium reflector structure. A series of axial temperature profiles for this component at various times following a 500 second full power operating period appears in Figure III-3. Since the actual graphite sublimation rate may have considerable influence on these profiles, as discussed in Chapter II, profiles from cases computed using both vacuum and no sublimation rate assumptions are shown.

Graphite Barrel Design - Precisely similar information to that just described for the Be-Ring Design appears in Figure III-4 for the Graphite Barrel Design.

PHOEBUS-II Design - The component of particular interest in determining the integrity of the core in the PHOEBUS-II design is the inner aluminum reflector. Axial temperature profiles for this component are displayed in Figure III-5.

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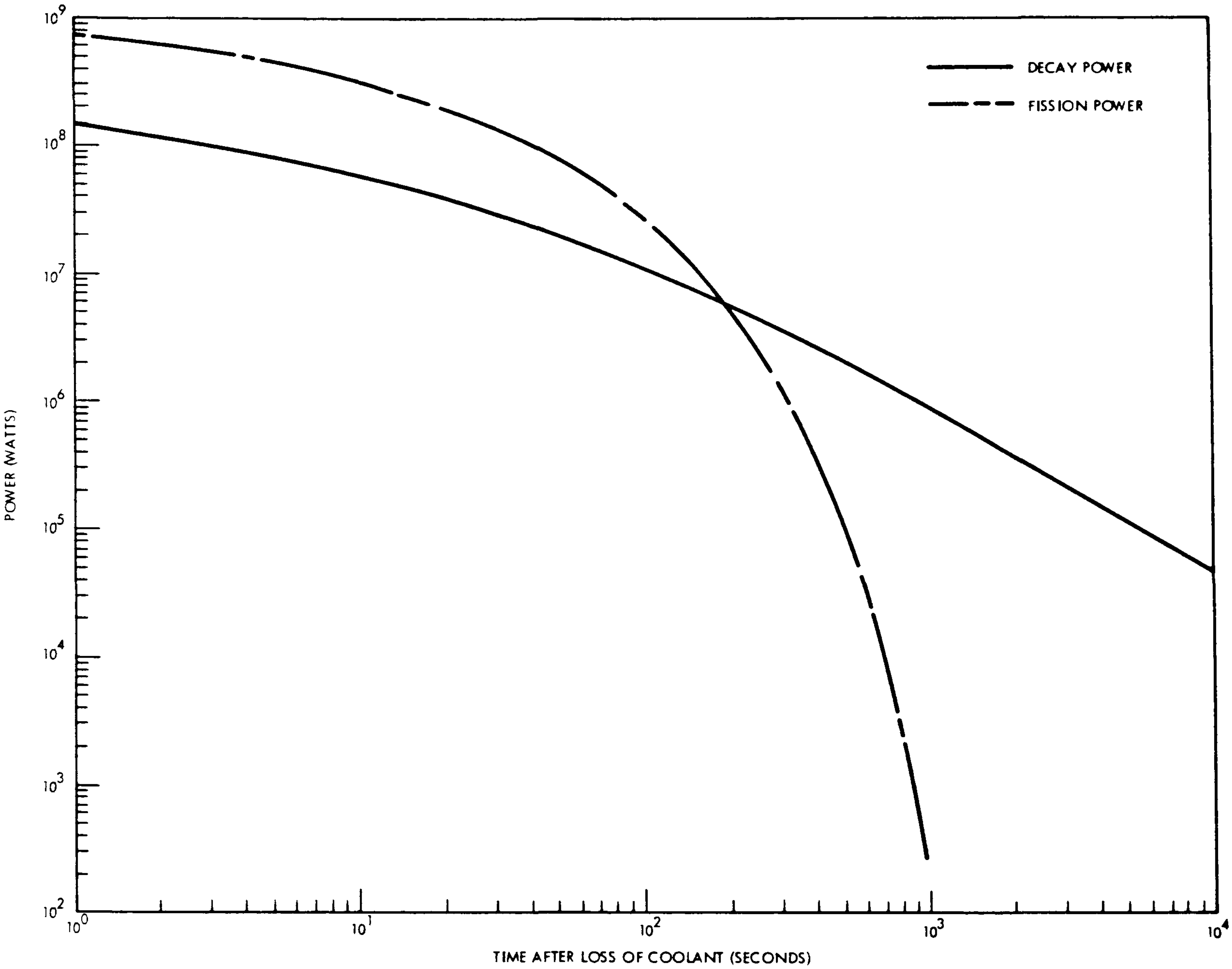

FIGURE III-1 REACTOR POWER HISTORY FOLLOWING A 30 SECOND 5000 MW FULL POWER OPERATING PERIOD AND LOSS OF COOLANT

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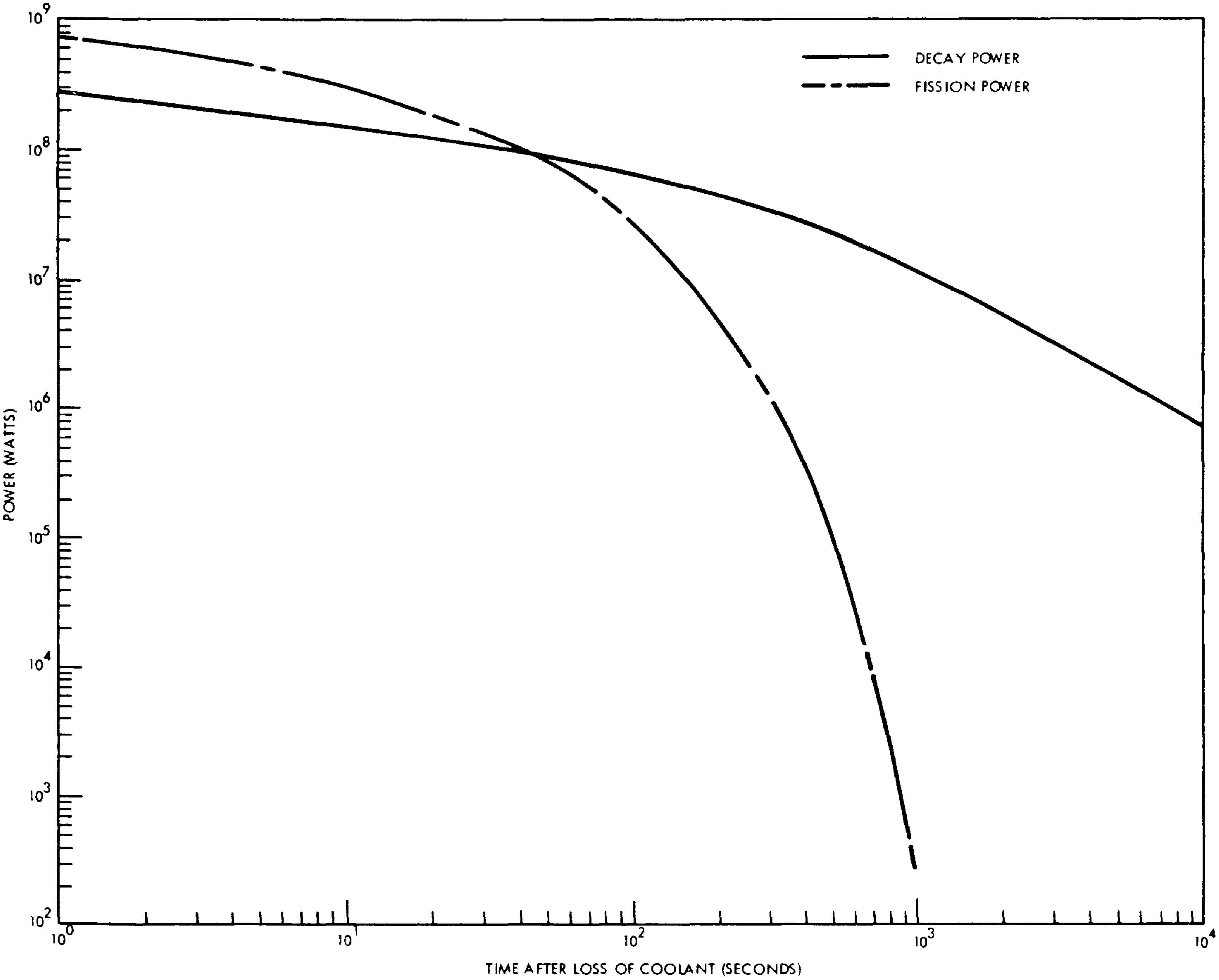

FIGURE III-2 REACTOR POWER HISTORY FOLLOWING A 500 SECOND 5000 MW FULL POWER OPERATING PERIOD AND LOSS OF COOLANT

[redacted]

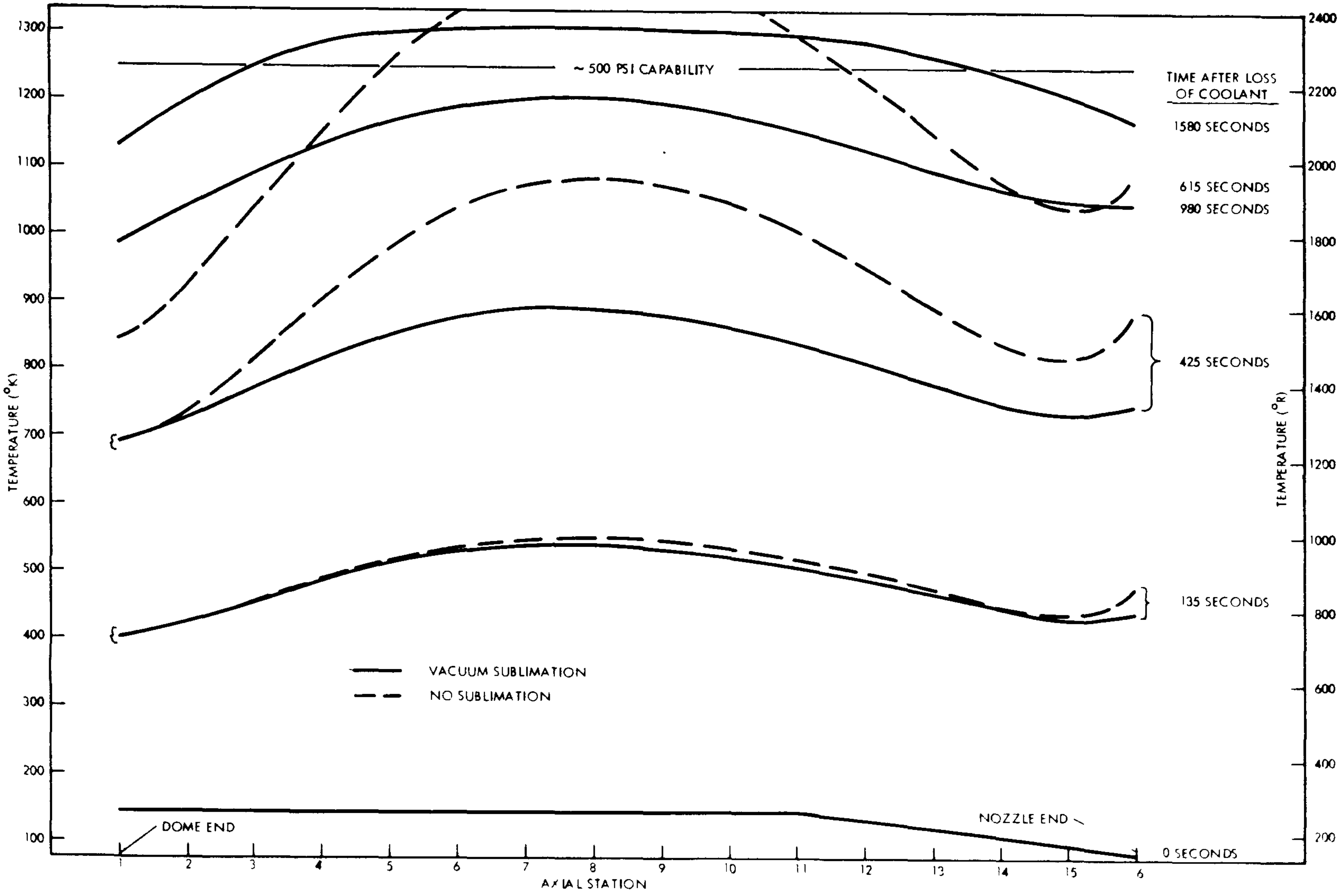

FIGURE III-3 AXIAL TEMPERATURE PROFILES IN THE BE-RING DESIGN BERYLLIUM REFLECTOR FOLLOWING A 500 SECOND FULL POWER OPERATING PERIOD AND LOSS OF COOLANT

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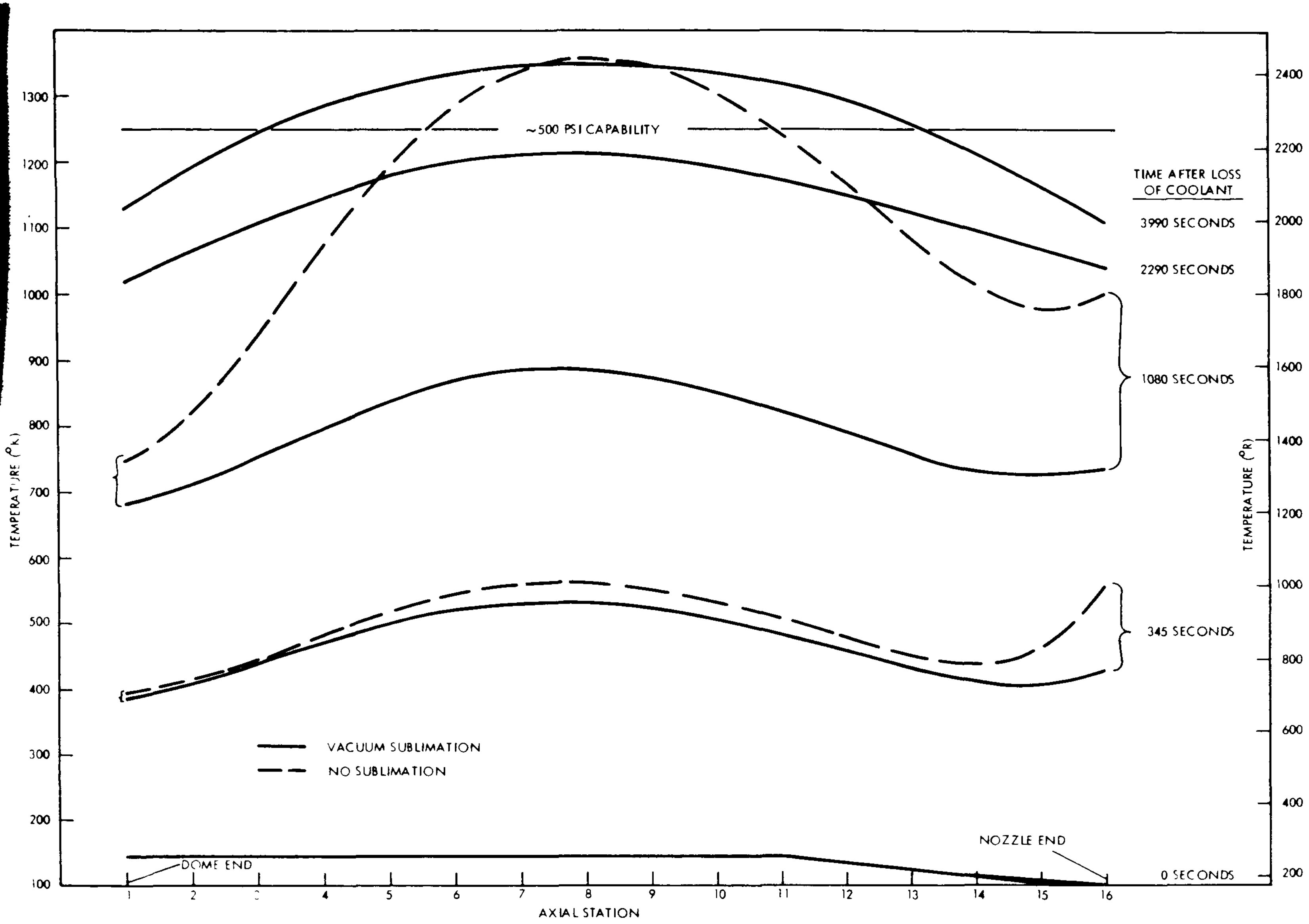

FIGURE III-4 AXIAL TEMPERATURE PROFILES IN THE GRAPHITE BARREL DESIGN BERYLLIUM REFLECTOR FOLLOWING A 500 SECOND FULL POWER OPERATING PERIOD AND LOSS OF COOLANT

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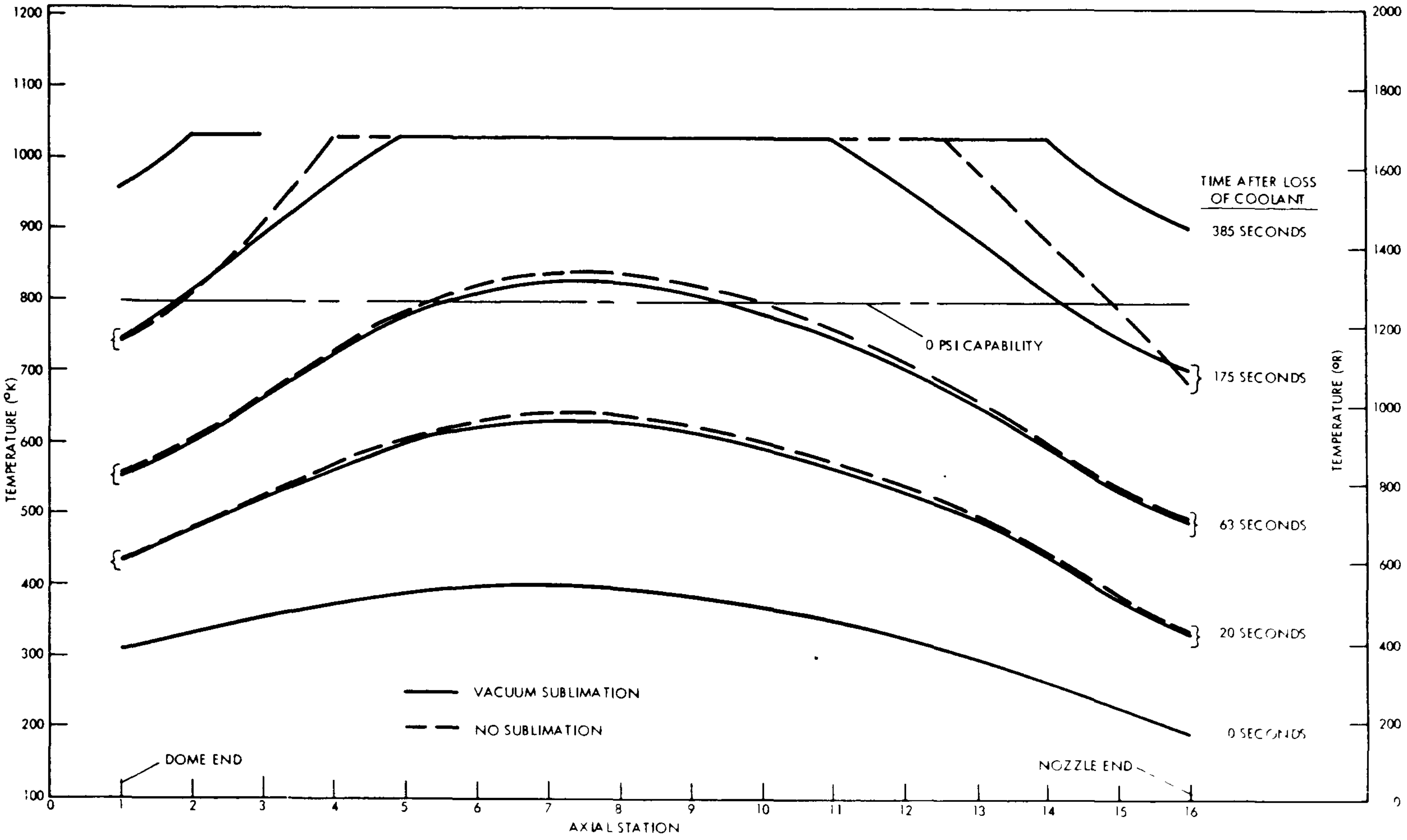

FIGURE III-5 AXIAL TEMPERATURE PROFILES IN THE PHOEBUS-II DESIGN ALUMINUM REFLECTOR FOLLOWING A 500 SECOND FULL POWER OPERATING PERIOD AND LOSS OF COOLANT

[redacted]

Some question has been raised as to the possibility of preserving the aluminum reflector (and hence the lateral support forces in the core) by allowing this component to expand under high temperature conditions into good thermal contact with the beryllium reflector. Thus a cooling mechanism, conductive heat transfer from inner to outer reflector, would be provided. A set of three computations were made to check this possibility. In the first, all radiative heat transfer between these components was assumed; in the second, all conductive transfer at a given location was assumed when the relative expansions of the two components indicated that contact between them at that location existed. Since the pressure between surfaces in contact is somewhat difficult to estimate, it was felt that a reasonable fraction of the surface area which might be in close enough contact to justify an assumption of zero contact resistance was about 0.7. Thus, a third computation was carried out in which the heat transfer mechanism was assumed to be 70 per cent conduction and 30 per cent radiation when contact between the component surfaces was indicated at a given location. The results of this investigation appear in Figures III-6, III-7, and III-8, in which the time-temperature histories of the inner and outer reflectors are given at the dome end, midplane, and nozzle end locations, respectively. A 500 second full power operating period using the vacuum sublimation model was chosen for this study.

The results shown in Figure III-5 were obtained using the third assumption, i.e., that if the relative expansions of the PHOEBUS-II inner and outer reflectors indicate that these components are in contact at any location, heat transfer is assumed to occur by conduction through 70 per cent of the contact area and by radiation from surface to surface over the remainder of the area at that location.

A series of detailed time-temperature histories for various locations in all of the components of interest appear in an Appendix to this document. The information presented in this chapter and quoted later in Chapter IV has been abstracted from basic data of the sort displayed there.

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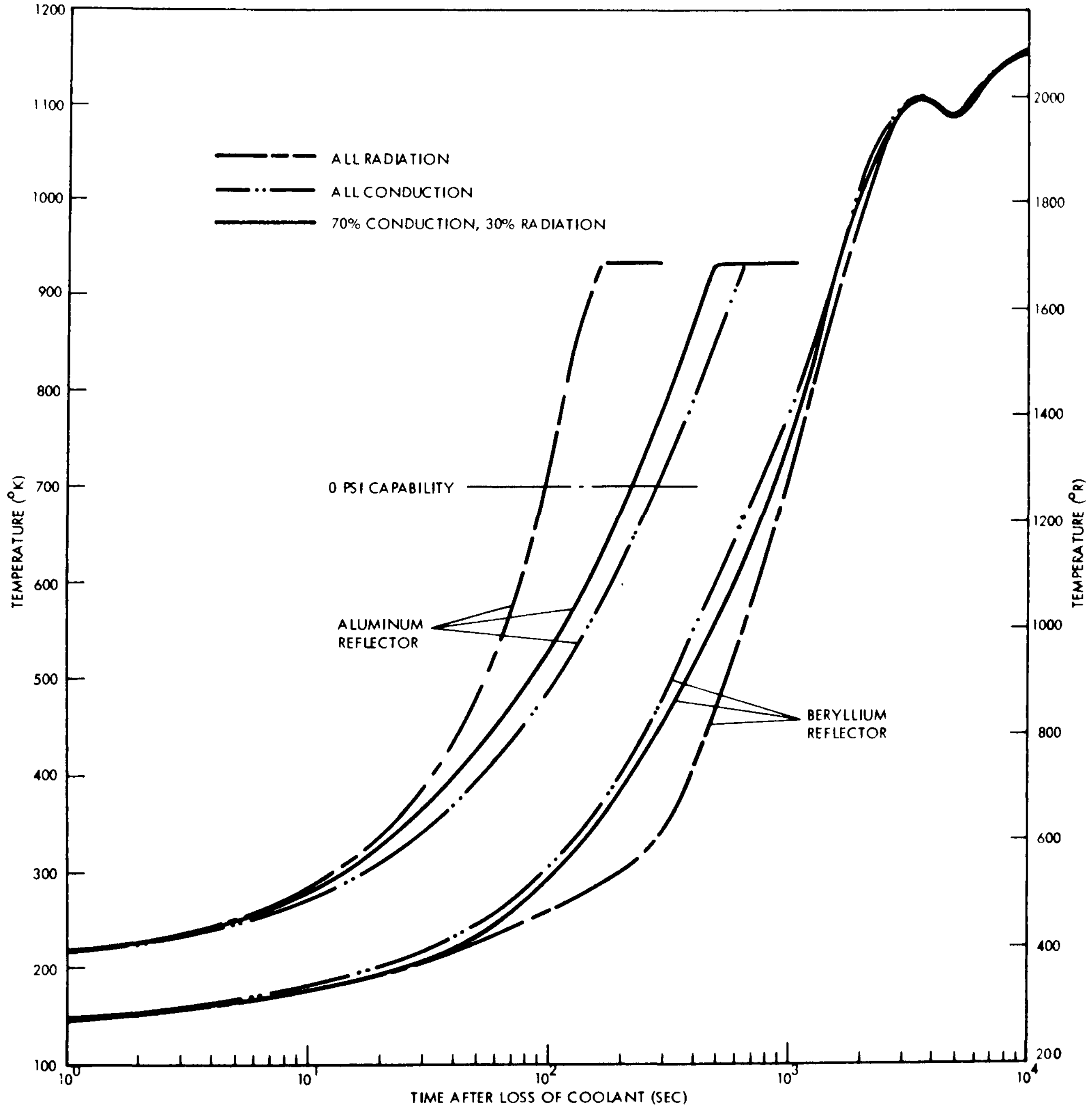

FIGURE III-6 TEMPERATURE HISTORIES OF THE PHOEBUS-II DESIGN ALUMINUM AND BERYLLIUM REFLECTORS AT THE DOME END LOCATION WITH VARIOUS HEAT TRANSFER MODES

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[redacted]

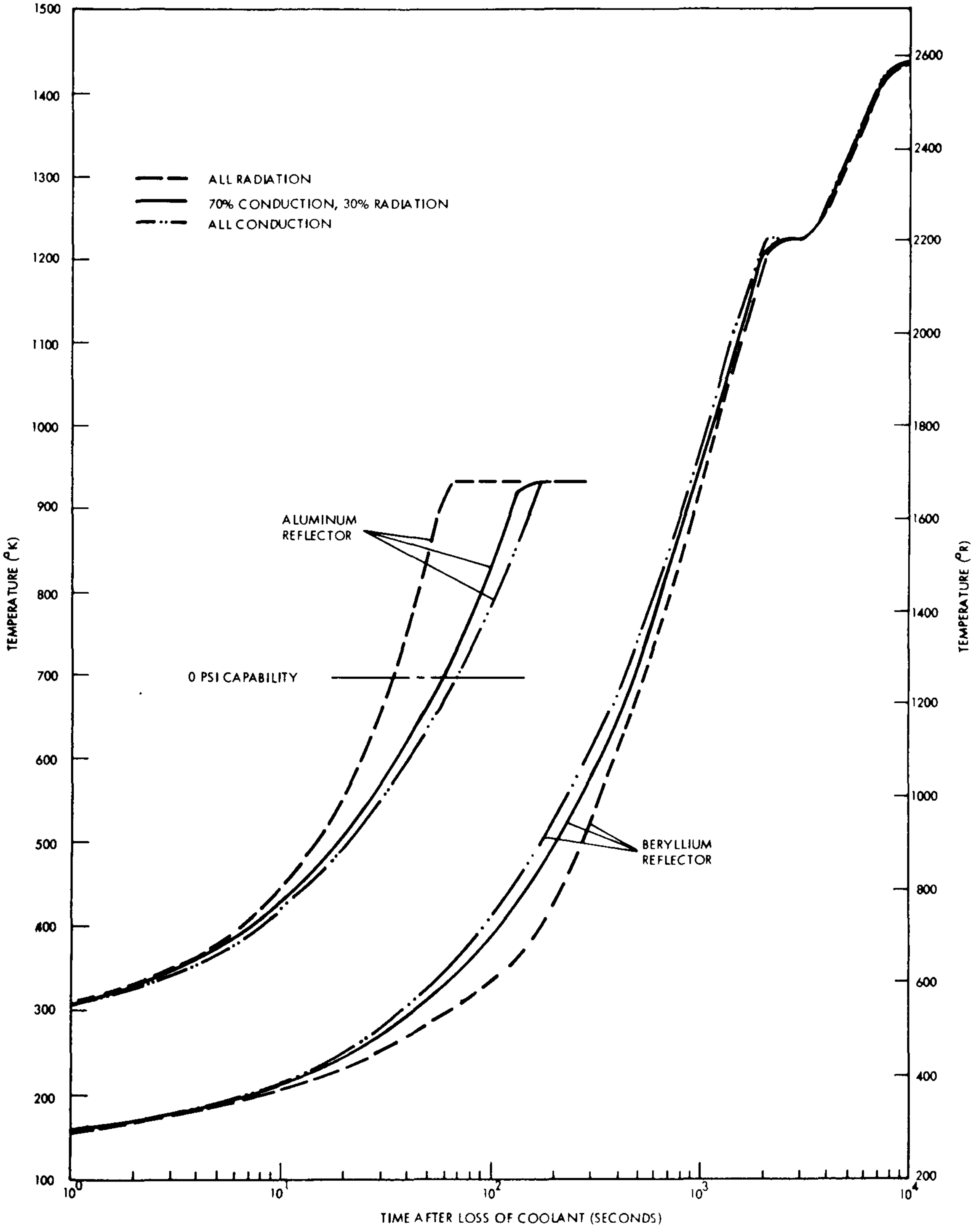

FIGURE III-7 TEMPERATURE HISTORIES OF THE PHOEBUS-II DESIGN ALUMINUM AND BERYLLIUM REFLECTORS AT THE MIDPLANE LOCATION WITH VARIOUS HEAT TRANSFER MODES

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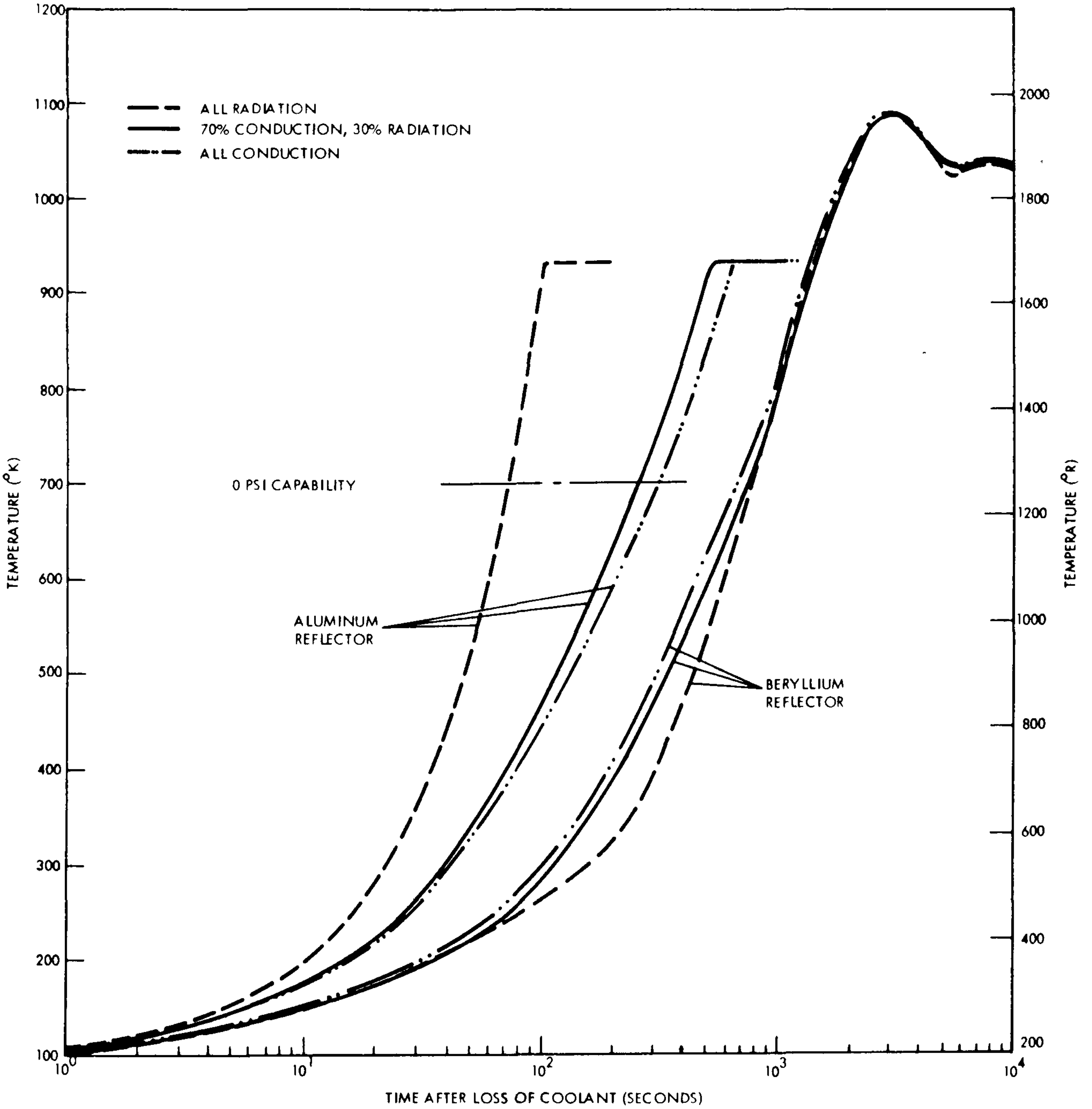

FIGURE III-8 TEMPERATURE HISTORIES OF THE PHOEBUS-II DESIGN ALUMINUM AND BERYLLIUM REFLECTORS AT THE NOZZLE END LOCATION WITH VARIOUS HEAT TRANSFER MODES

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CHAPTER IV SUMMARY AND COMPARATIVE EVALUATION

The major components of interest in determining whether or not a reactor core can be maintained in an intact configuration are those which comprise the lateral support system. In the Be-Ring and Graphite Barrel designs, the component which contributes lateral support and is subject to high temperature failure is the beryllium reflector; in the PHOEBUS-II design, it is the inner aluminum reflector. Therefore, an estimate of the effective lifetime of the lateral support system can be obtained from an examination of the temperature histories of these components in each design. Extrapolation of WANL Materials Manual data on the yield and ultimate tensile strength of beryllium as a function of temperature indicates that the beryllium reflector structure may have a tensile capability of ~1000 psi up to 1960°R and of ~500 psi up to 2250°R. An estimate of the bundling force in the reflector due to the core lateral support system in two of the designs is ~400-500 psi. Therefore, a measure of the effective lifetime of the lateral support system at all axial locations within the beryllium reflector in the Be-Ring and Graphite Barrel designs can be taken as the length of time after loss of coolant required for its temperature at that location to reach 2250°R.

Lateral support forces in the PHOEBUS-II aluminum reflector can be maintained only so long as the integrity of the aluminum barrel persists. Since no estimate of the bundling force in the reflector is available, an upper limit on its effective lifetime can be obtained by measuring the length of time after loss of coolant required for its temperature at any axial location to reach 1260°R, at which time the material capability is ~0 psi.

These effective lifetimes for the Be-Ring and Graphite Barrel beryllium reflectors are summarized in Table IV-1 along with some other events of interest. Similar information on the PHOEBUS-II beryllium outer reflector has also been included for general interest and comparison.

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TABLE IV-1 EVENTS OF INTEREST IN THE POST-OPERATIONAL THERMAL HISTORY OF THREE REACTOR DESIGNS

Component	Event	Location	Be-Ring				Graphite Barrel				Phoebus-II			
			30 Seconds		500 Seconds		30 Seconds		500 Seconds		30 Seconds		500 Seconds	
			No Sub.	Vac. Sub.	No Sub.	Vac. Sub.	No Sub.	Vac. Sub.	No Sub.	Vac. Sub.	No Sub.	Vac. Sub.	No Sub.	Vac. Sub.
Beryllium Reflector	1000 psi Capability (~1960°R)	Dome End	2200	3500	1075	1400	4200	(g)	1750	2990	(q)	(r)	1530	2900
		Midplane	900	1600	425	700	1890	4270	850	1700	1250	3300	550	1440
		Nozzle End	1250	(a)	650	1150	3390	(h)	1280	2990	(s)	(t)	1000	(u)
	*500 psi Capability (~2250°R)	Dome End	(b)	(c)	1500	(e)	(i)	----	2350	(l)	----	----	3000	(w)
		Midplane	1025	2760	525	1125	2290	(j)	975	2790	1550	(v)	650	(x)
		Nozzle End	(d)	----	900	(f)	(k)	----	1700	(m)	----	----	1530	----
	Melting Starts (2790°R)	Dome End	----	----	----	----	----	----	(n)	----	----	----	(z)	----
		Midplane	3100	----	830	----	4800	----	1325	(o)	(y)	----	1050	----
		Nozzle End	----	----	----	----	----	----	(p)	----	----	----	(aa)	----
	Completely Melted	Dome End	----	----	----	----	----	----	----	----	----	----	----	----
		Midplane	4550	----	1200	----	----	----	1800	----	----	----	1600	----
		Nozzle End	----	----	----	----	----	----	----	----	----	----	----	----
Support Plate	*0 psi Capability (~1260°R)	Entire Component	600	650	135	135	700	700	155	155	750	800	230	230
Aluminum Reflector	*0 psi Capability (~1260°R)	Dome End									750	780	215	225
		Midplane									200	430	55	55
		Nozzle End									400	590	215	260
	Melting Starts (1680°R)	Dome End									1500	1800	480	500
		Midplane									350	980	115	135
		Nozzle End									750	1400	380	525
	Completely Melted	Dome End									2400	3100	800	900
		Midplane									475	1400	170	250
		Nozzle End									1200	3100	575	900

* This event is a measure of the effective lifetime of the component.

(a) 1908°R maximum at 2350 sec
(b) 2105°R maximum at 3400 sec
(c) 1980°R maximum at 3500 sec
(d) 2140°R maximum at 2300 sec
(e) 2250°R maximum at 5400 sec
(f) 2115°R maximum at 4100 sec
(g) 1825°R maximum at 6900 sec
(h) 1730°R maximum at 5900 sec
(i) 2025°R maximum at 5000 sec
(j) 2090°R maximum at 6400 sec
(k) 2000°R maximum at 3600 sec
(l) 2180°R maximum at 8190 sec
(m) 2035°R maximum at 6190 sec
(n) 2485°R maximum at 4400 sec
(o) 2680°R maximum at 9200 sec
(p) 2460°R maximum at 3300 sec
(q) 1960°R maximum at 4800 sec
(r) 1775°R maximum at 5100 sec
(s) 1945°R maximum at 2850 sec
(t) 1640°R maximum at 4400 sec
(u) 1960°R maximum at 3000 sec
(v) 2090°R maximum at 4500 sec
(w) 2000°R maximum at 3500 sec
(x) 2205°R maximum at 2300 sec
(y) 2700°R maximum at 5000 sec
(z) 2430°R maximum at 5000 sec
(aa) 2320°R maximum at 3900 sec

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The table also includes information on the behavior of the aluminum reactor core support plate. The support plate could provide valuable axial support to the fuel clusters under the loads imposed by the use of an ATS countermeasure. Alternatively, an exact knowledge of the material conditions in this reactor location at the time of activation of an explosive destruct countermeasure system is imperative in order that the charge required for penetration of the forward components and the timing of firing may be computed.

The condition of the poison system following a loss of coolant accident must be determined in order to estimate if, and if so, when, the reactor might become critical during its post-operational history. Even a small excursion, could well generate enough heat to materially alter the computed post-operational temperature profiles. Preliminary data indicate that the Boral poison material may melt out at the midplane as soon as 6 to 16 seconds after loss of coolant. However, a more detailed study based on several more sophisticated models than have been previously used are currently underway. Results of this study will be reported at a later date.

In many cases, a component never reaches a temperature which would reduce its strength at a given location to the value specified in the table. For example, the temperature of the Be-Ring Design beryllium reflector at the dome end location never reaches a value of 2250°R following a 30 second engine operation and failure. In each case of this kind, a note has been included to indicate the maximum temperature achieved at that location and the time after failure at which this maximum is predicted.

The data from the table indicate that lateral support system total failure in the PHOEBUS-II design will occur within 12 minutes at most if loss of coolant should occur after a relatively short engine operating period, and within three to four minutes if the engine operating period is a relatively long one. These conclusions are based on 70 per cent conduction cooling of the inner reflector when it is in contact with the beryllium. As was pointed out in Chapter III, additional conduction cooling would not alter them. Thus, insufficient time

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is available after a suborbital accident which would lead to land impact of the debris to guarantee effective ATS countermeasure action. In the event of engine failure and loss of coolant early in an orbital mission, the reactor core can begin to disassemble within minutes of failure, which insures prompt re-entry of the debris in a random fashion with the accompanying high dose rates described in Chapter I.

In the Be-Ring Design, effective lateral support can be maintained for at least 15 minutes (and possibly for an indefinite period) following late suborbital system failure. Early orbital system failure is not expected to lead to disassembly of the reactor core. Thus, time for countermeasure action is available in the suborbital case, as is the full orbital lifetime of the core in early orbital failure cases. The data support a similar conclusion for the Graphite Barrel Design reactor.

The data indicate that the support plate, as it is presently envisioned for all designs examined, will provide little or no axial support during ATS or other countermeasure action.

A final conclusion may be drawn. This is, under the severe accident conditions represented by loss of coolant, the Graphite Barrel Design provides the best opportunity to guarantee a minimum risk of radiological hazard to the Earth's population; the Be-Ring Design the next best opportunity; and the PHOEBUS-II Design the least, based on the present design features of each.

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CHAPTER V RECOMMENDATIONS FOR EXTENSION OF THE STUDY

There are a number of areas in which it is felt that extension and/or refinement of the models described in this document should provide data which would be useful and necessary in the prediction of the behavior of a flight reactor under severe accident conditions.

1. The aerodynamic behavior, orbit lifetime, and possibly the core integrity depend on the condition of the nozzle and aft end of the pressure vessel under loss of coolant conditions. These components should be incorporated into the study.
2. A number of types of control drum and poison systems have been proposed which differ in design configuration and construction materials. These designs should be studied carefully and one selected which provides the greatest possibility of survival so that the reactor may be maintained in a subcritical condition at all times following any system failure.
3. The effects of fission product diffusion on post-operational temperatures should be determined for the flight engine reactor as was done for the NRX designs.
4. A realistic estimate of the rate of sublimation and removal of graphite from the core should be obtained and incorporated into the study.
5. The post-operational history and integrity of these concepts as modifications are proposed to improve post-accident survival should be be investigated.

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APPENDIX

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INDEX OF PAGE NUMBERS FOR TEMPERATURE HISTORY PLOTS

Temperature History	NERVA Beryllium Ring Design				NERVA Graphite Barrel Design				PHOEBUS-II Design			
	30 sec		500 sec		30 sec		500 sec		30 sec		500 sec	
	VS	NS	VS	NS	VS	NS	VS	NS	VS	NS	VS	NS
Fuel Cluster at Dome End	A-2	A-13	A-24	A-41								
Fuel Cluster at Midplane	A-3	A-14	A-25	A-42								
Fuel Cluster at Nozzle End	A-4	A-15	A-26	A-43								
Fuel Cluster Average	A-5	A-16	A-27	A-44	A-52	A-60	A-68	A-79	A-87	A-95	A-103	A-114
Filler Strips at Dome End	A-6	A-17	A-28	A-45								
Filler Strips at Midplane	A-7	A-18	A-29	A-46								
Filler Strips at Nozzle End	A-8	A-19	A-30	A-47								
Seals at Dome End			A-31				A-69				A-104	
Seals at Midplane			A-32				A-70				A-105	
Seals at Nozzle End			A-33				A-71				A-106	
Spacers at Dome End			A-34									
Spacers at Midplane			A-35									
Spacers at Nozzle End			A-36									
Beryllium Reflector at Dome End	A-9	A-20	A-37	A-48	A-53	A-61	A-72	A-80	A-88	A-96	A-107	A-115
Beryllium Reflector at Midplane	A-10	A-21	A-38	A-49	A-54	A-62	A-73	A-81	A-89	A-97	A-108	A-116
Beryllium Reflector at Nozzle End	A-11	A-22	A-39	A-50	A-55	A-63	A-74	A-82	A-90	A-98	A-109	A-117
Support Plate at Nozzle End	A-12	A-23	A-40	A-51	A-56	A-64	A-75	A-83	A-91	A-99	A-110	A-118
Inner Reflector at Dome End					A-57	A-65	A-76	A-84	A-92	A-100	A-111	A-119
Inner Reflector at Midplane					A-58	A-66	A-77	A-85	A-93	A-101	A-112	A-120
Inner Reflector at Nozzle End					A-59	A-67	A-78	A-86	A-94	A-102	A-113	A-121

30 sec and 500 sec refer to a 30 and 500 second full power operation before loss of coolant.
VS = the vacuum sublimation model.
NS = the no sublimation model.

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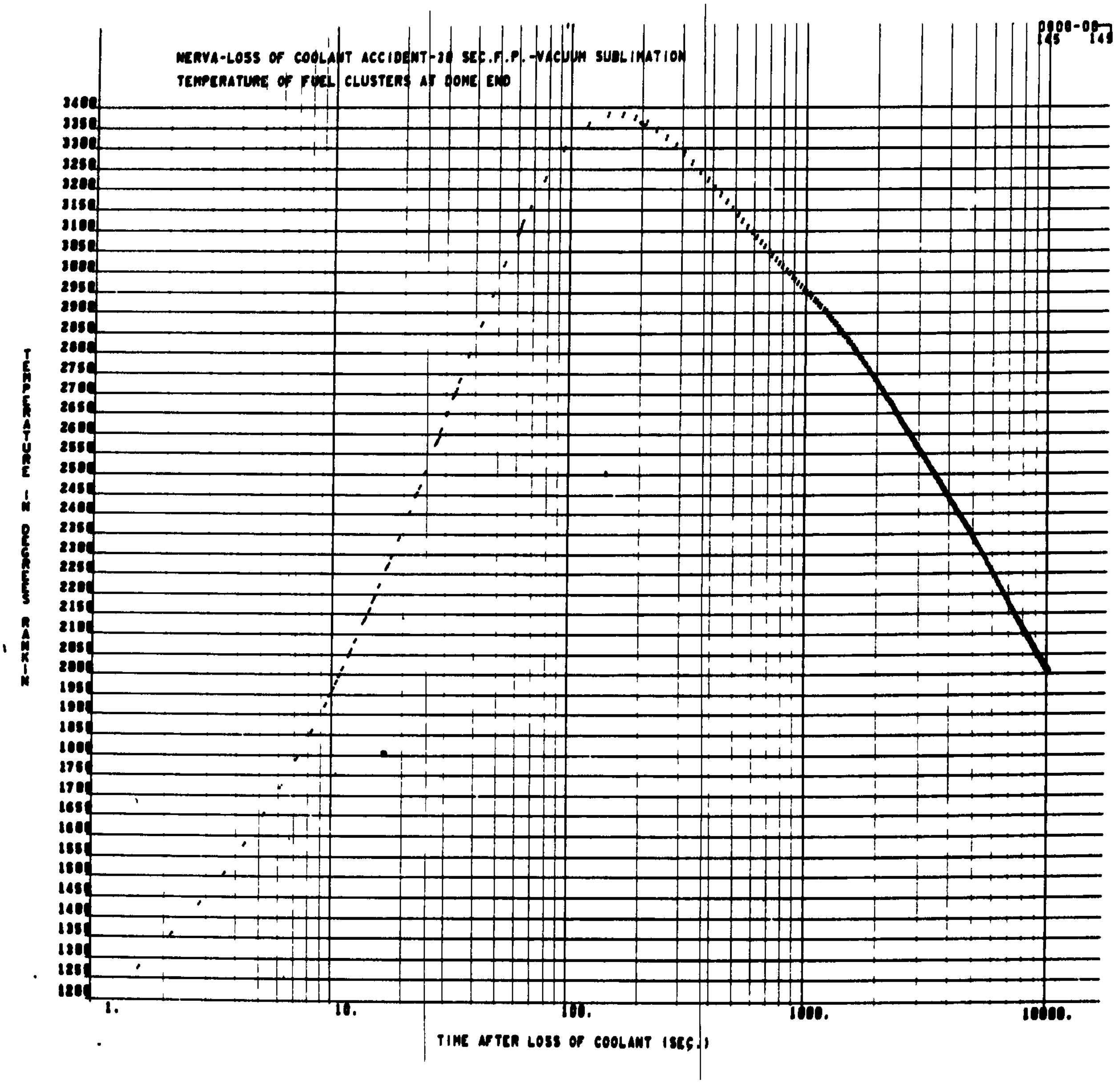
WANL-TME-1431



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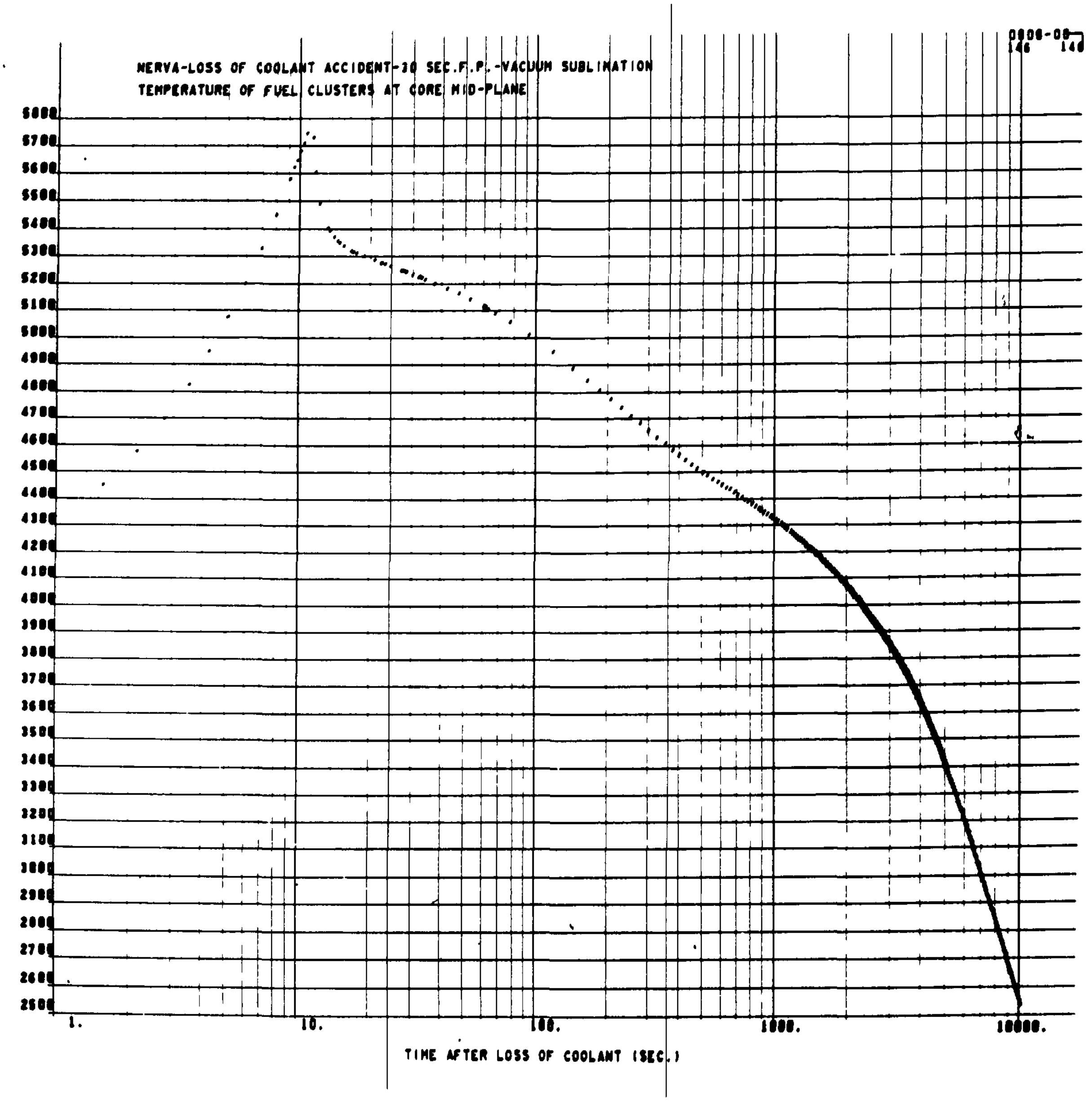

NERVA-LOSS OF COOLANT ACCIDENT-30 SEC.F.P.-VACUUM SUBLIMATION
TEMPERATURE OF FUEL CLUSTERS AT CORE MID-PLANE

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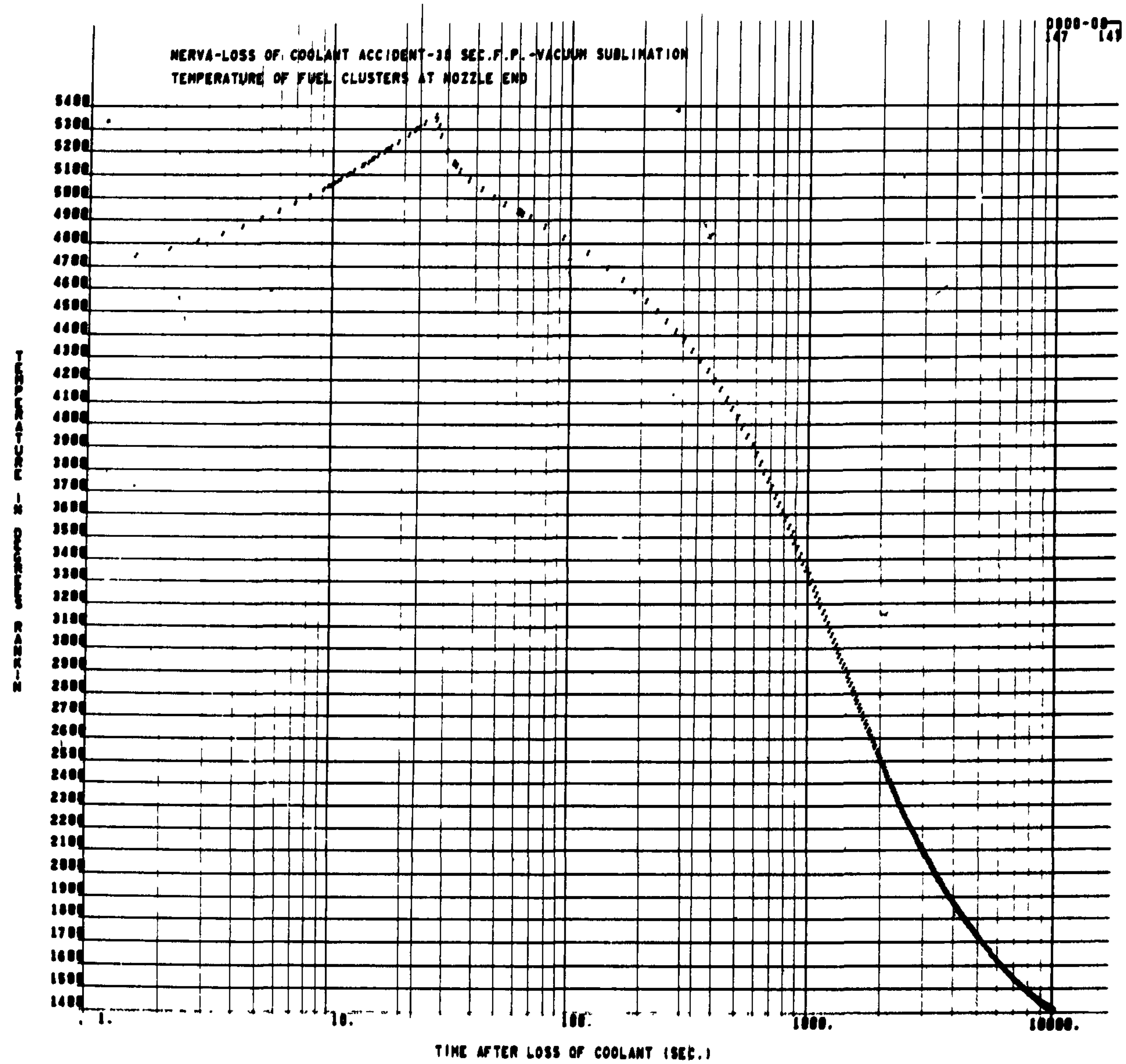

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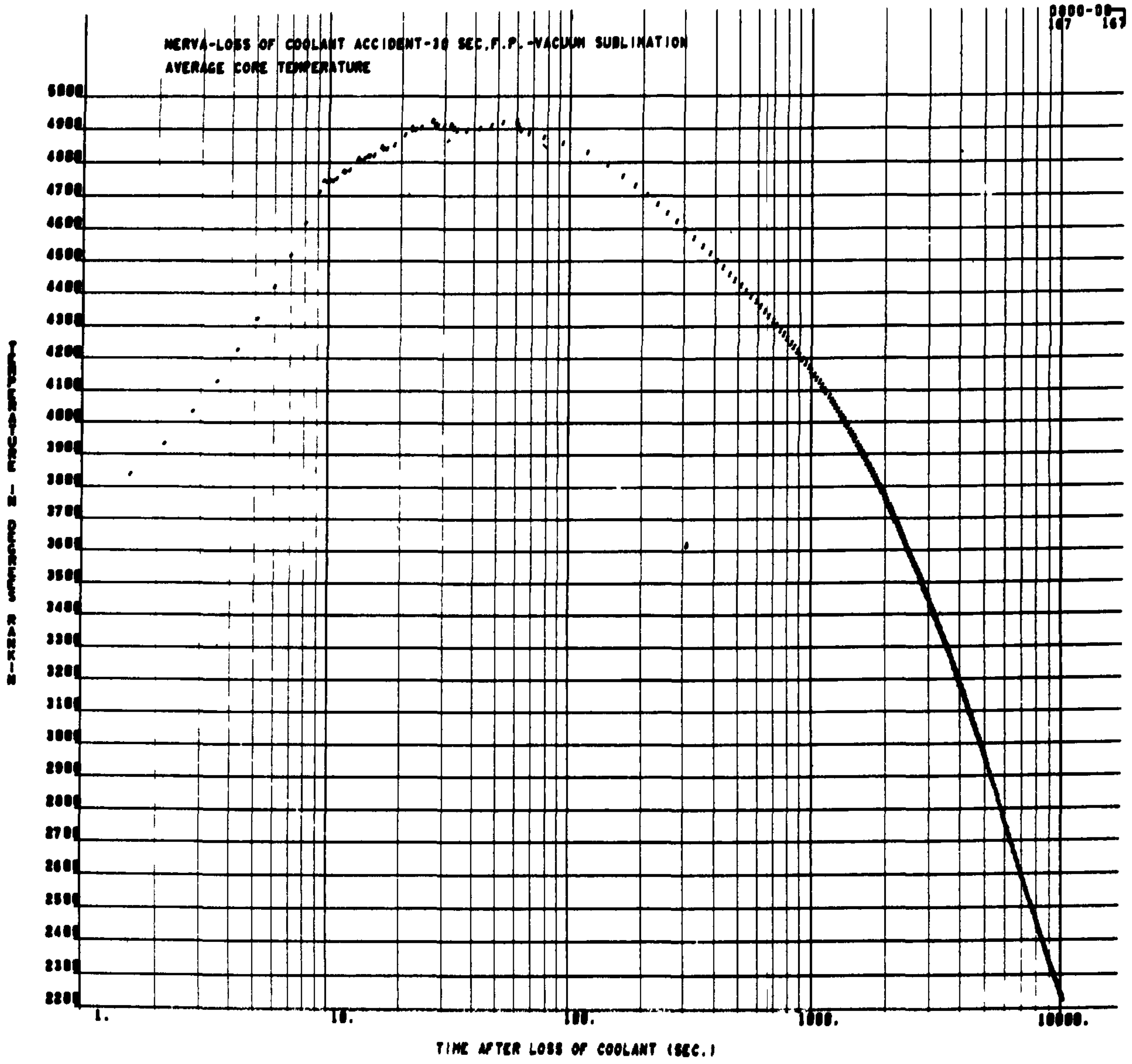

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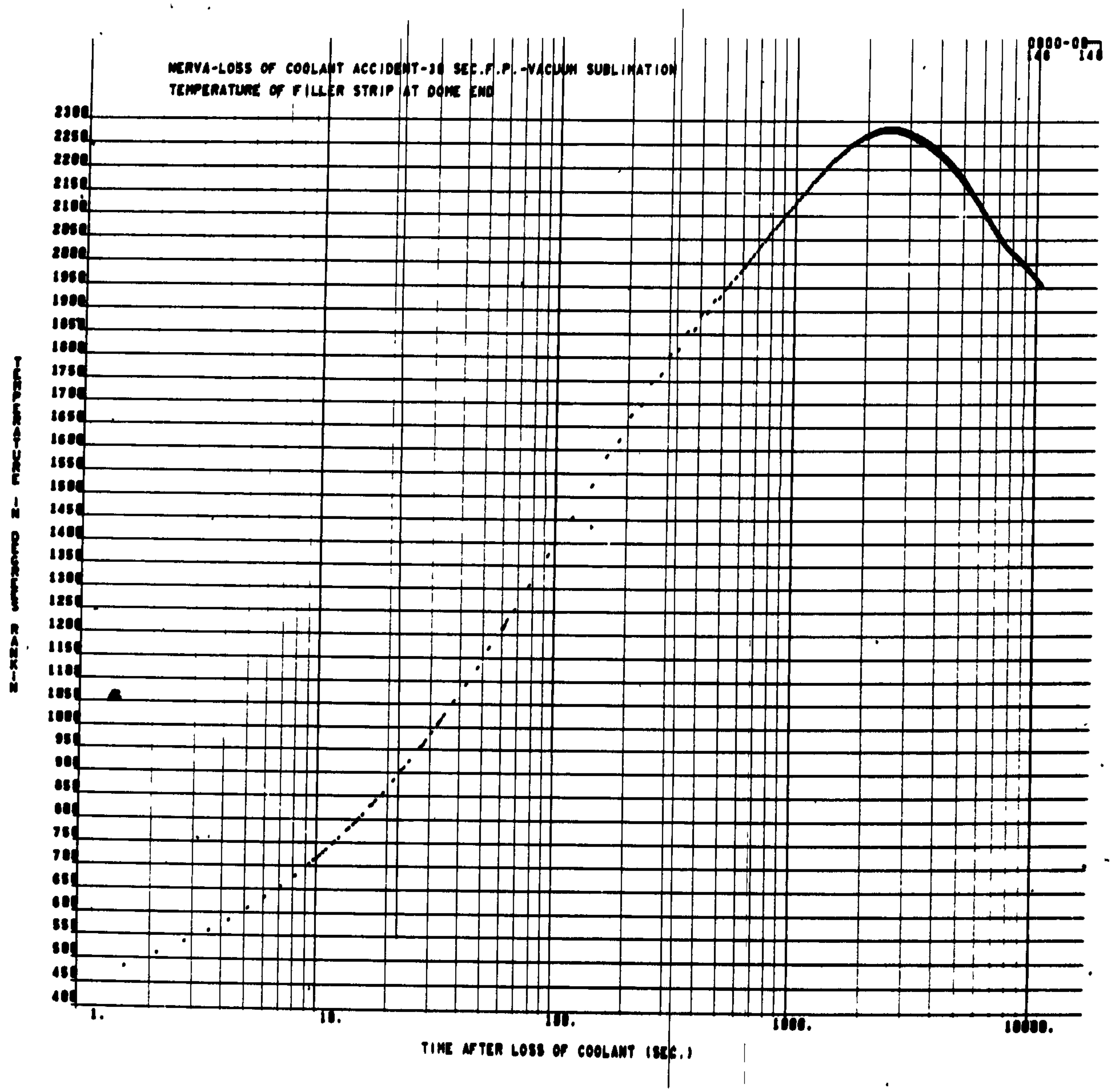

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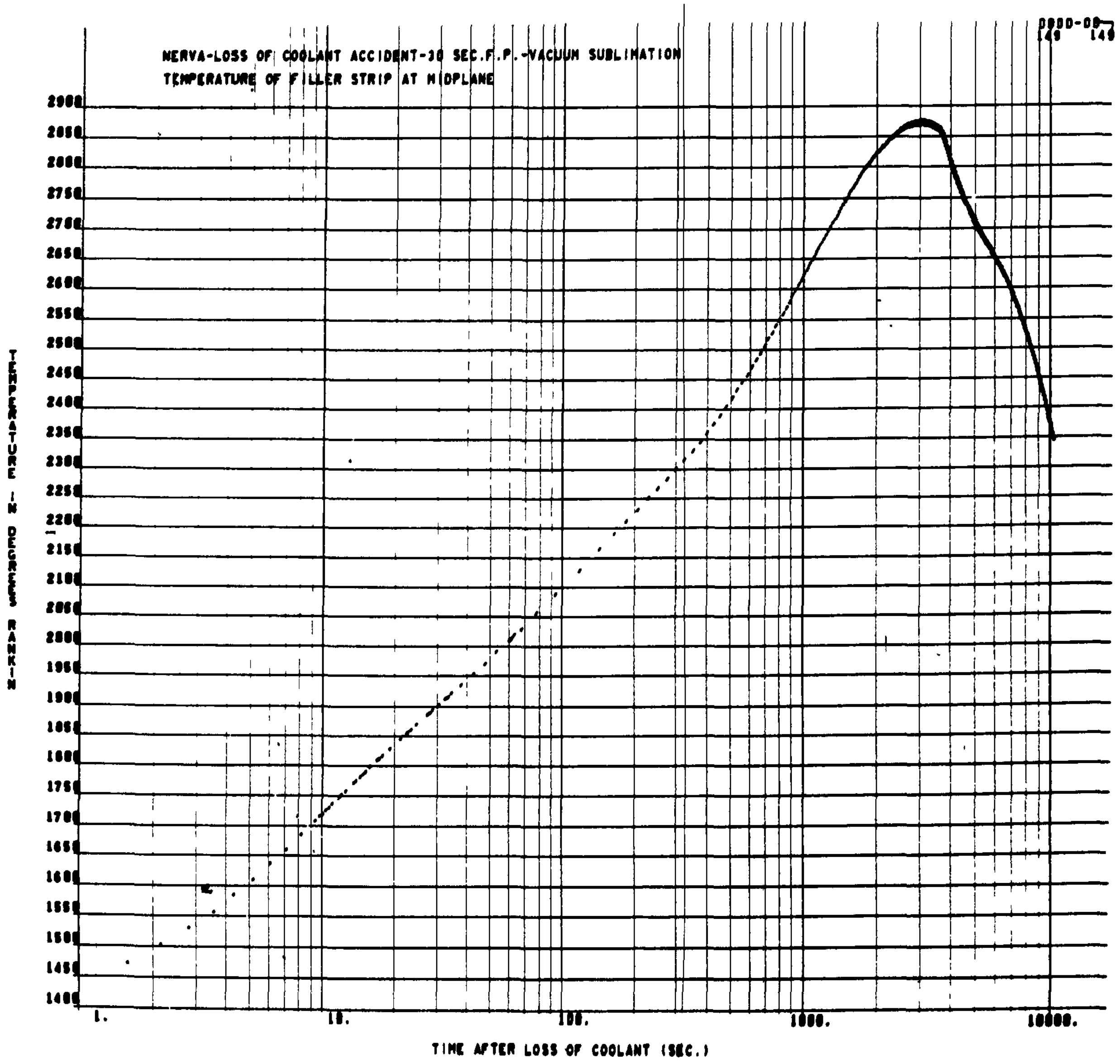

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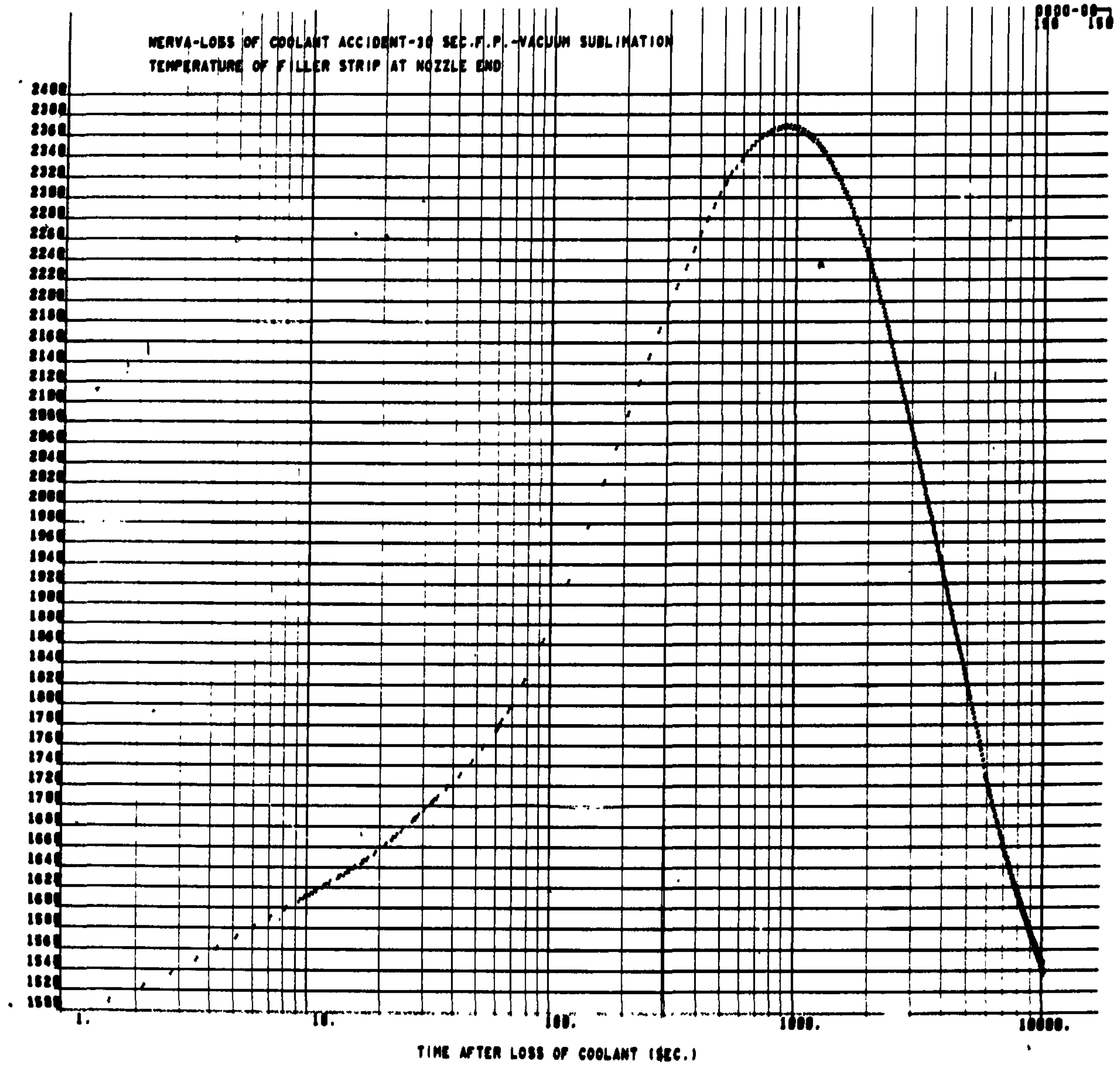

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TEMPERATURE OF FILLER STRIP AT NOZZLE END

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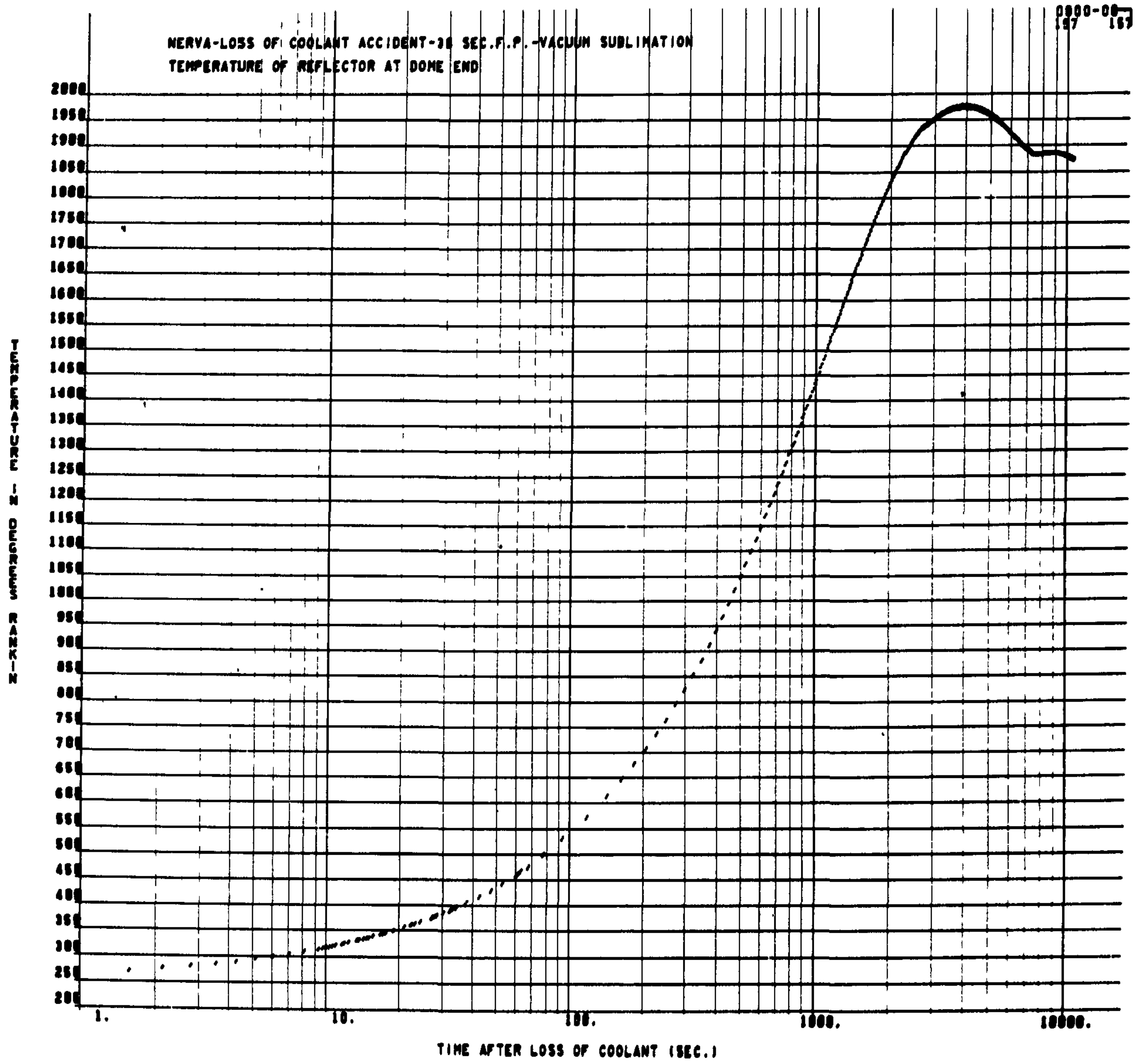

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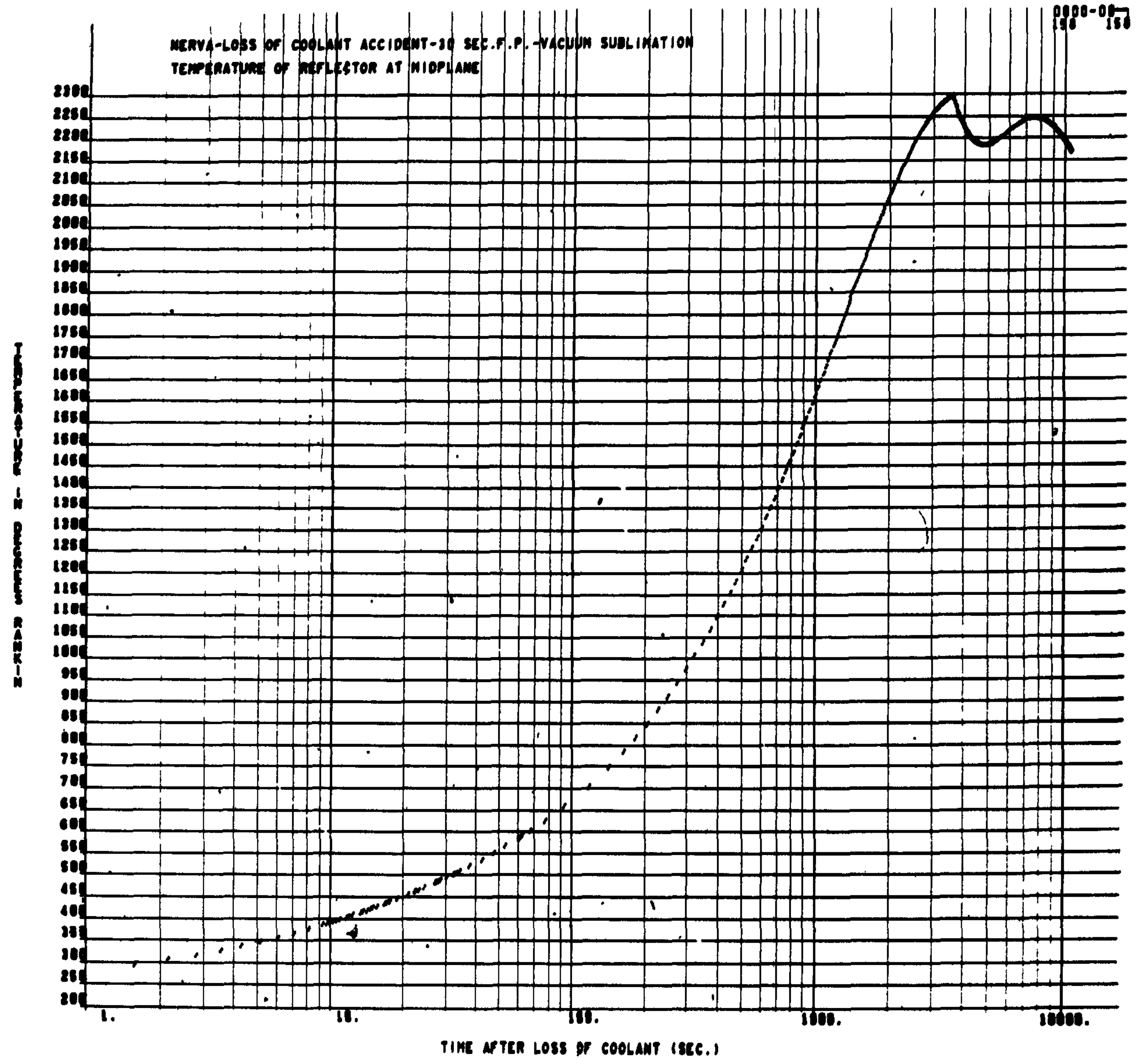
WANL-TME-1431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TEMPERATURE OF REFLECTOR AT MIDPLANE

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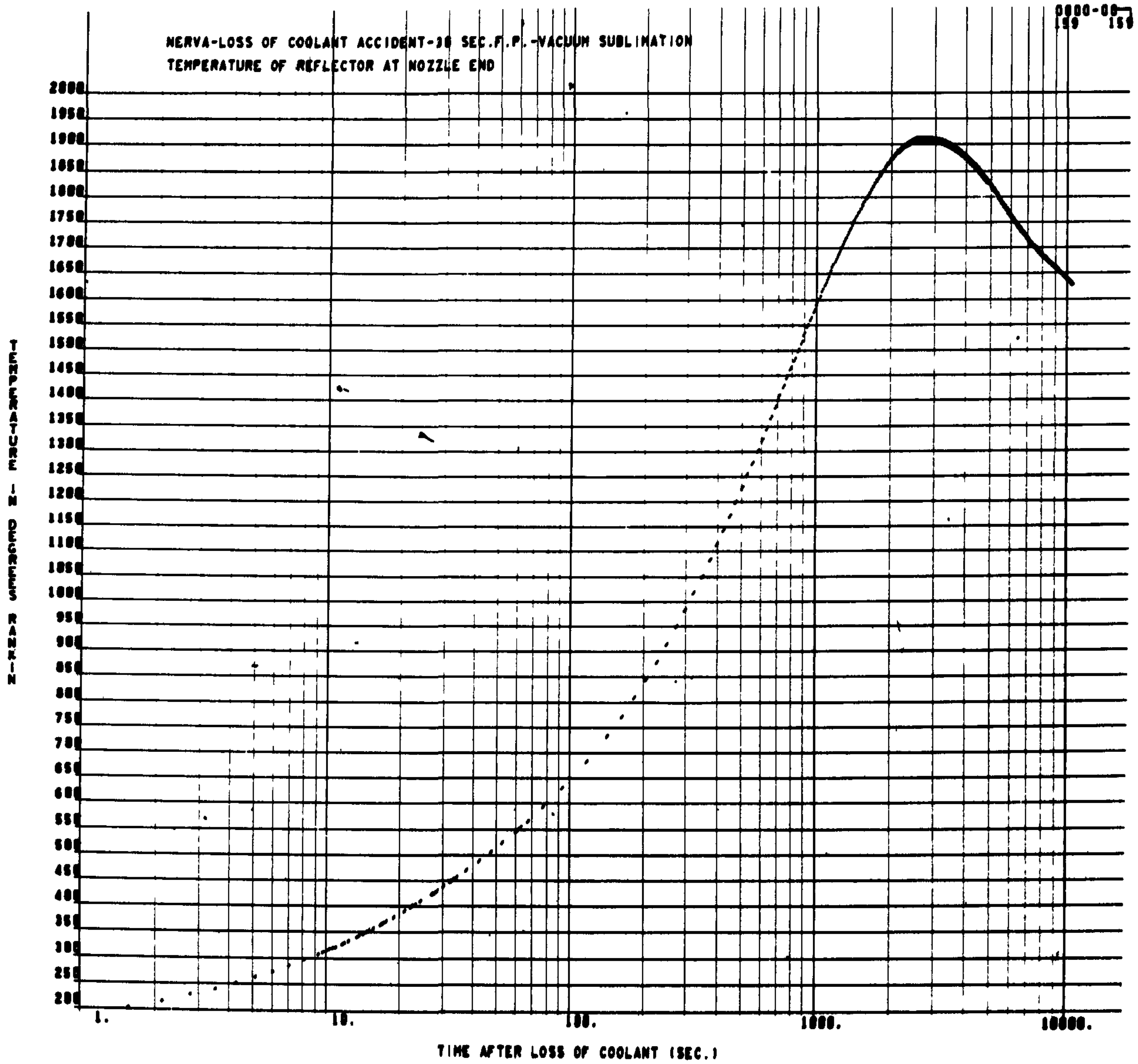

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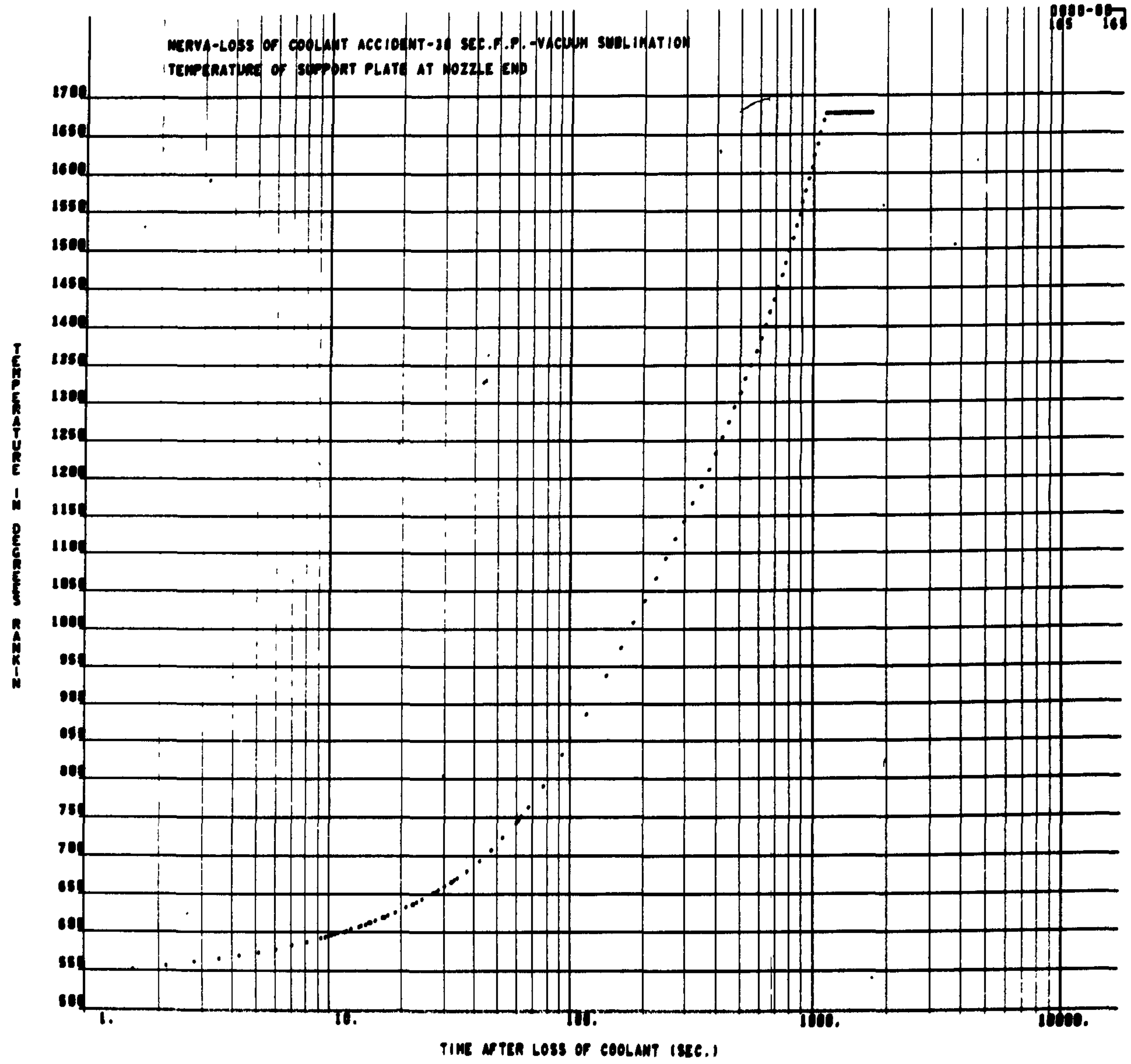

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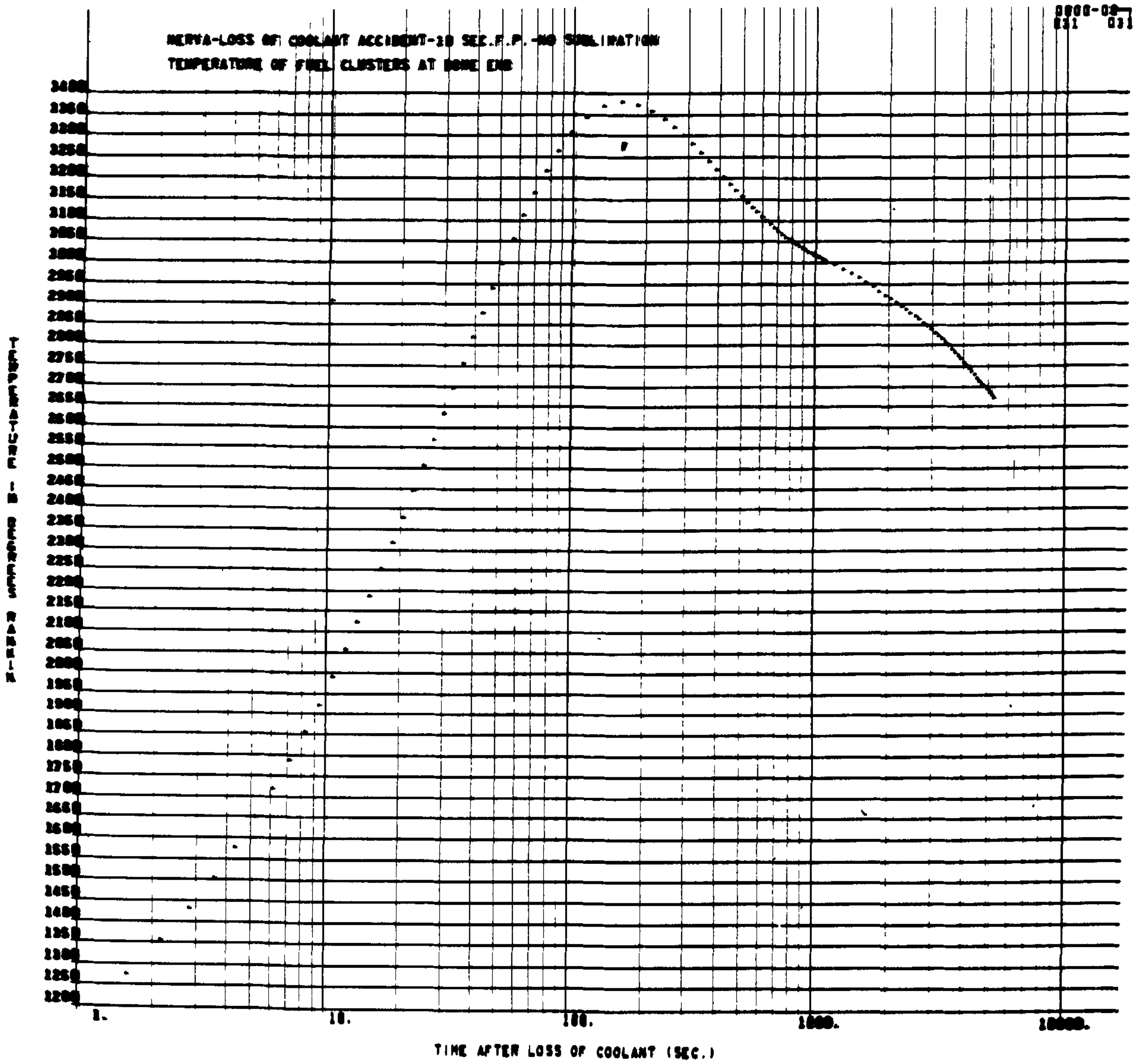

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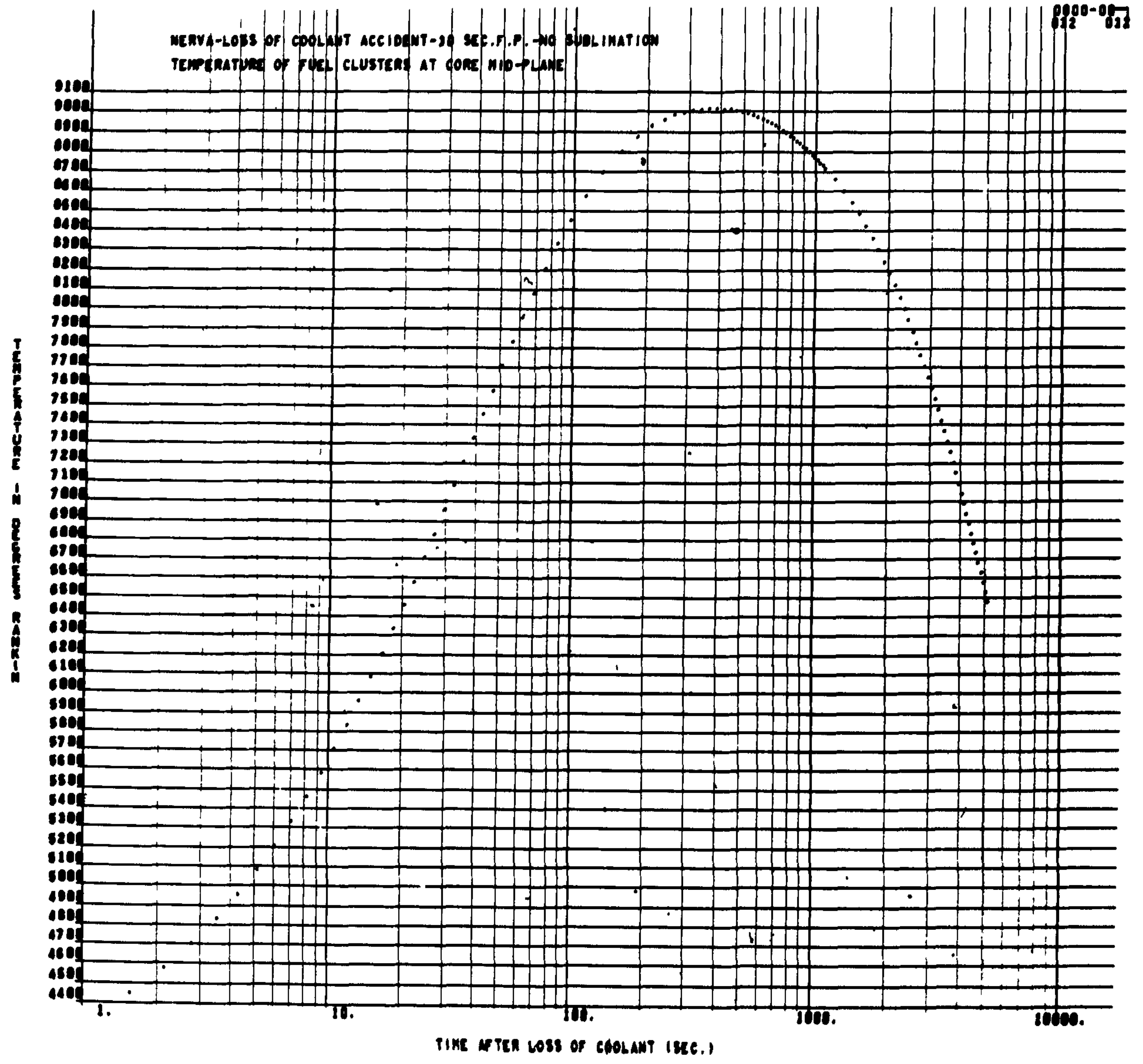

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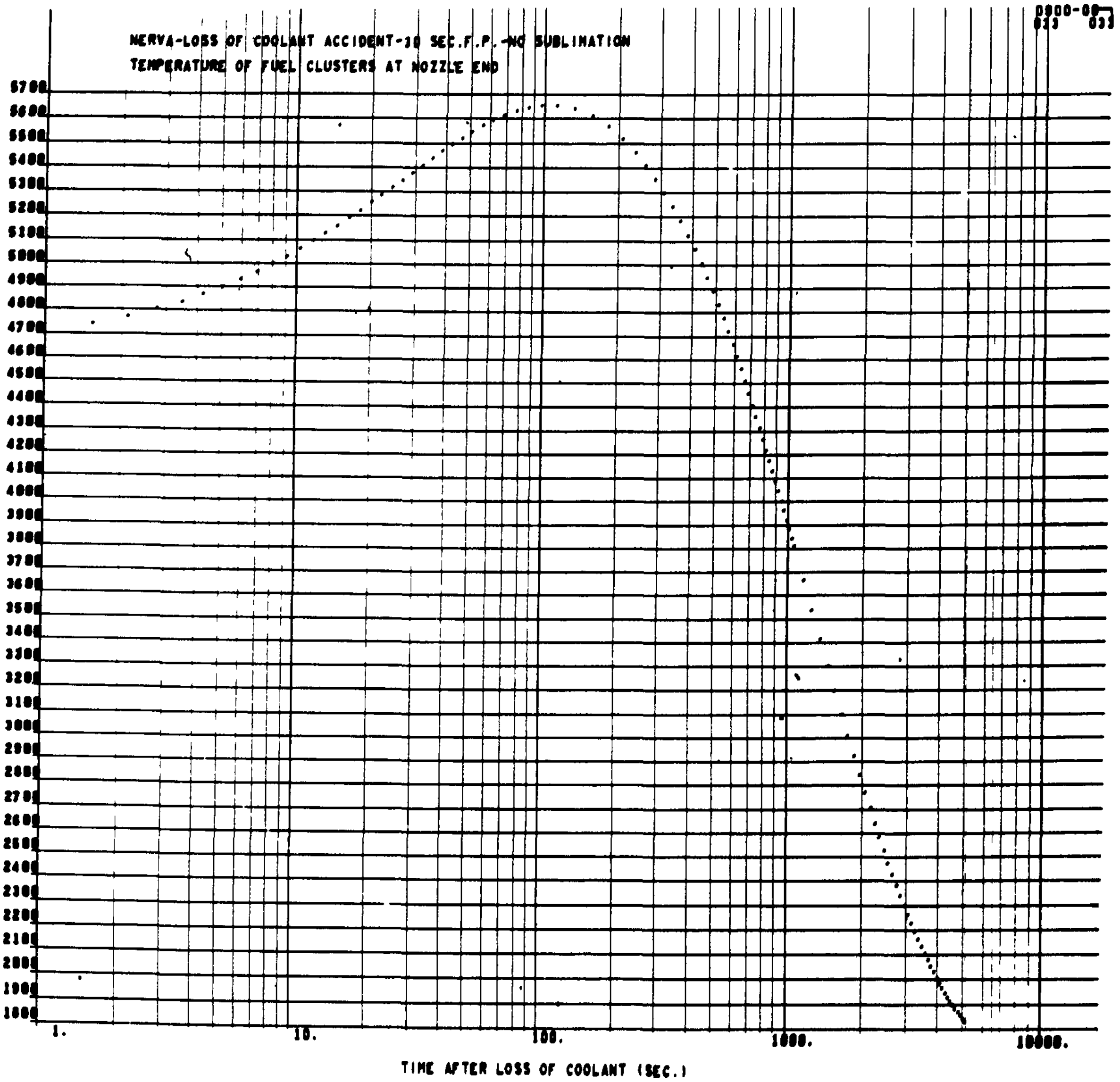

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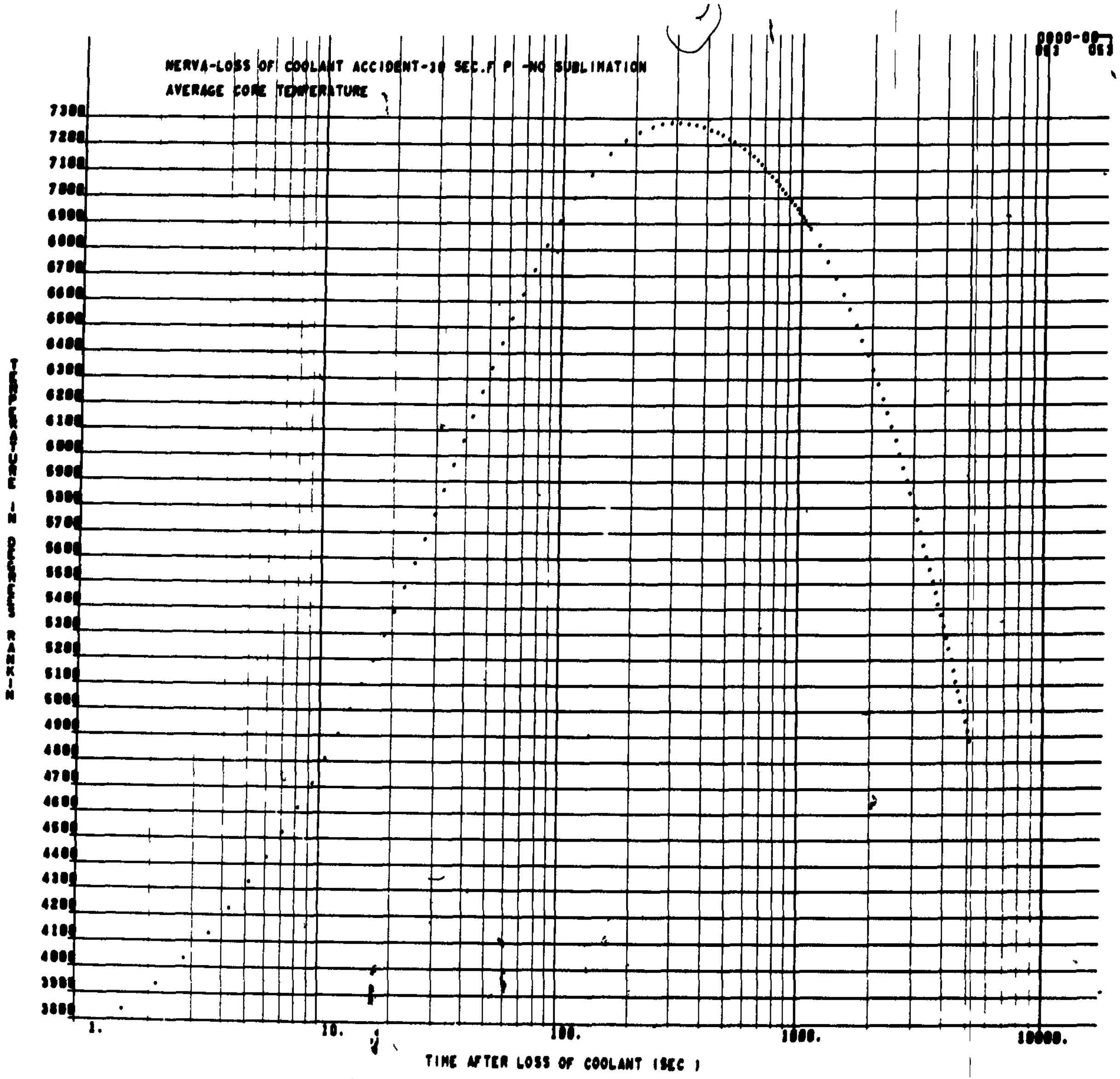

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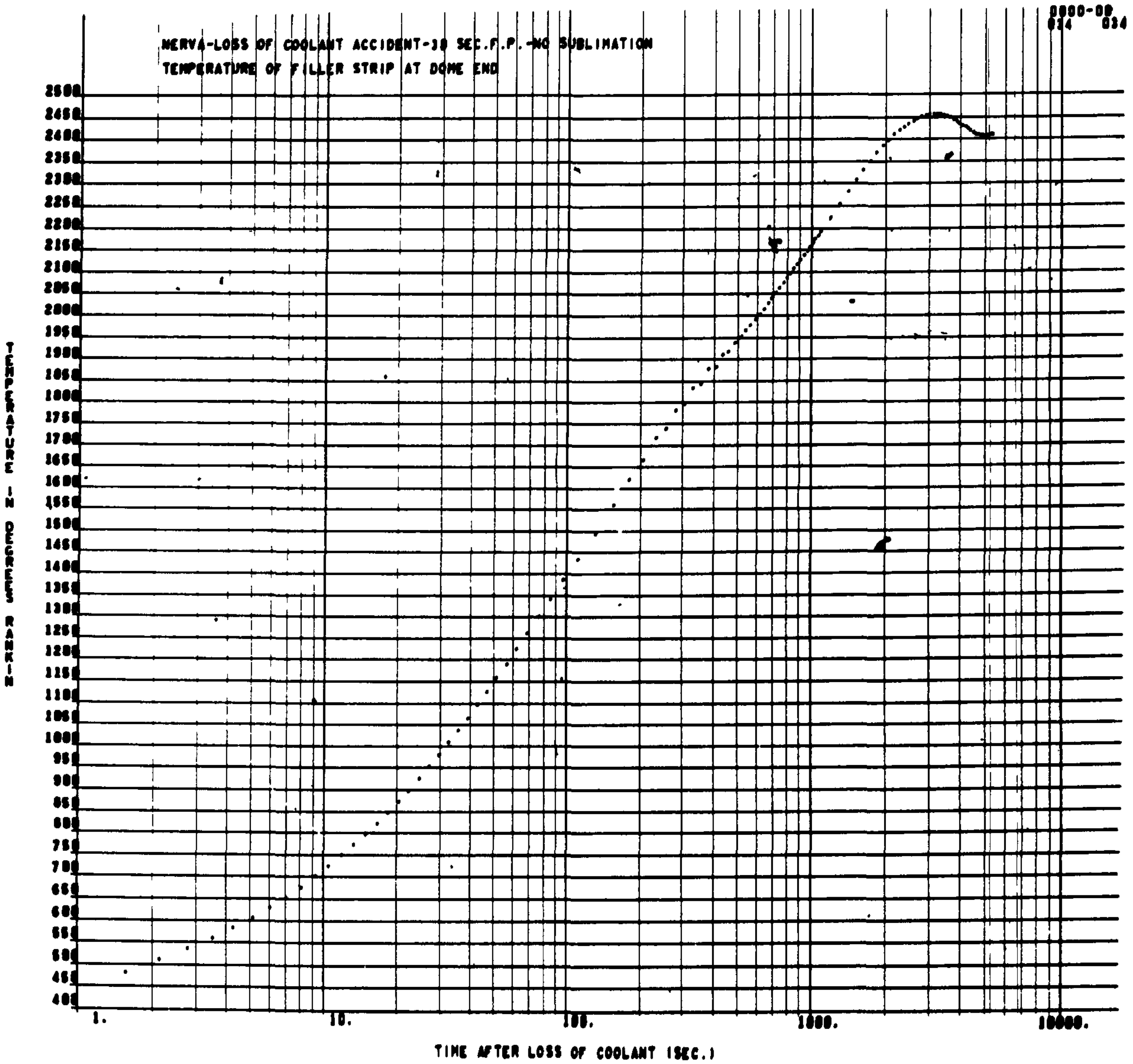

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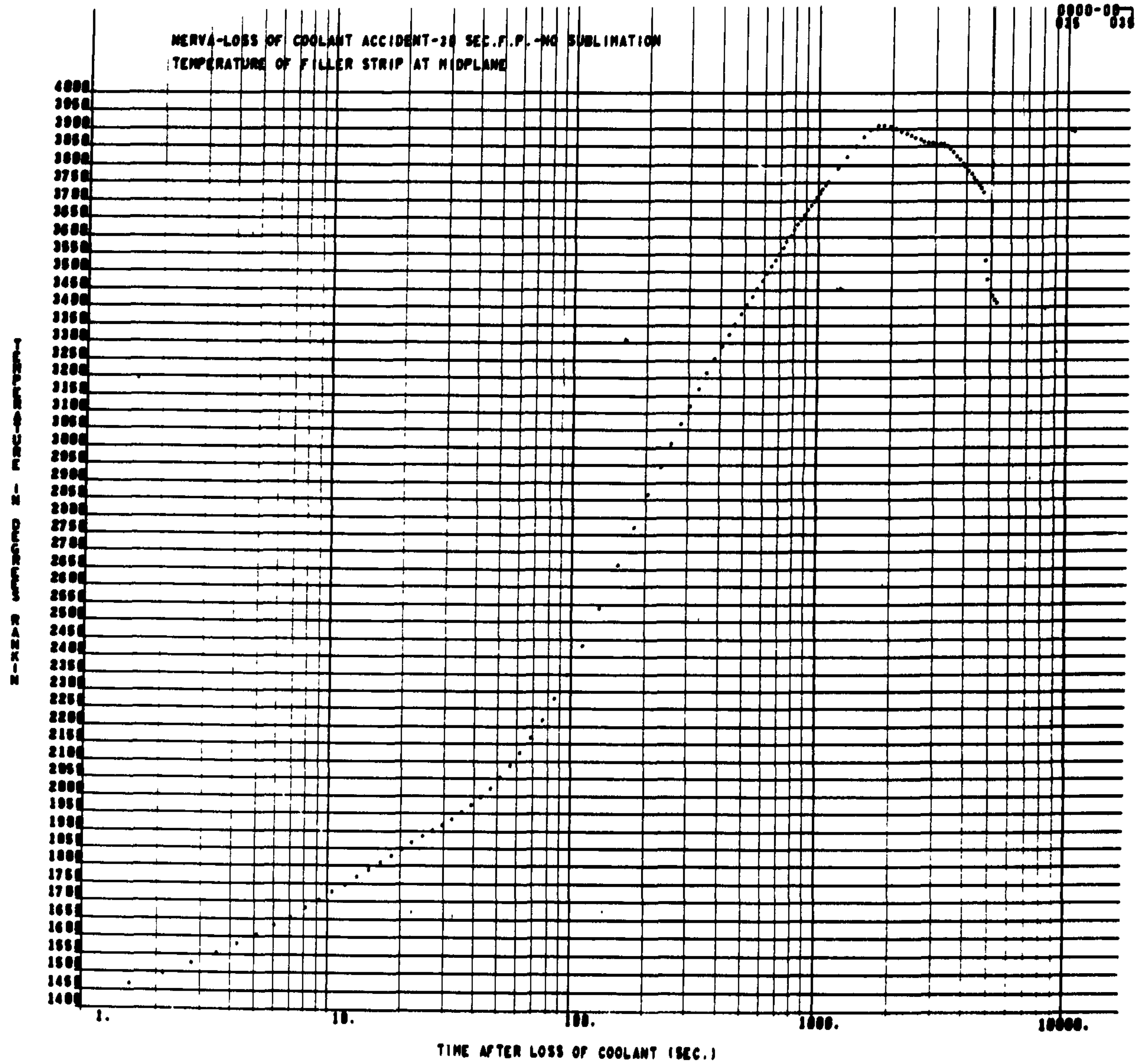

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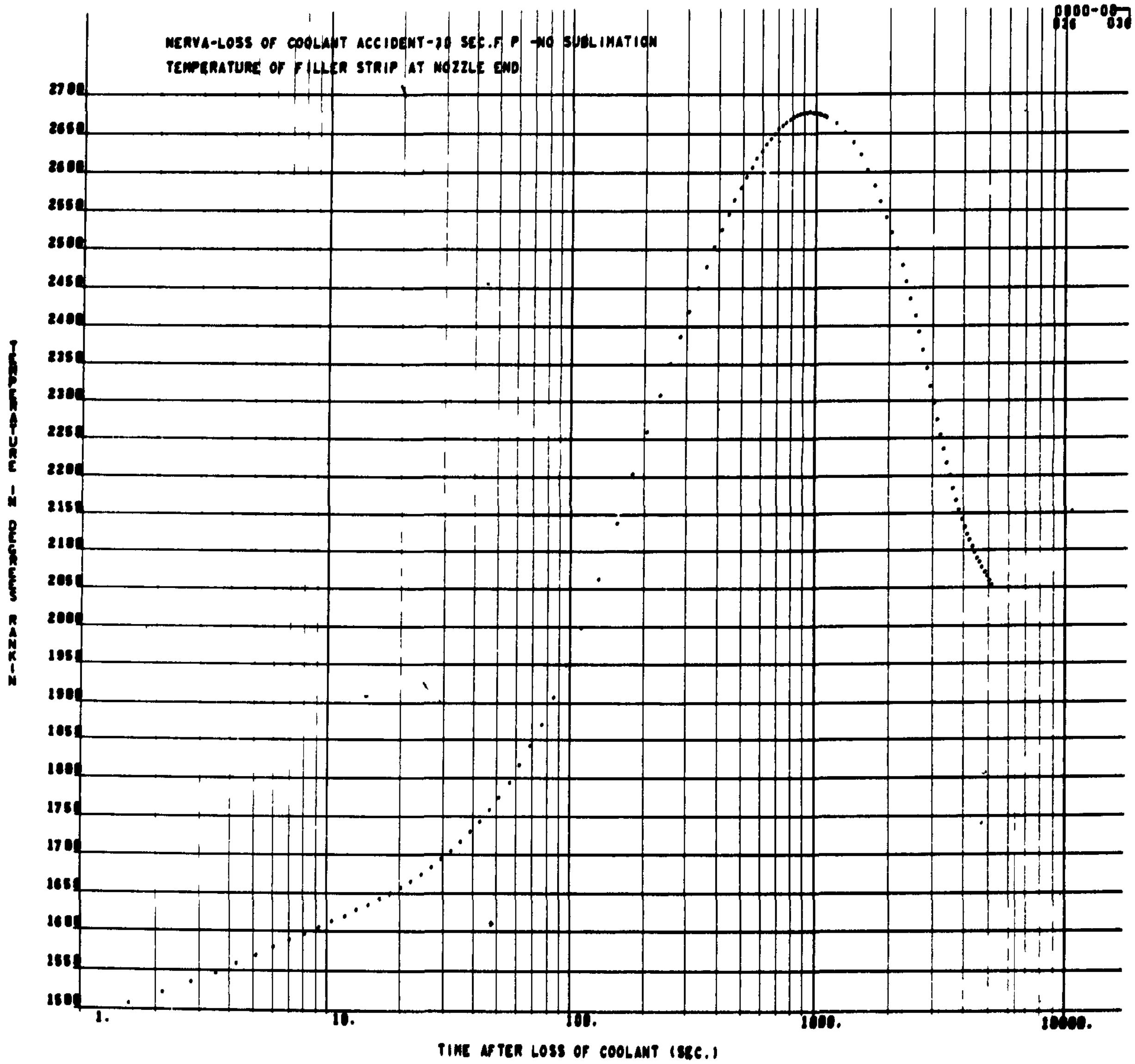

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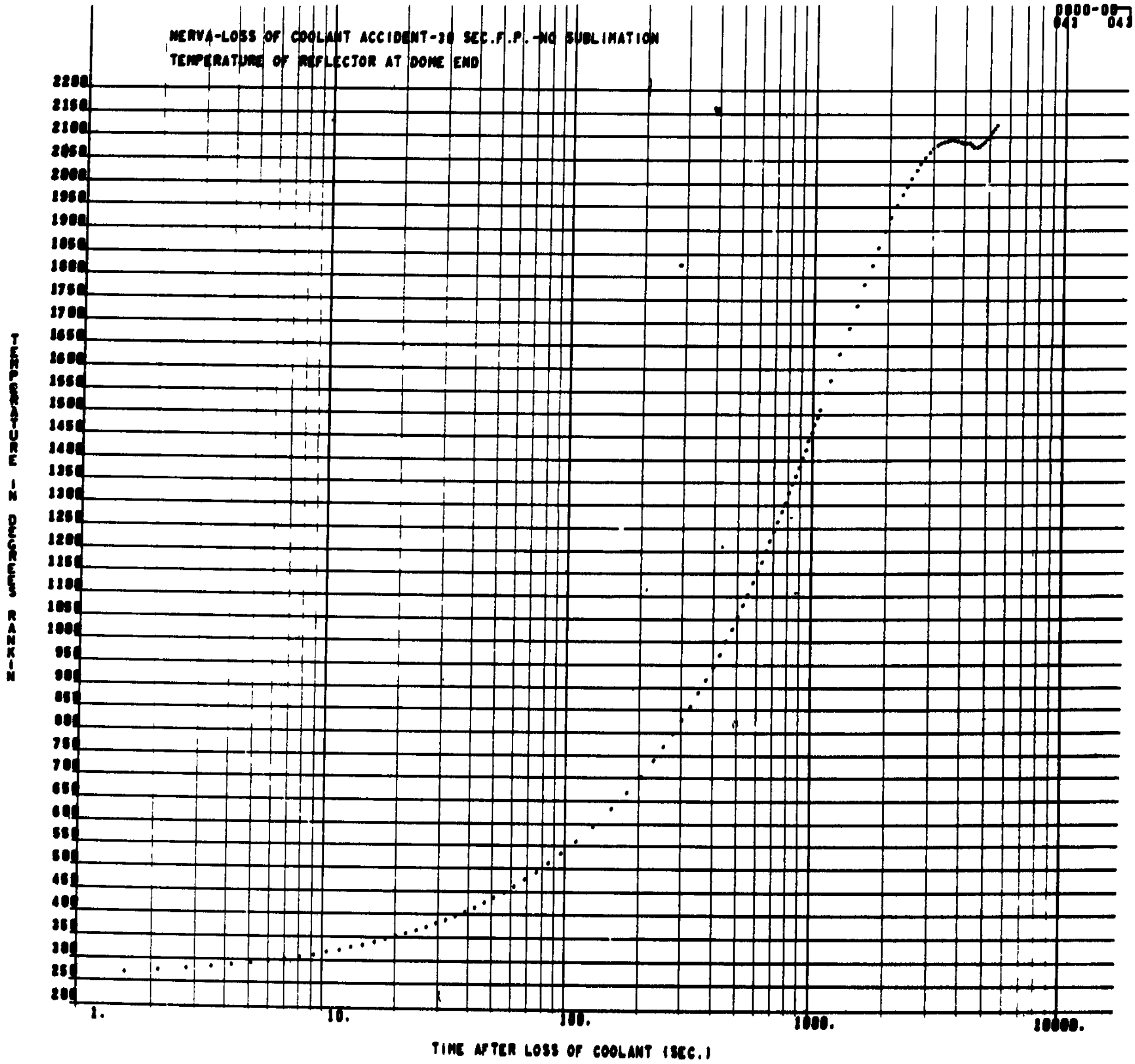

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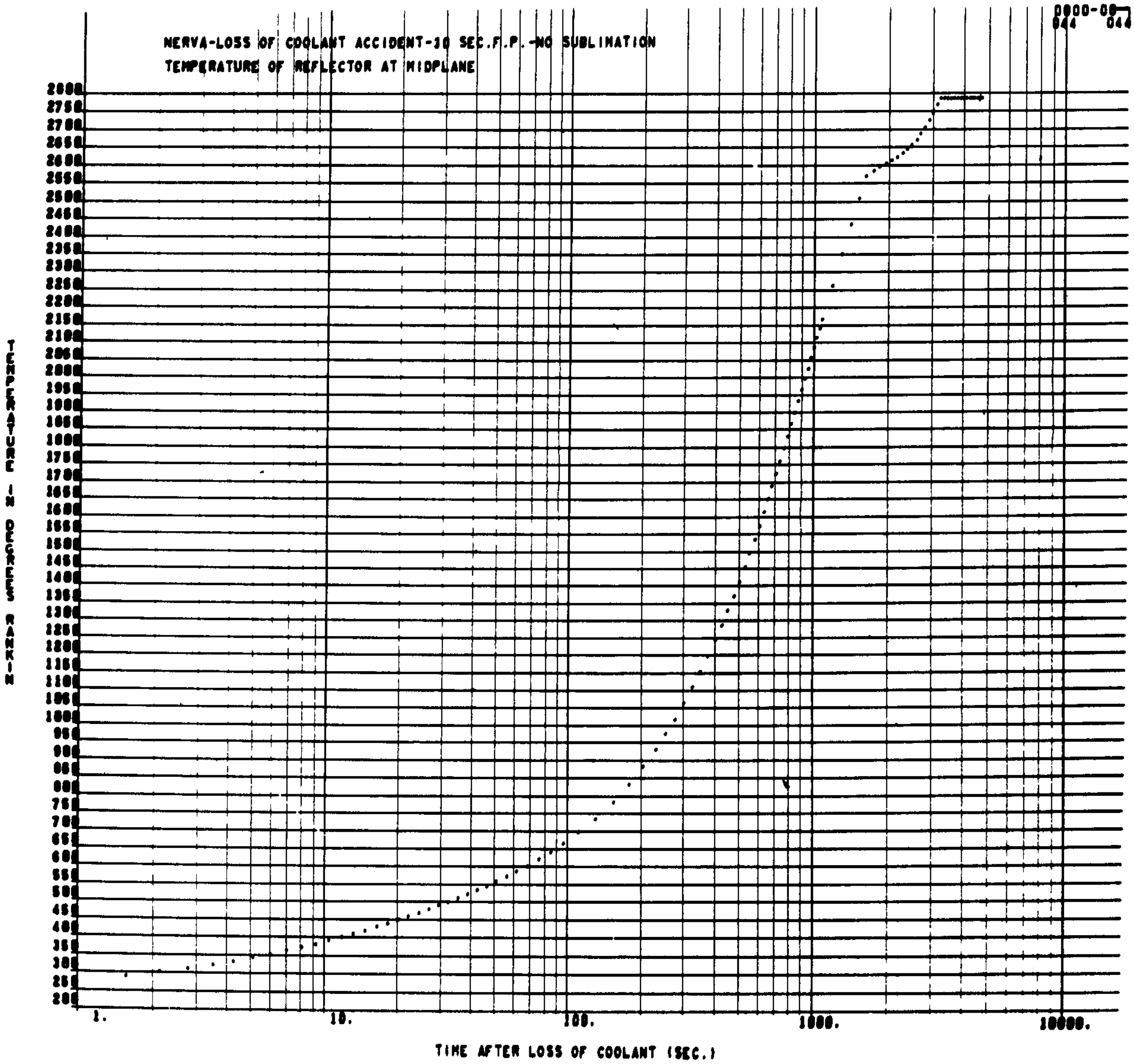
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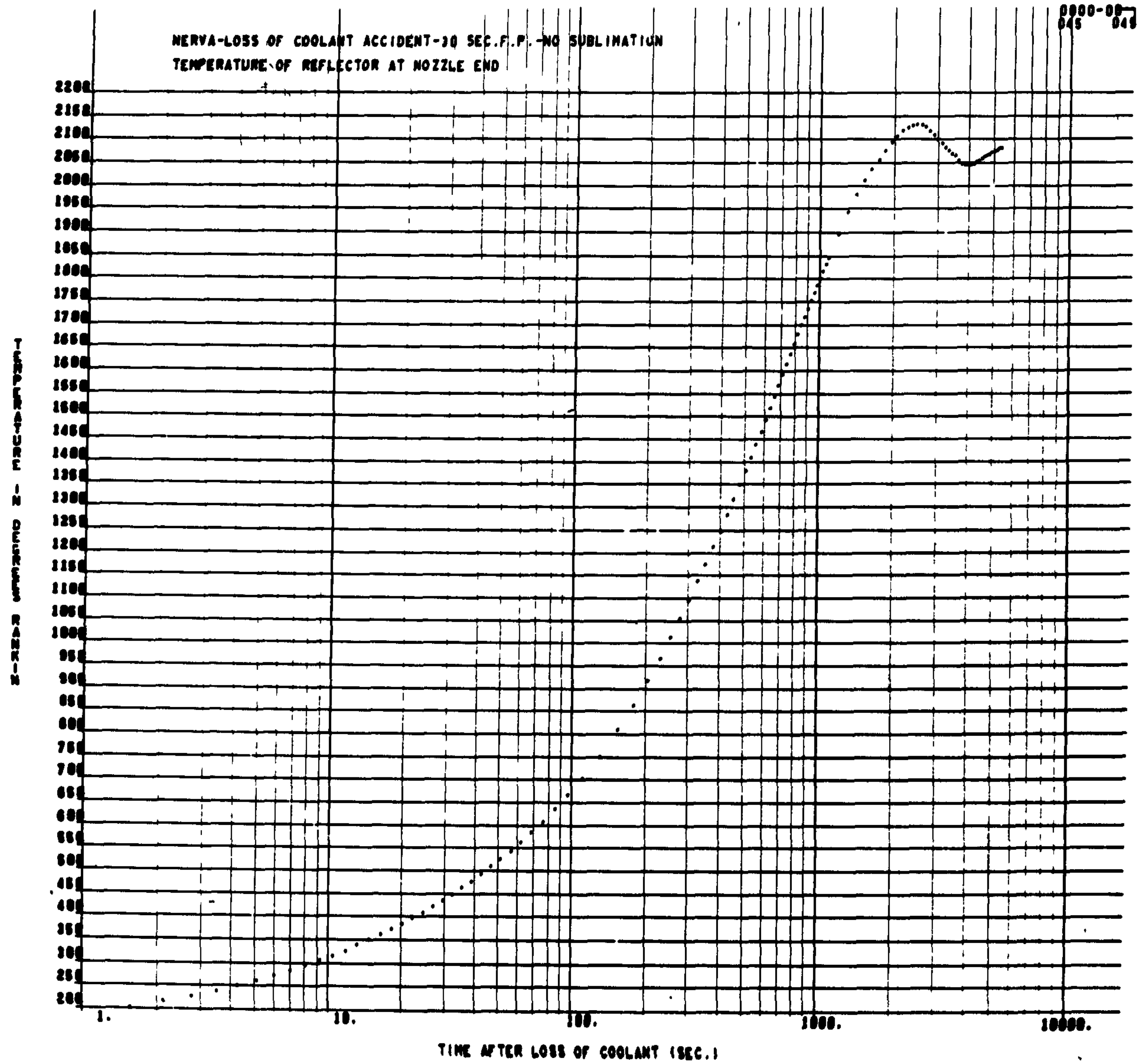
NERVA-LOSS OF COOLANT ACCIDENT-30 SEC.F.P.-NO SUBLIMATION
TEMPERATURE OF REFLECTOR AT MIDPLANE
TEMPERATURE IN DEGREES RANKIN
2800
2750
2700
2650
2600
2550
2500
2450
2400
2350
2300
2250
2200
2150
2100
2050
2000
1950
1900
1850
1800
1750
1700
1650
1600
1550
1500
1450
1400
1350
1300
1250
1200
1150
1100
1050
1000
950
900
850
800
750
700
650
600
550
500
450
400
350
300
250
200
1.
10.
100.
1000.
10000.
TIME AFTER LOSS OF COOLANT (SEC.)


NERVA-LOSS OF COOLANT ACCIDENT-30 SEC.F.P.-NO SUBLIMATION
TEMPERATURE OF REFLECTOR AT NOZZLE END
TEMPERATURE IN DEGREES RANKIN
2200
2150
2100
2050
2000
1950
1900
1850
1800
1750
1700
1650
1600
1550
1500
1450
1400
1350
1300
1250
1200
1150
1100
1050
1000
950
900
850
800
750
700
650
600
550
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1.
10.
100.
1000.
10000.
TIME AFTER LOSS OF COOLANT (SEC.)

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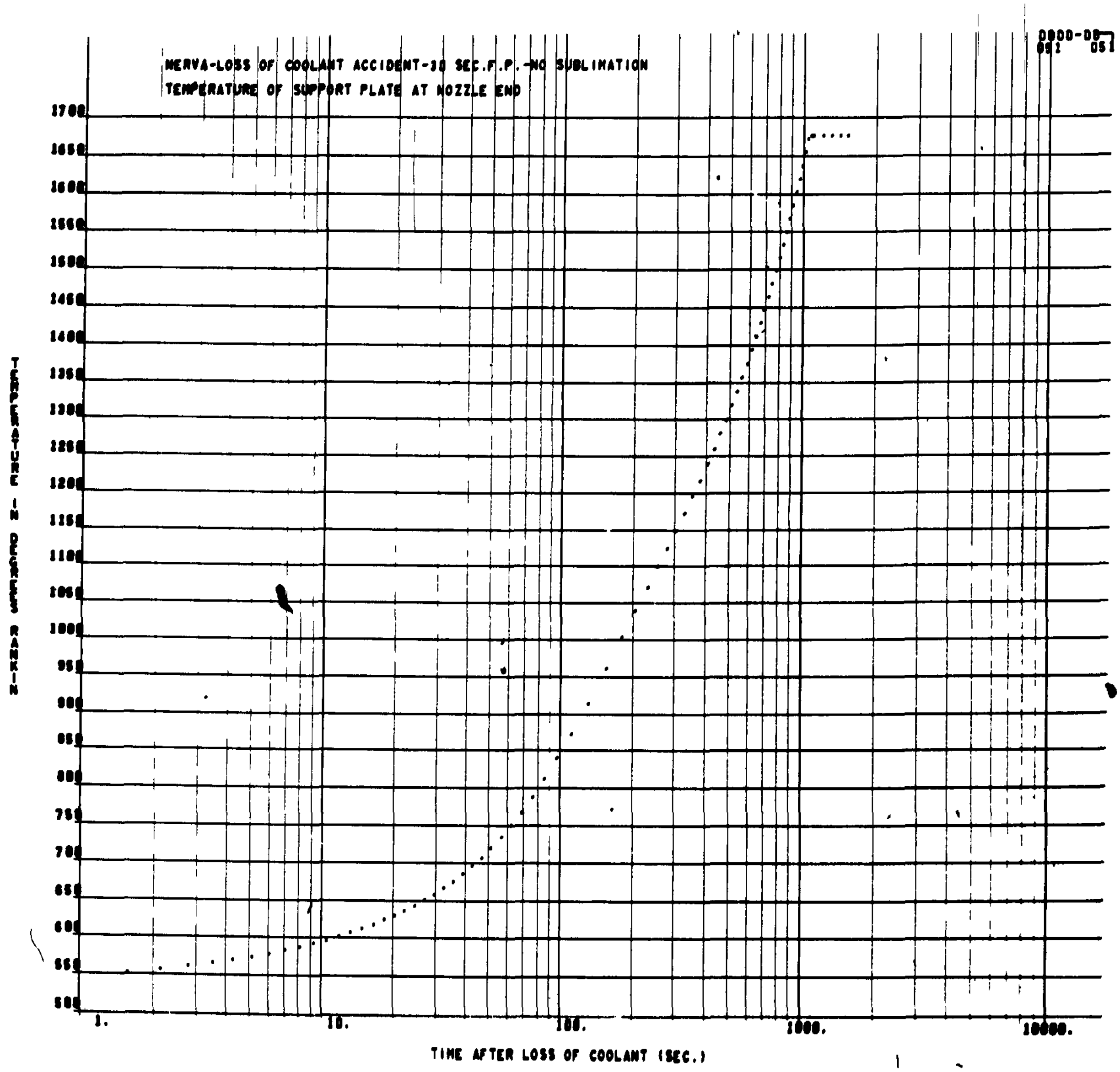

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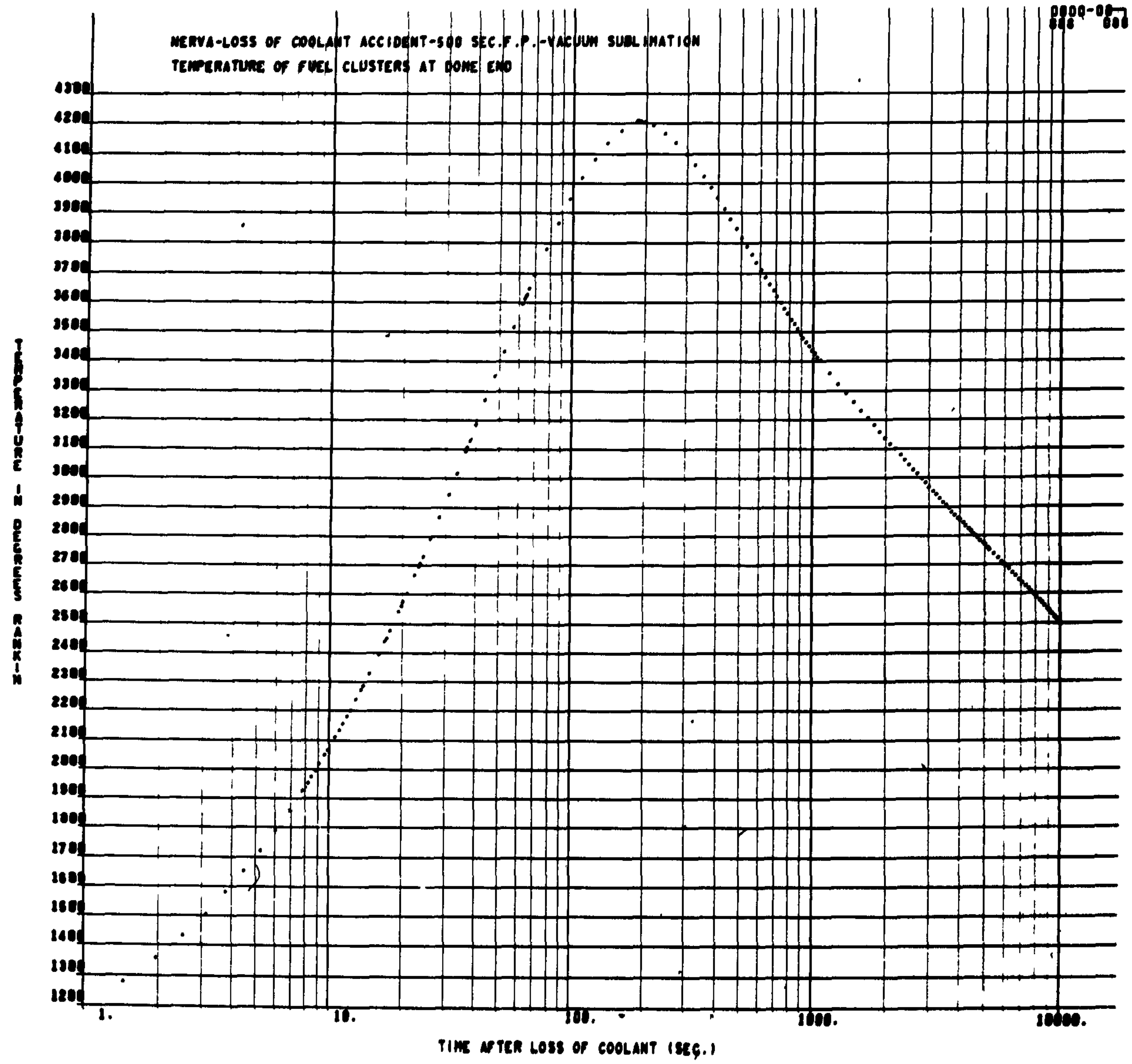

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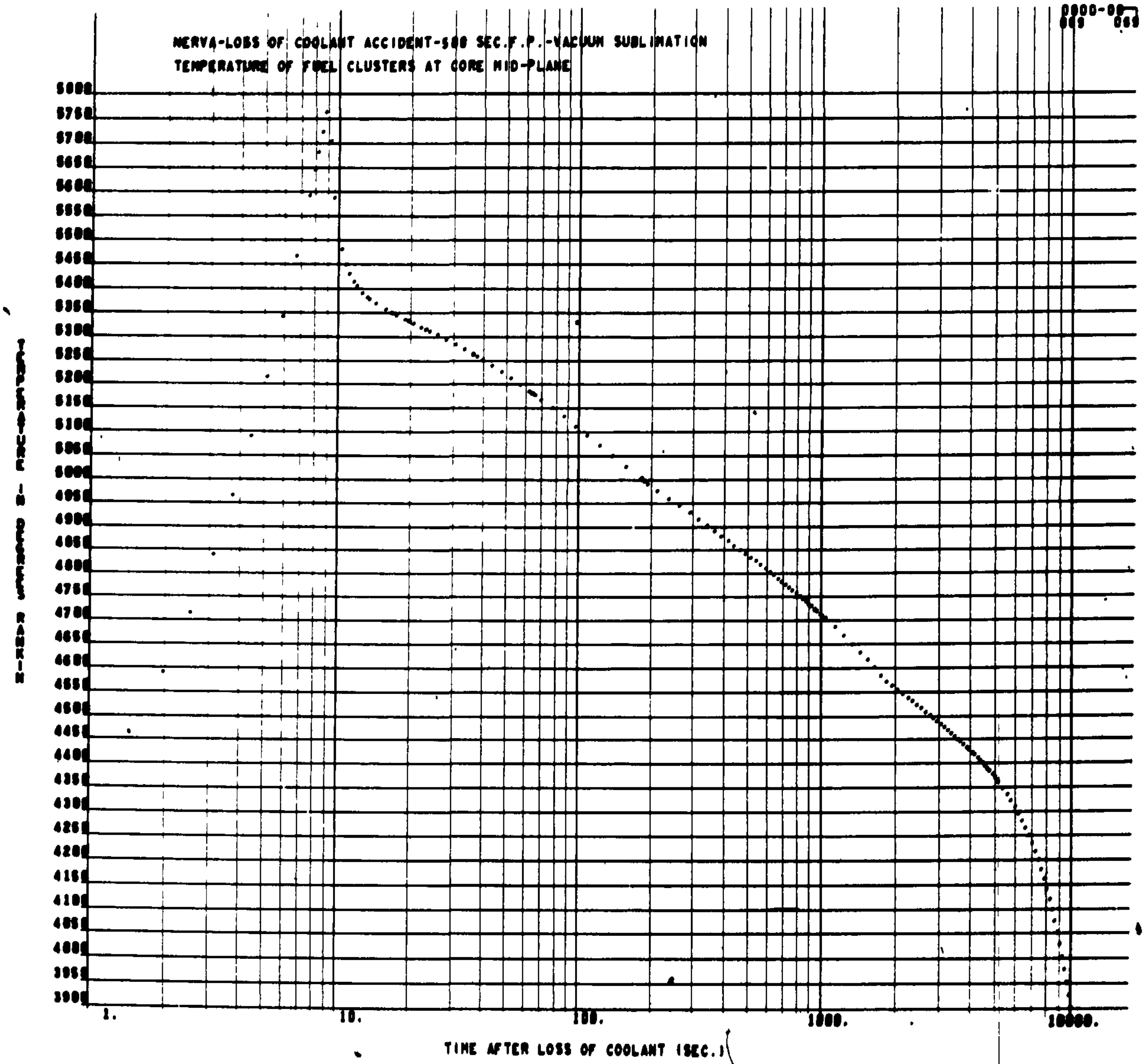
WANL-TME-1431



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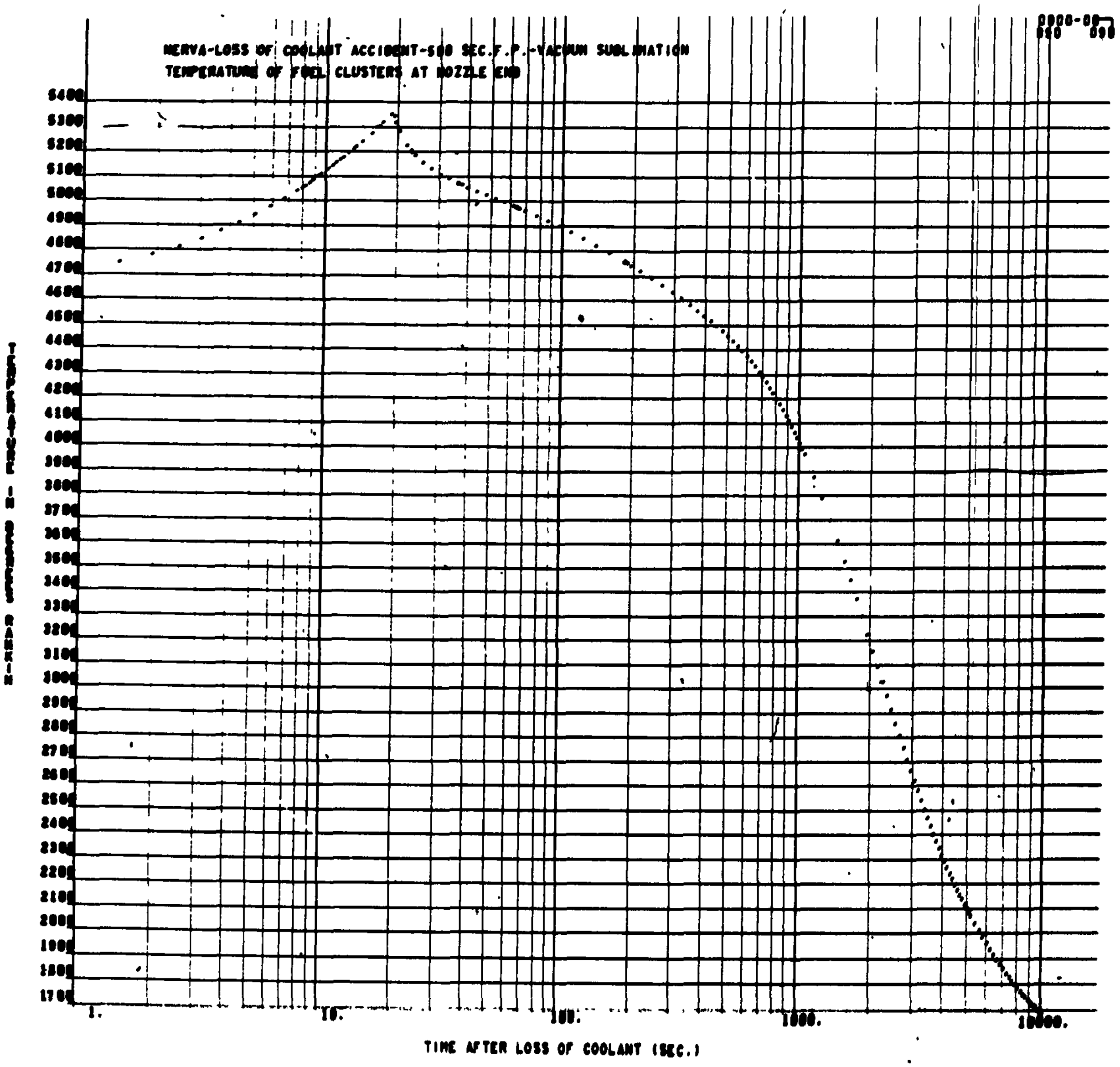

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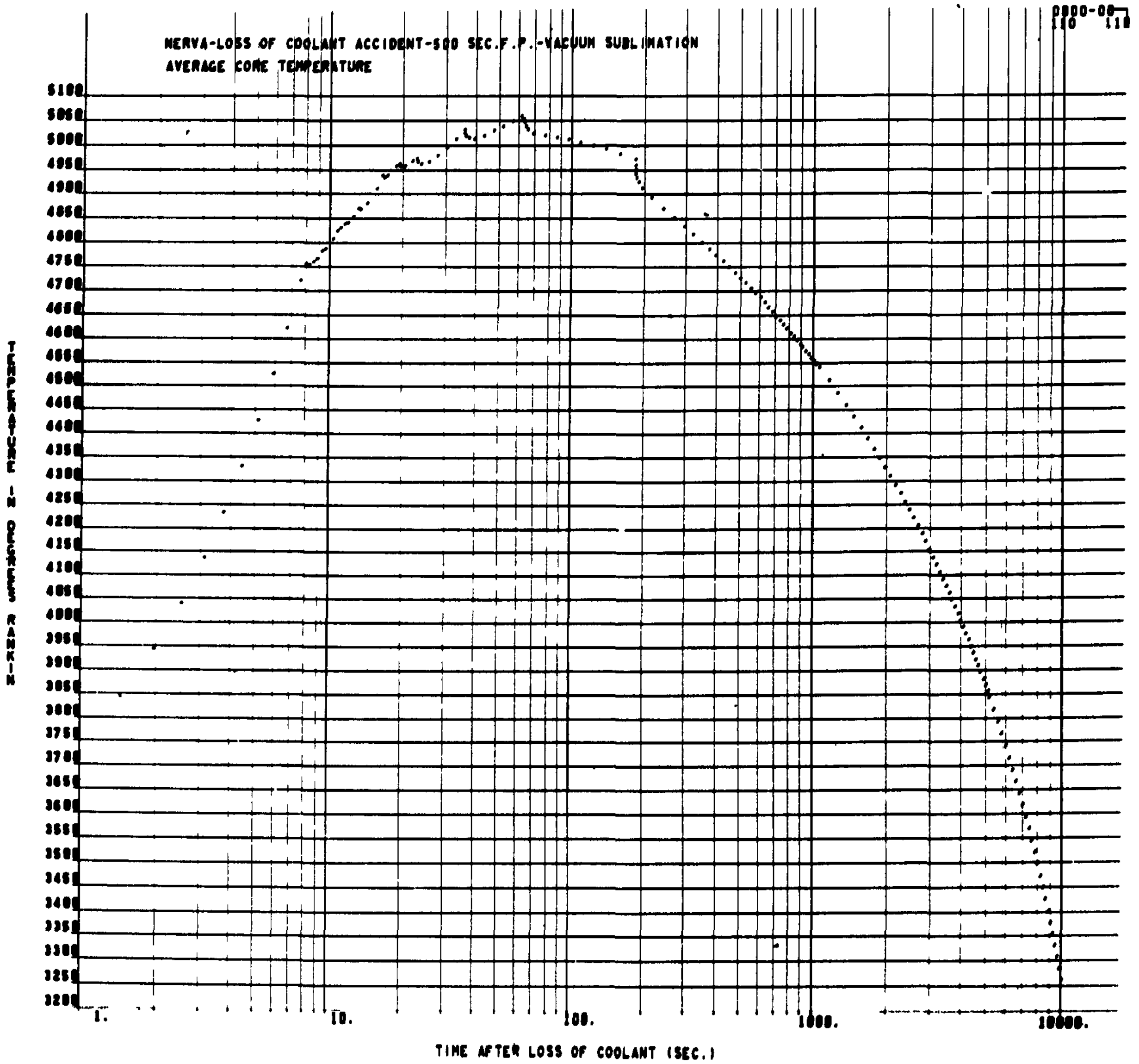

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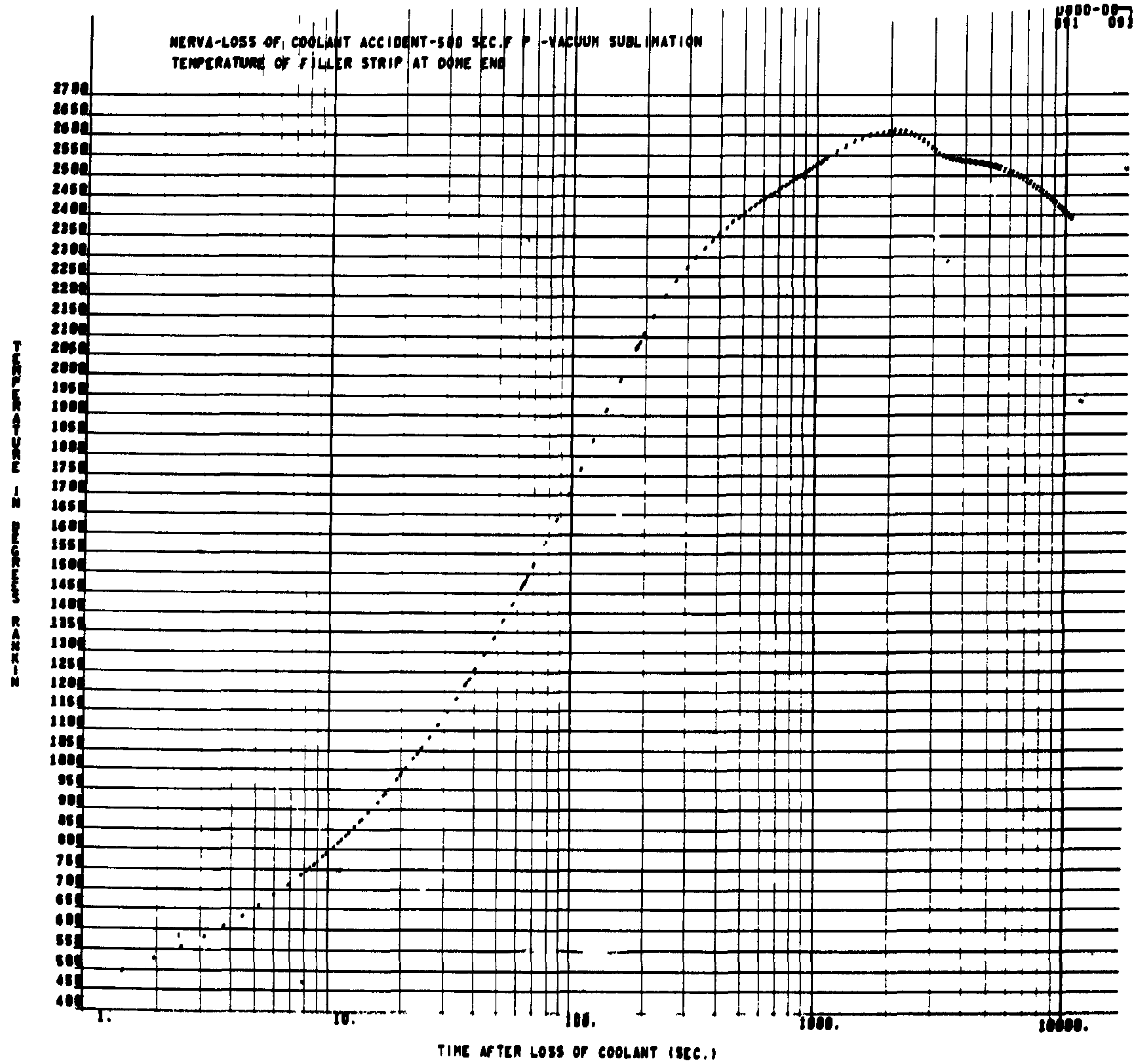

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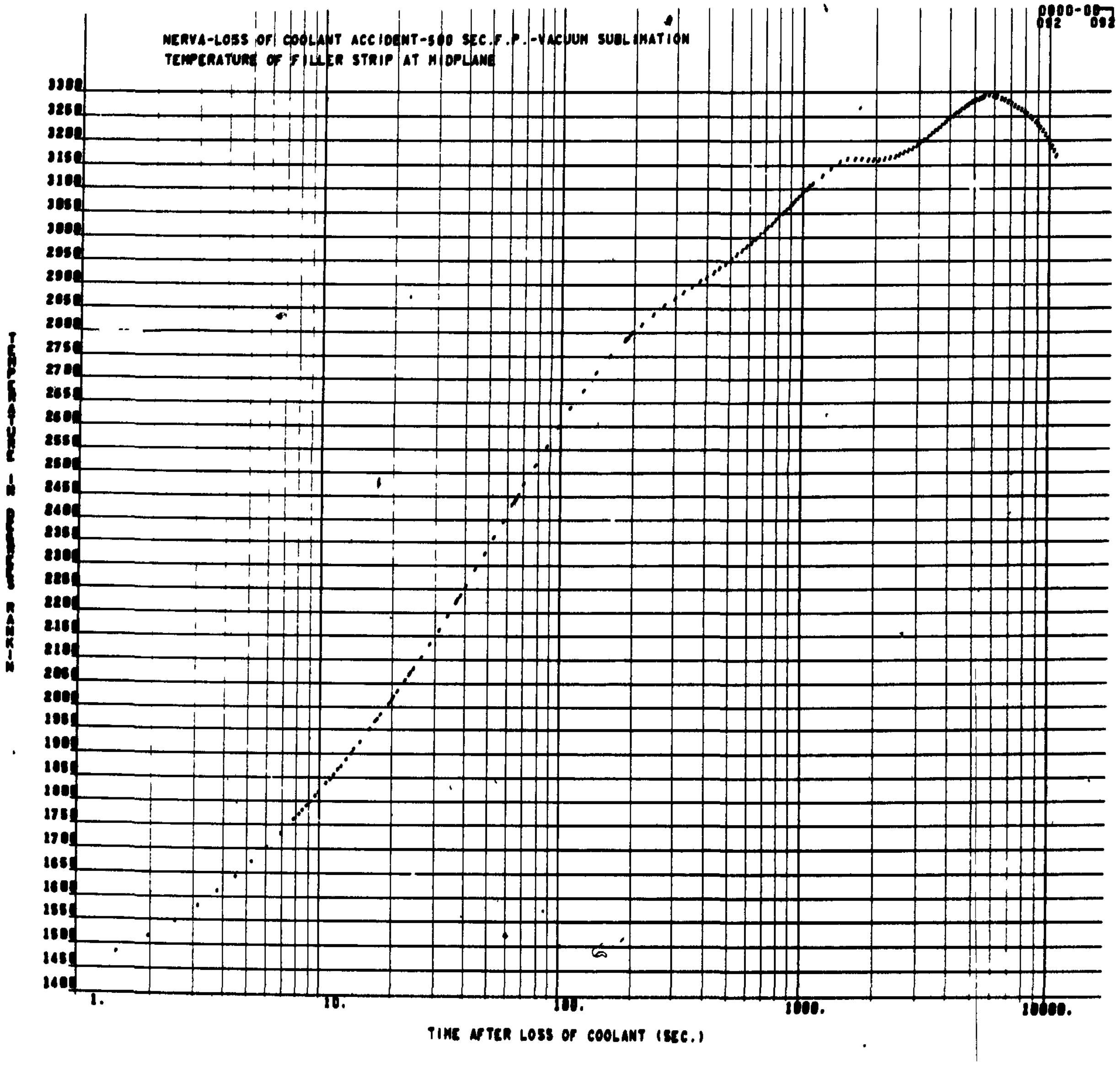

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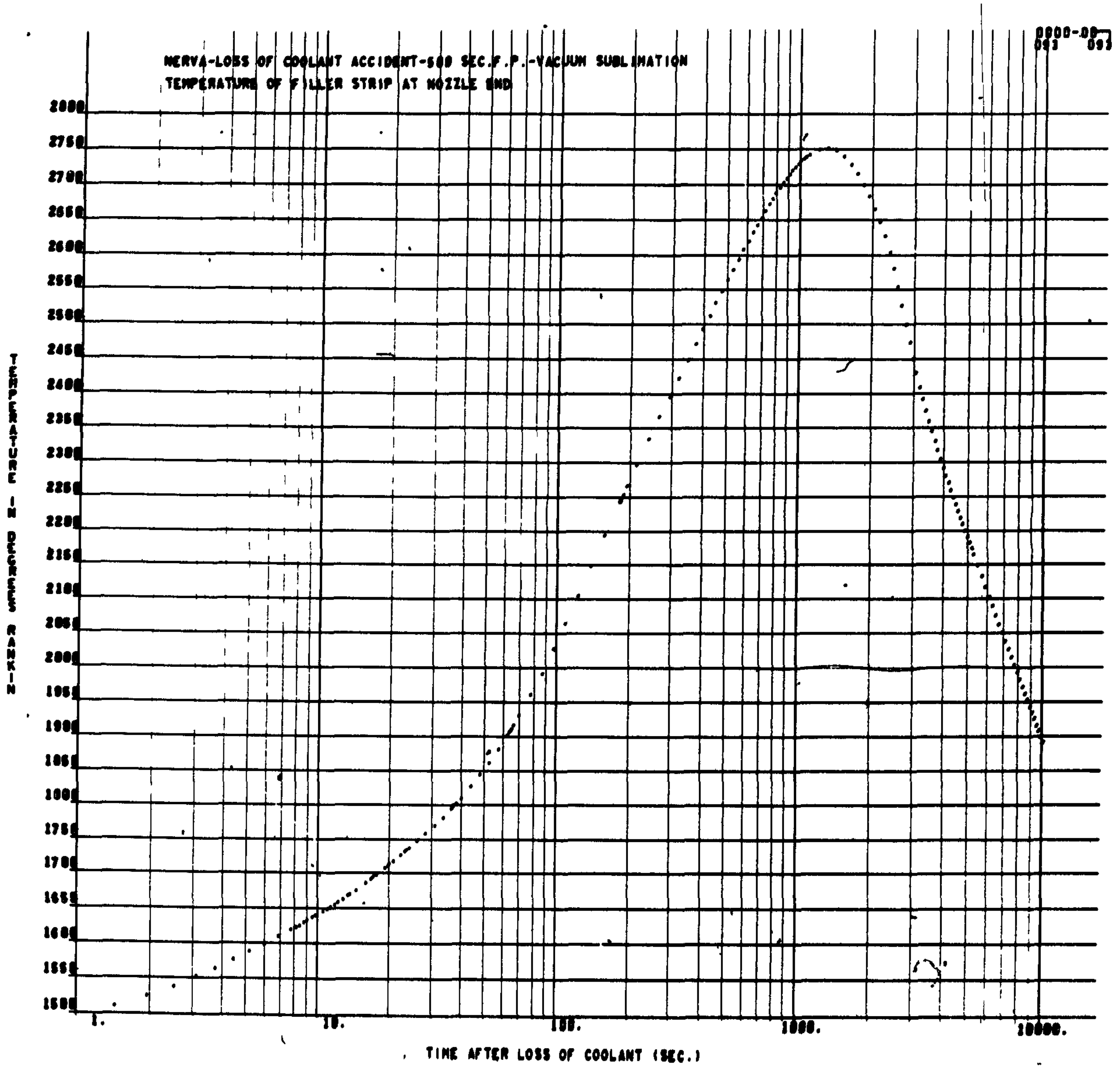

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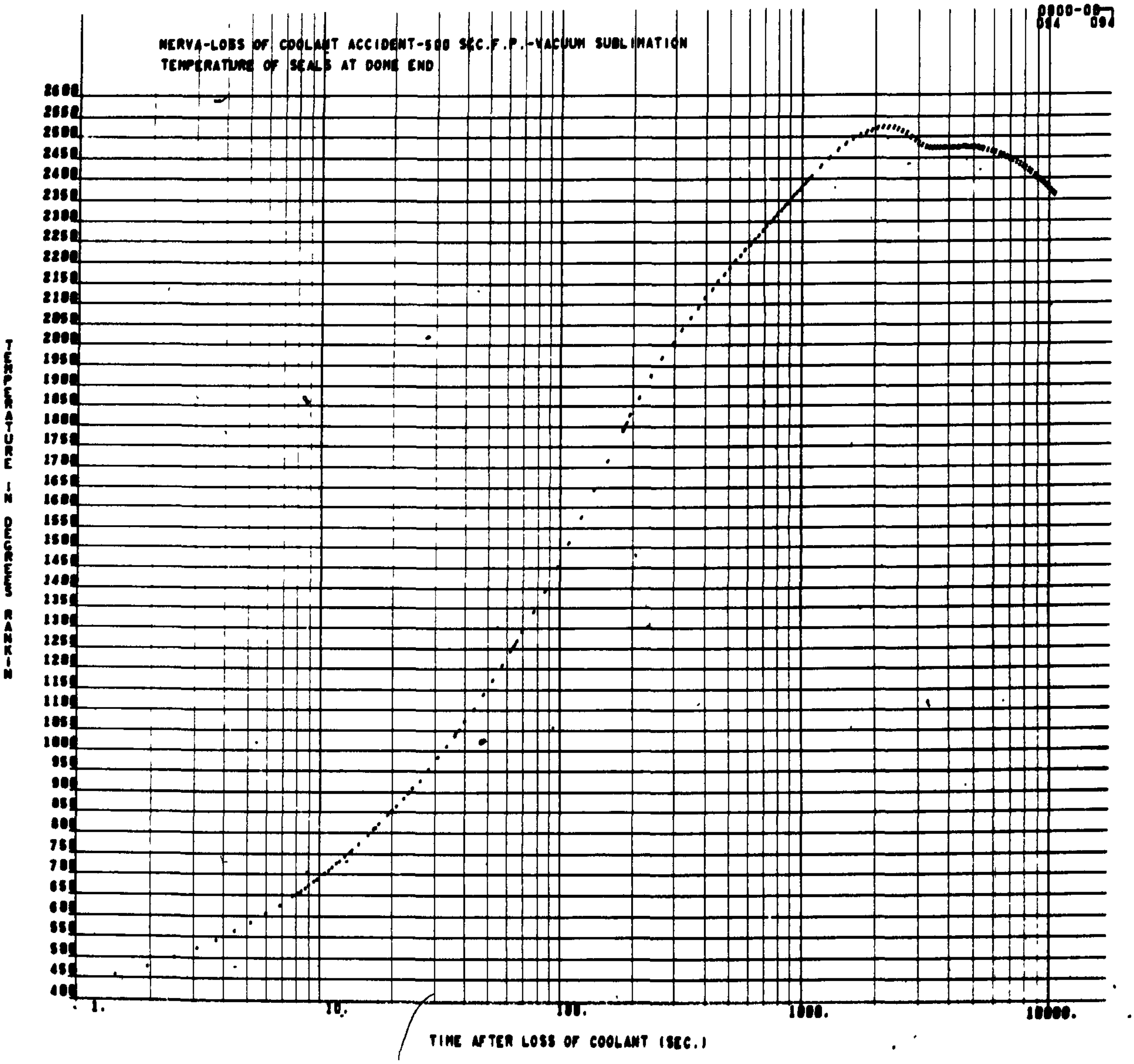

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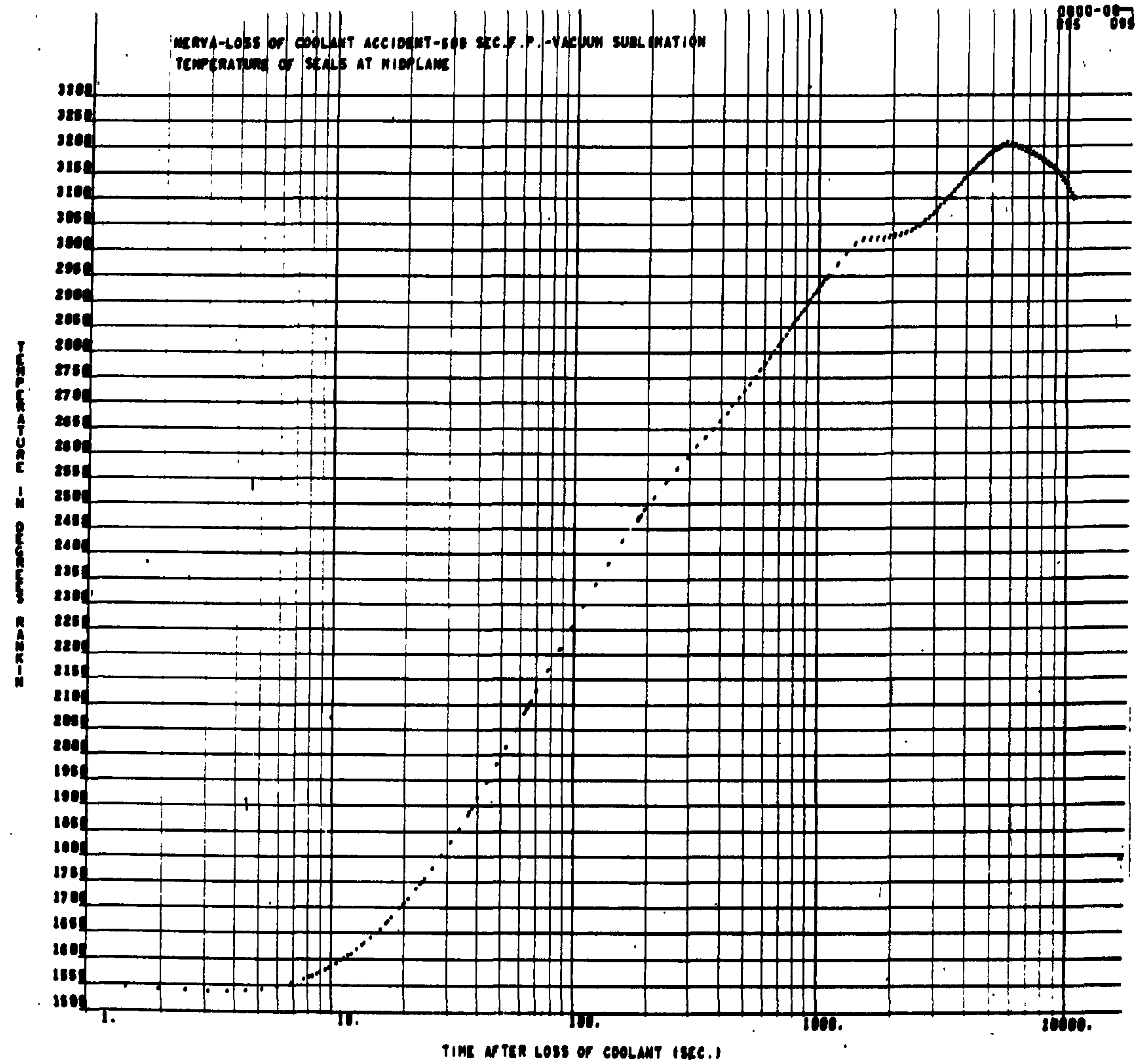

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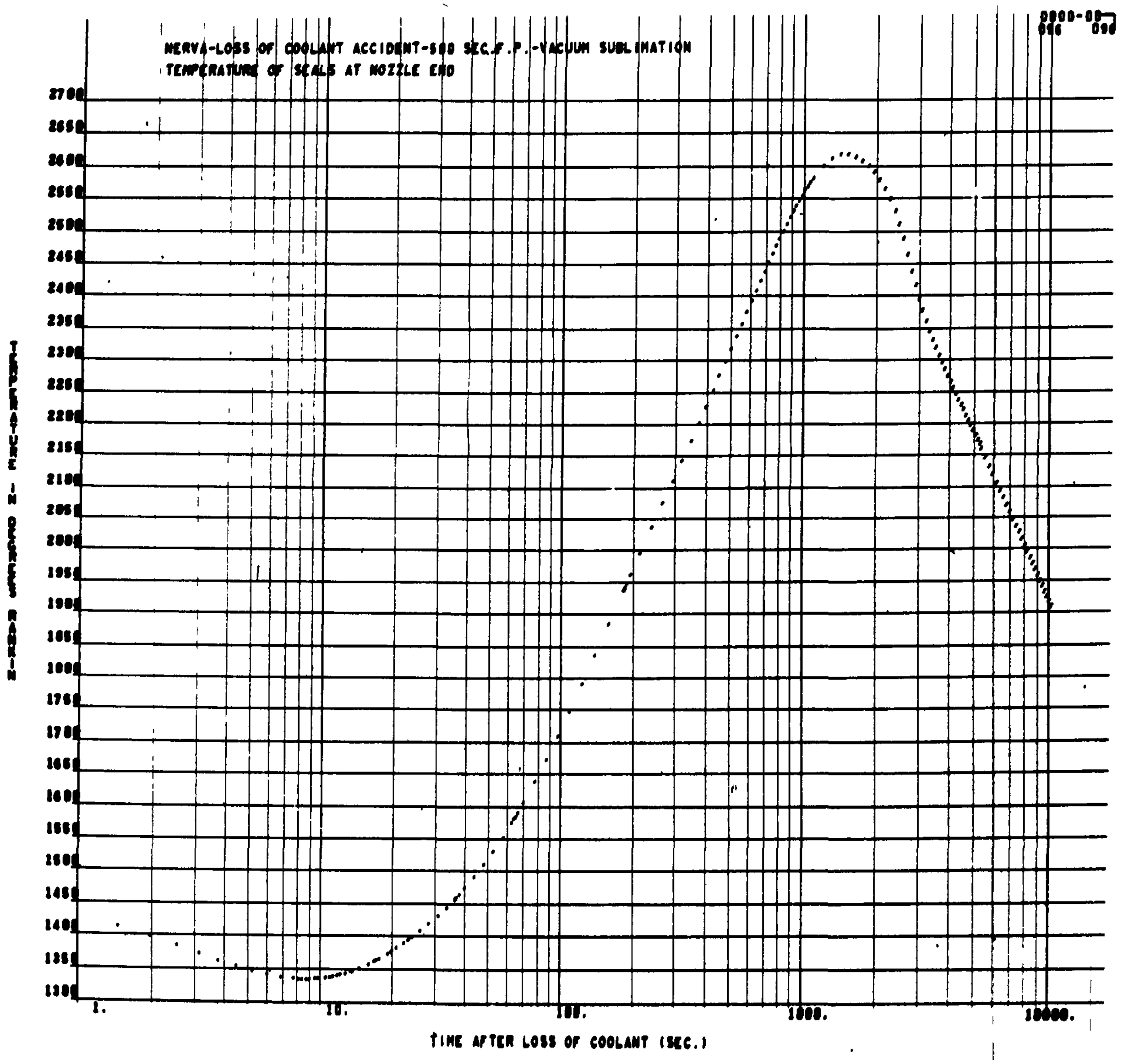

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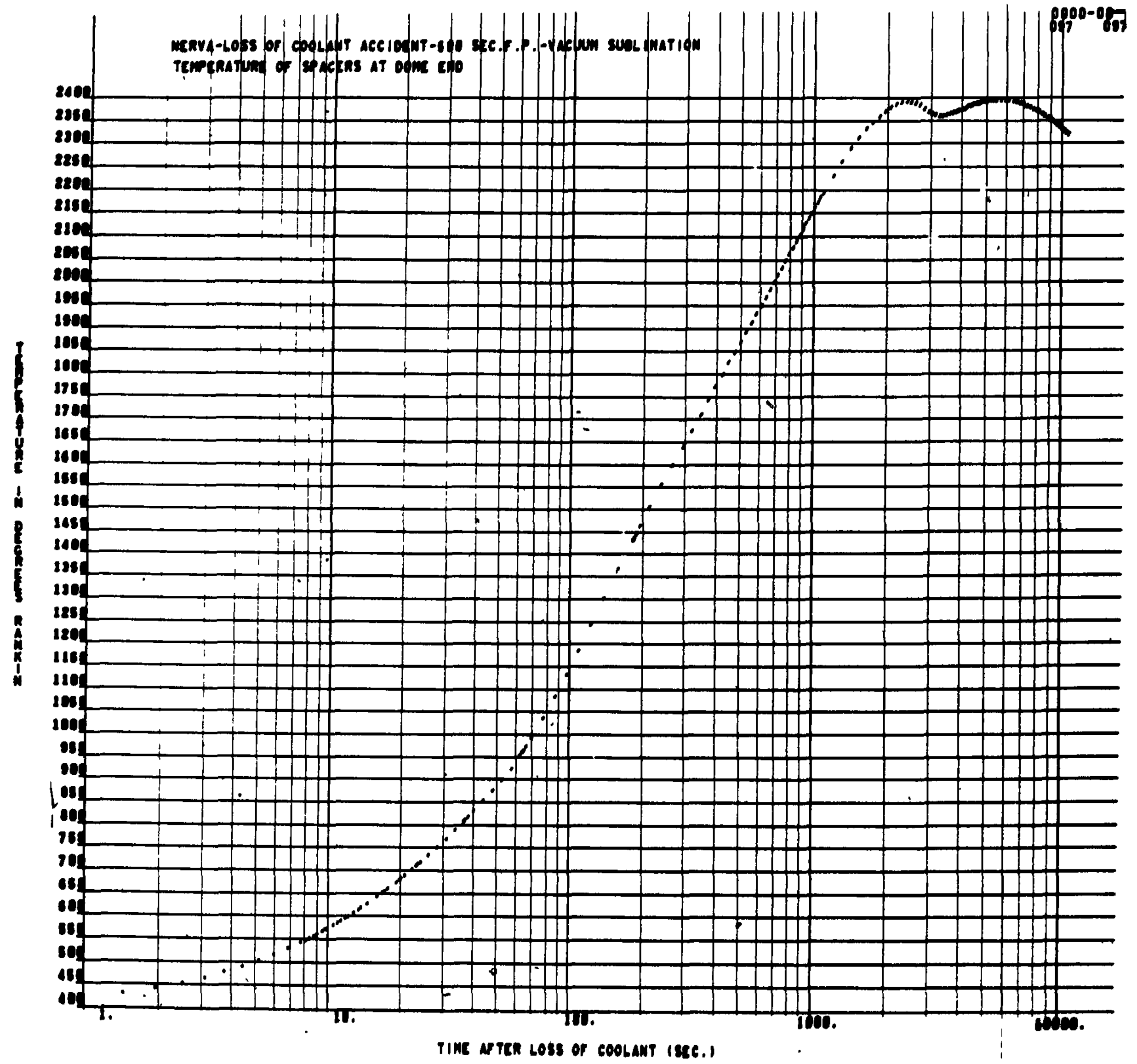

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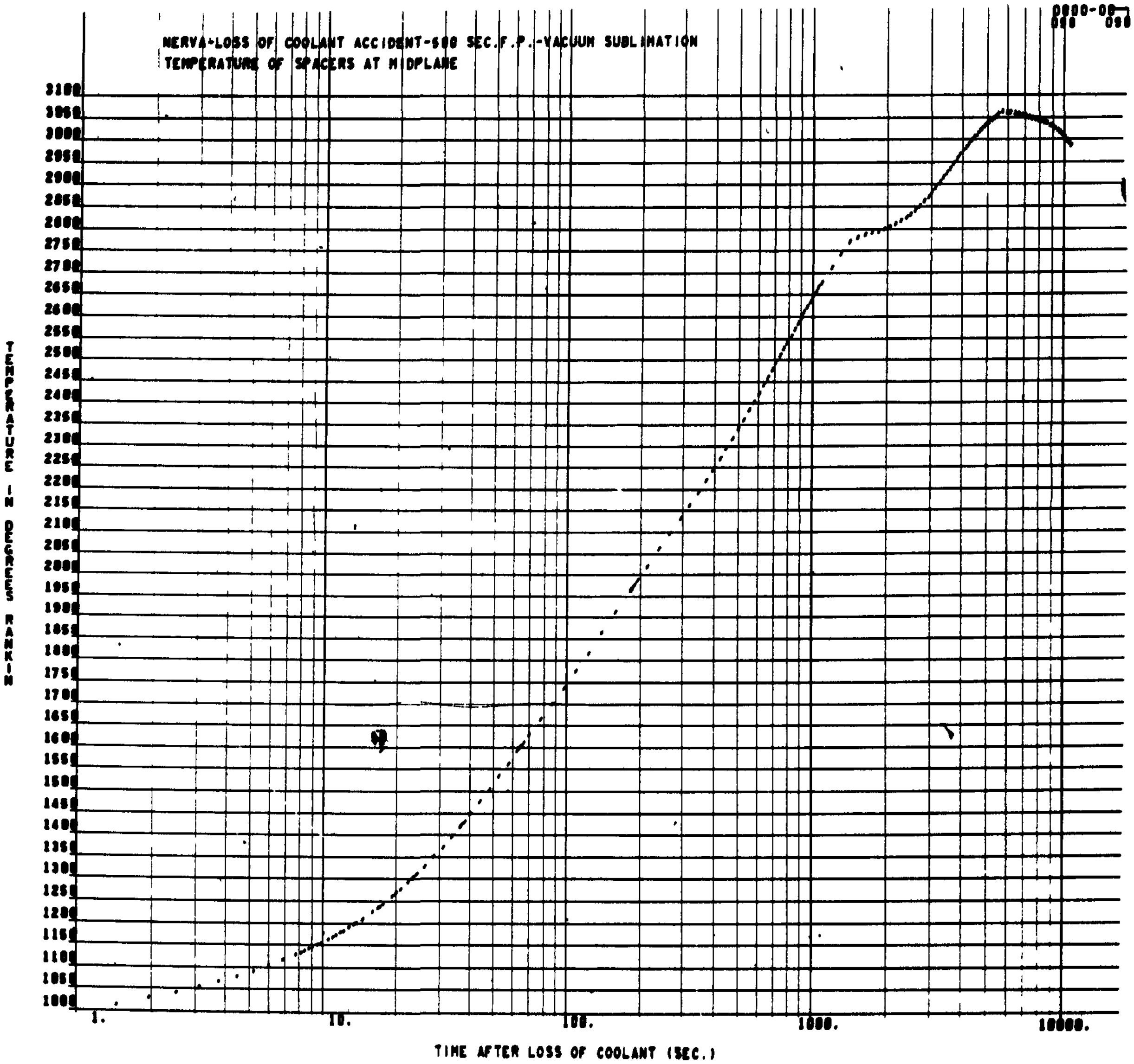

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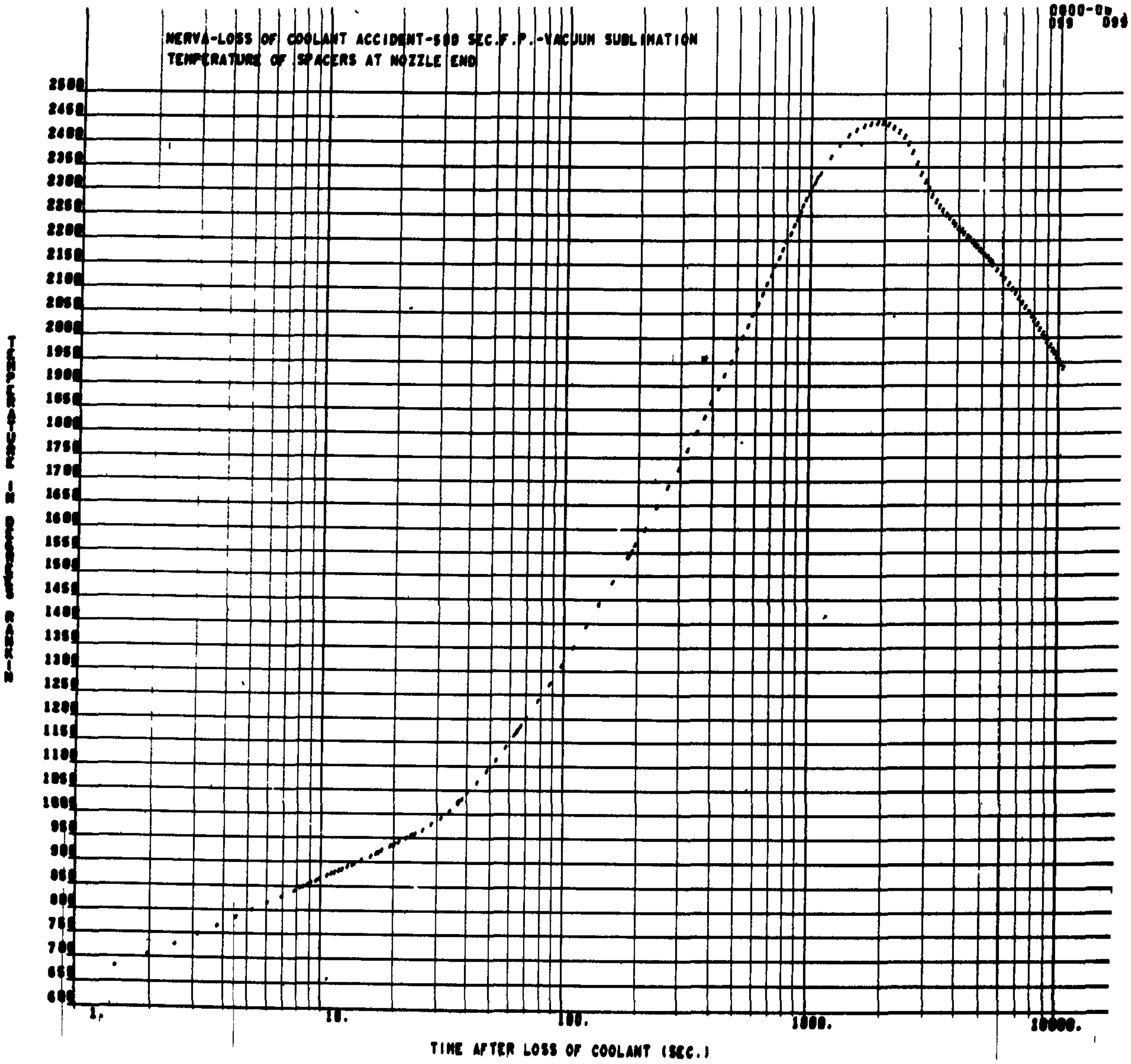

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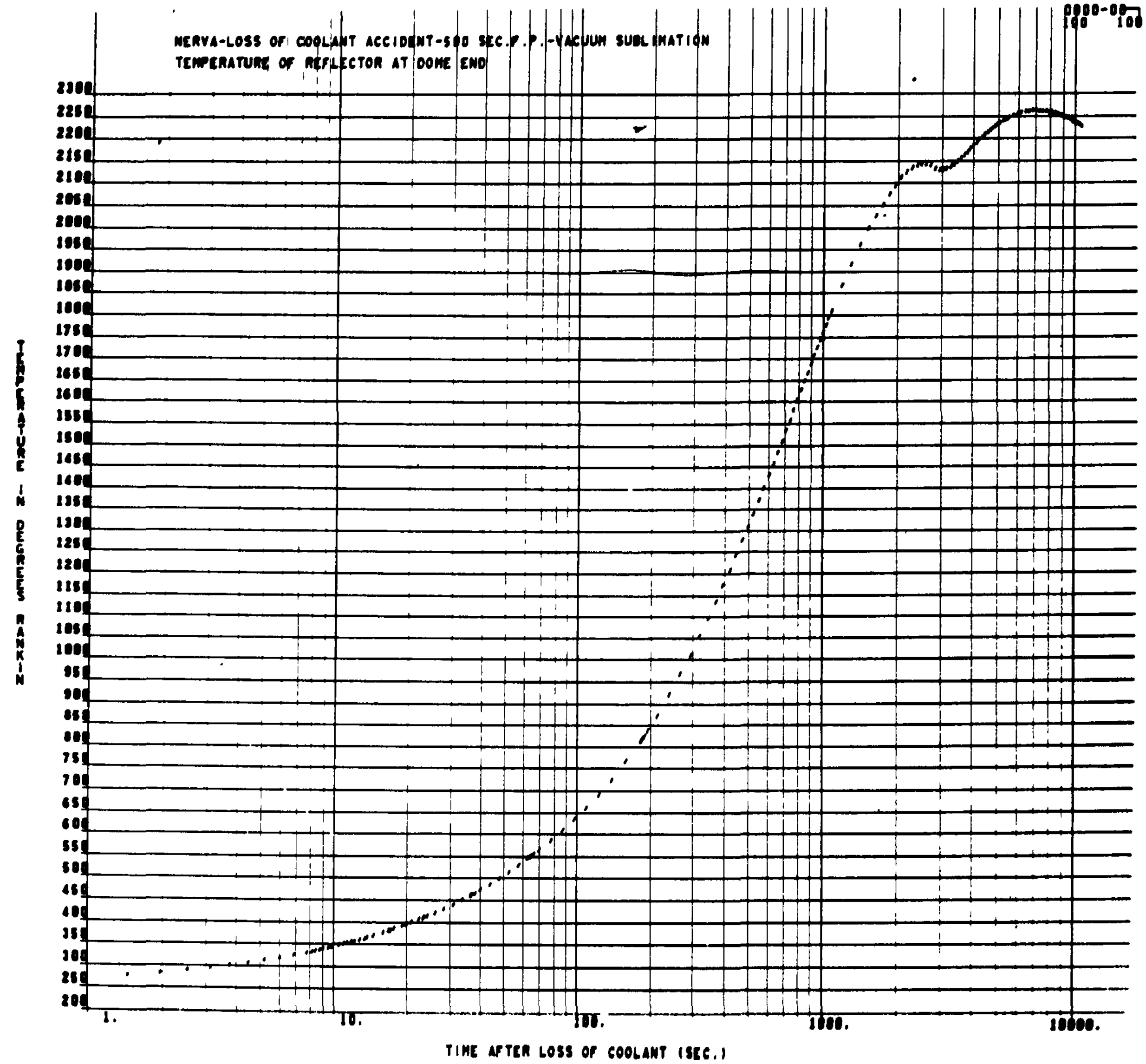

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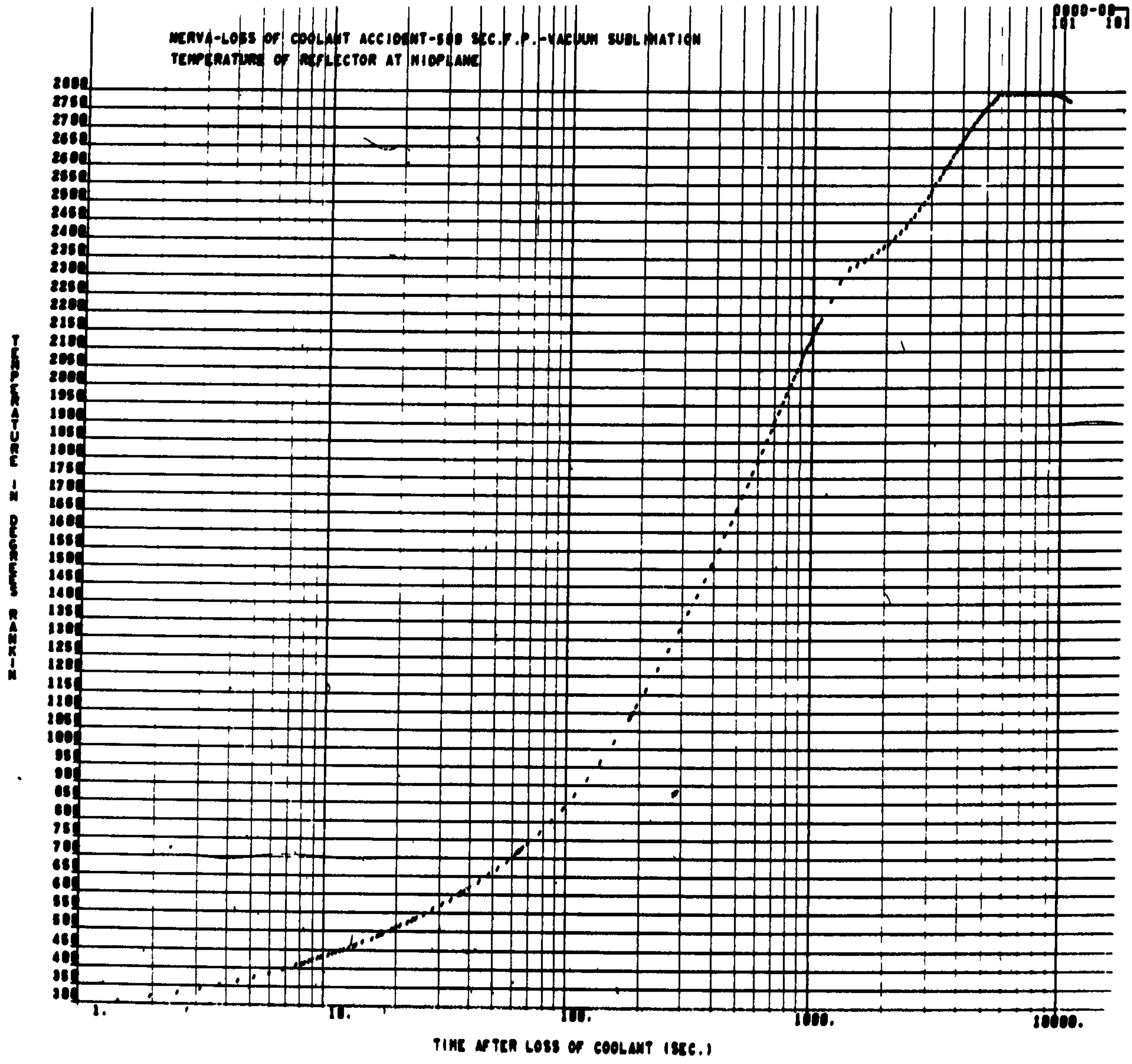

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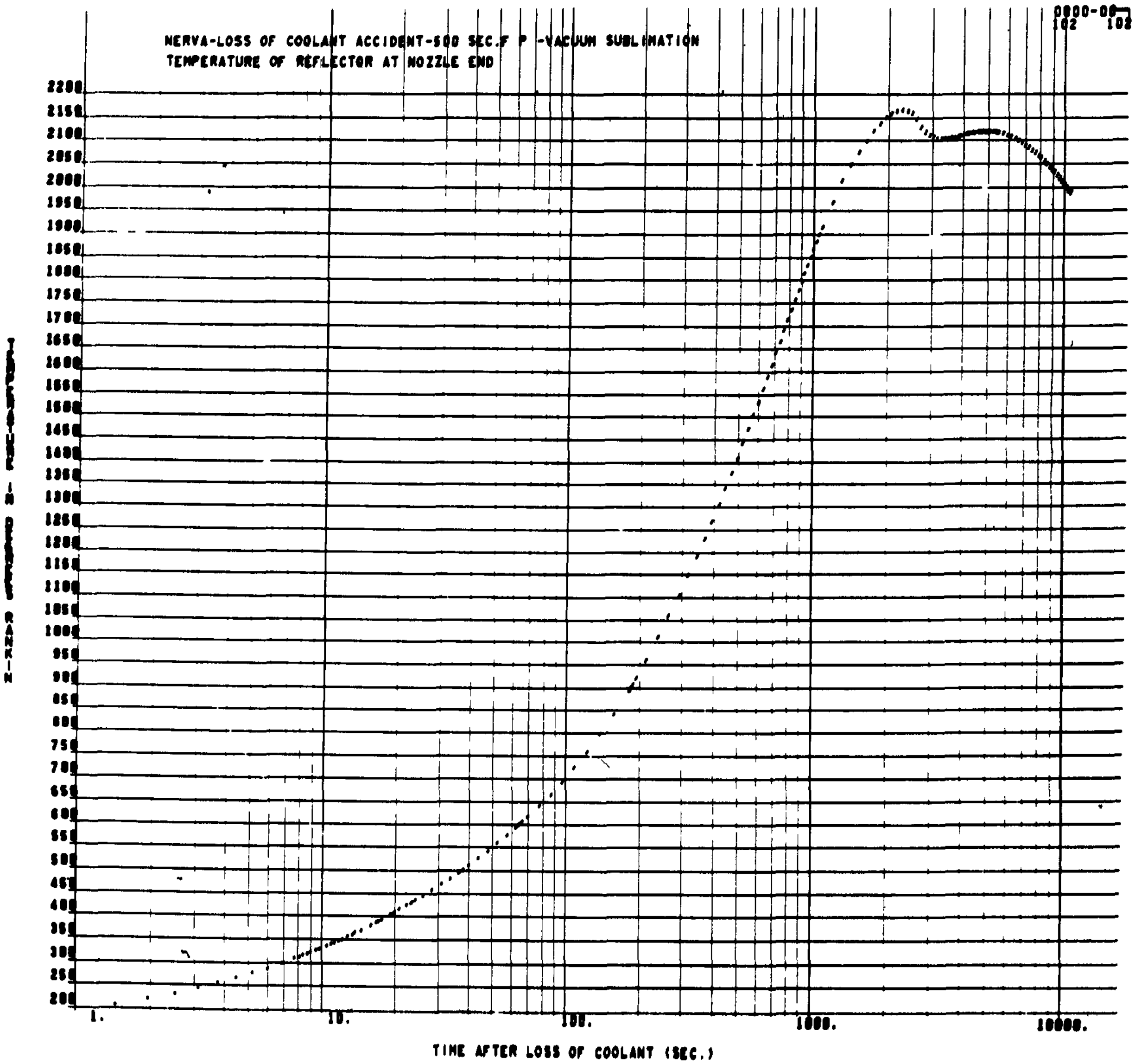

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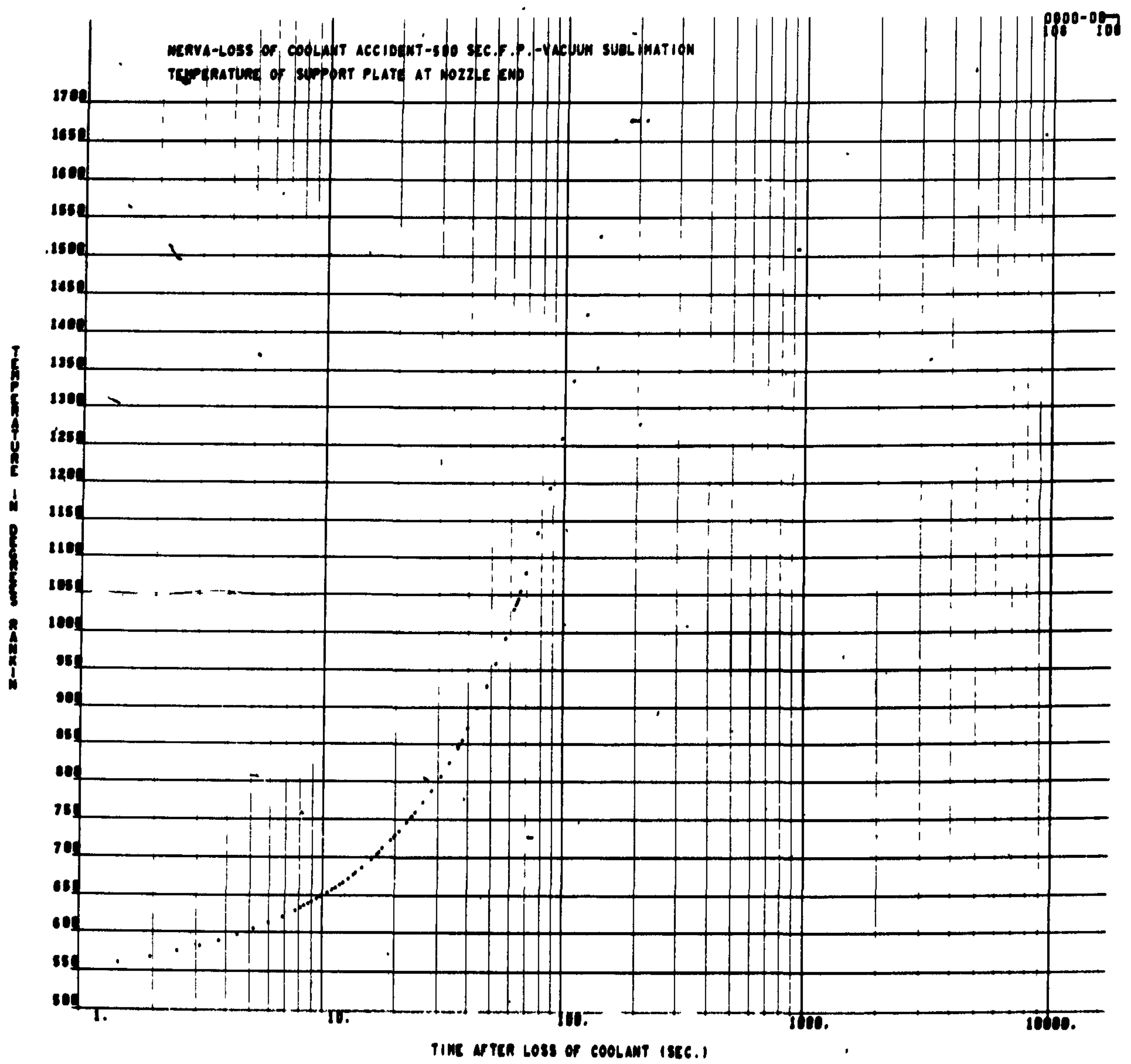

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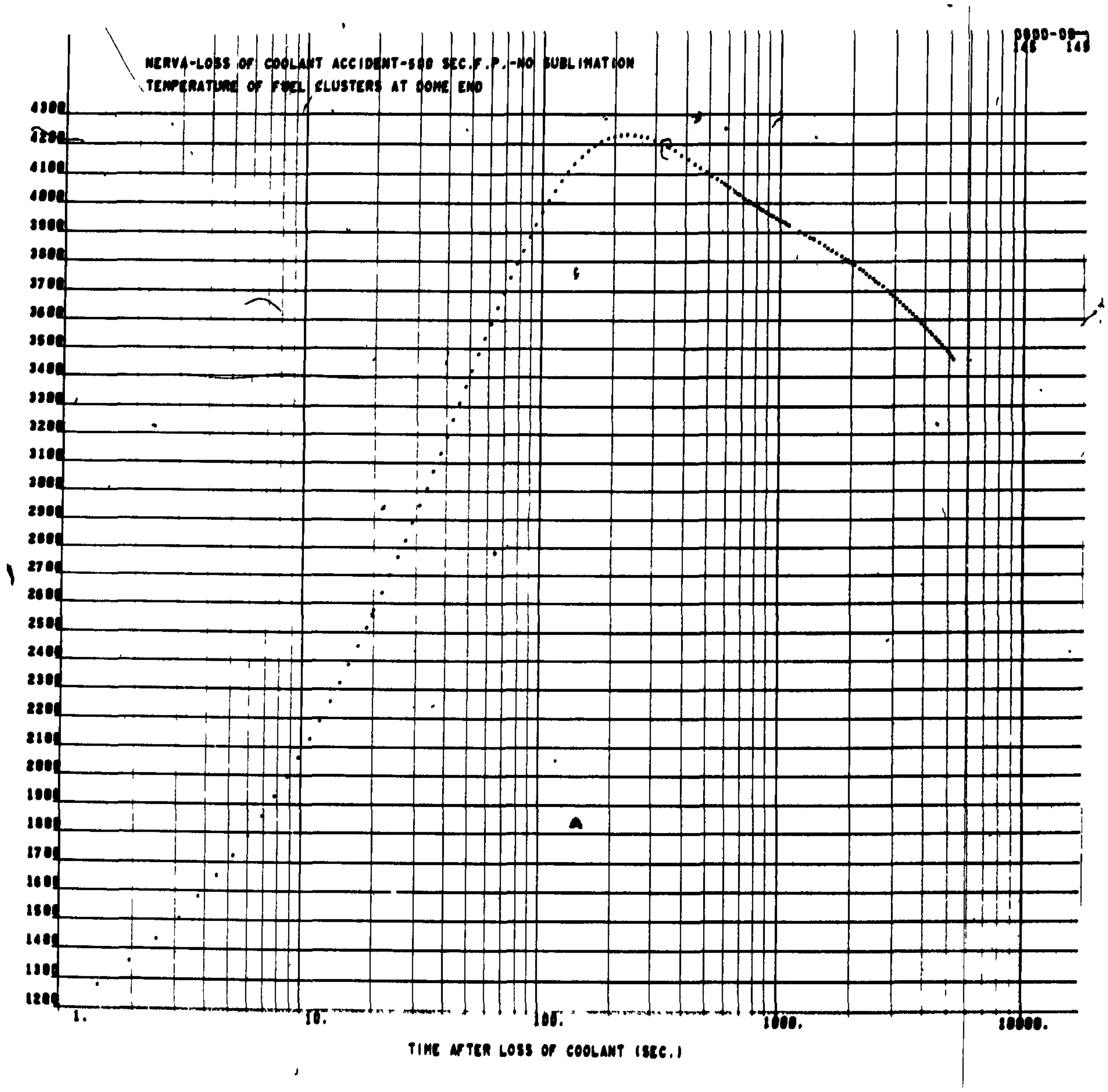

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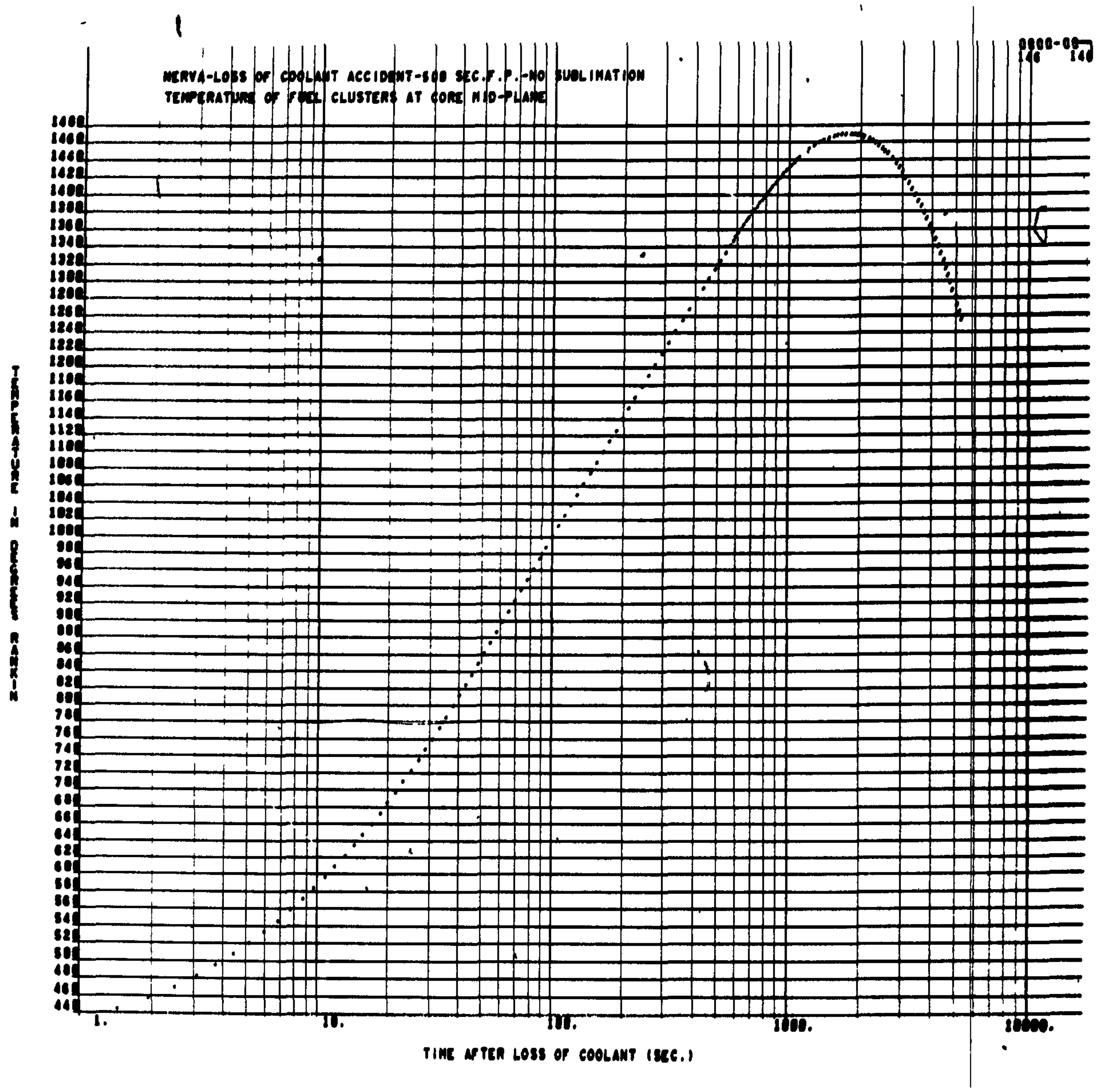

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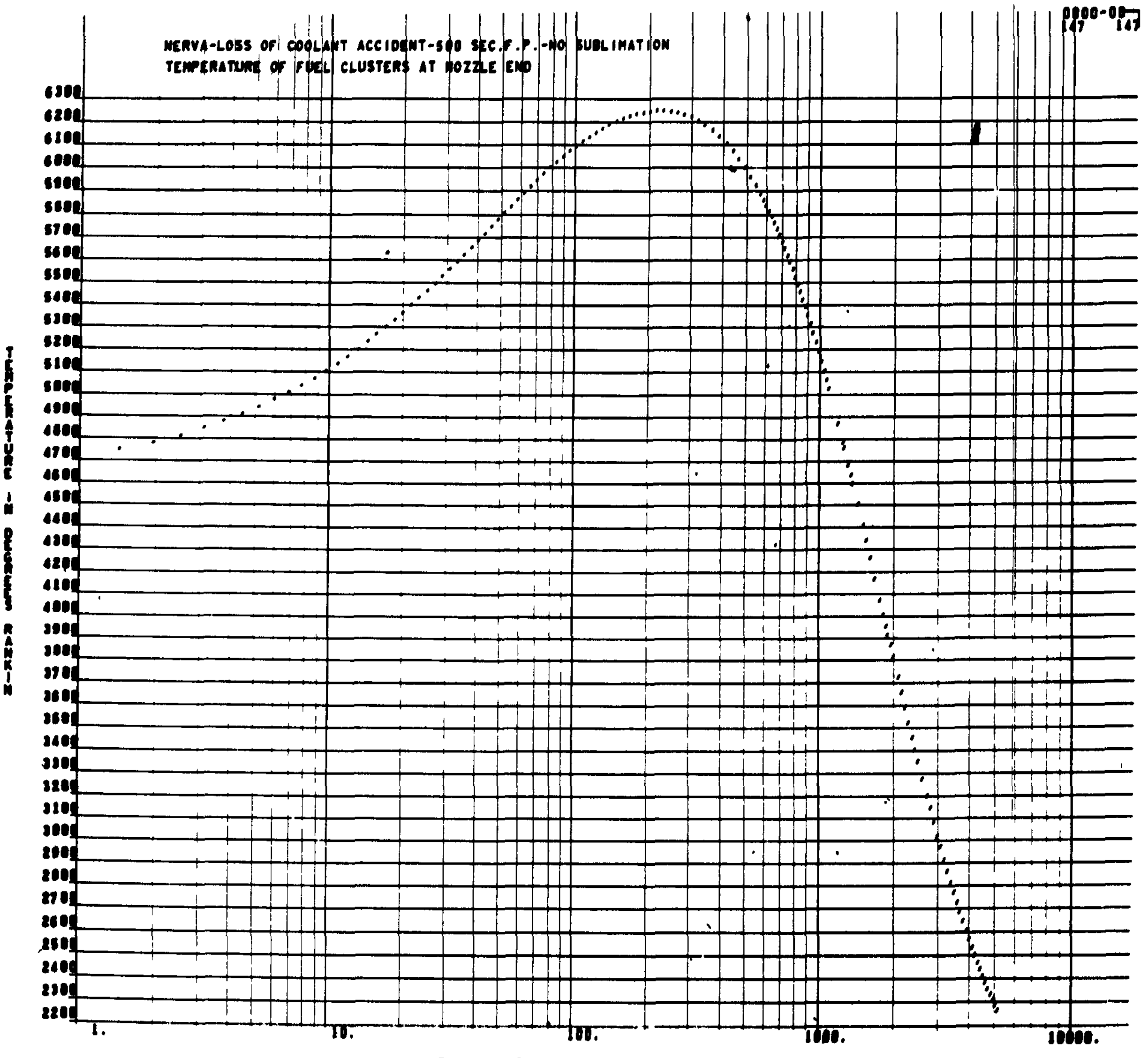

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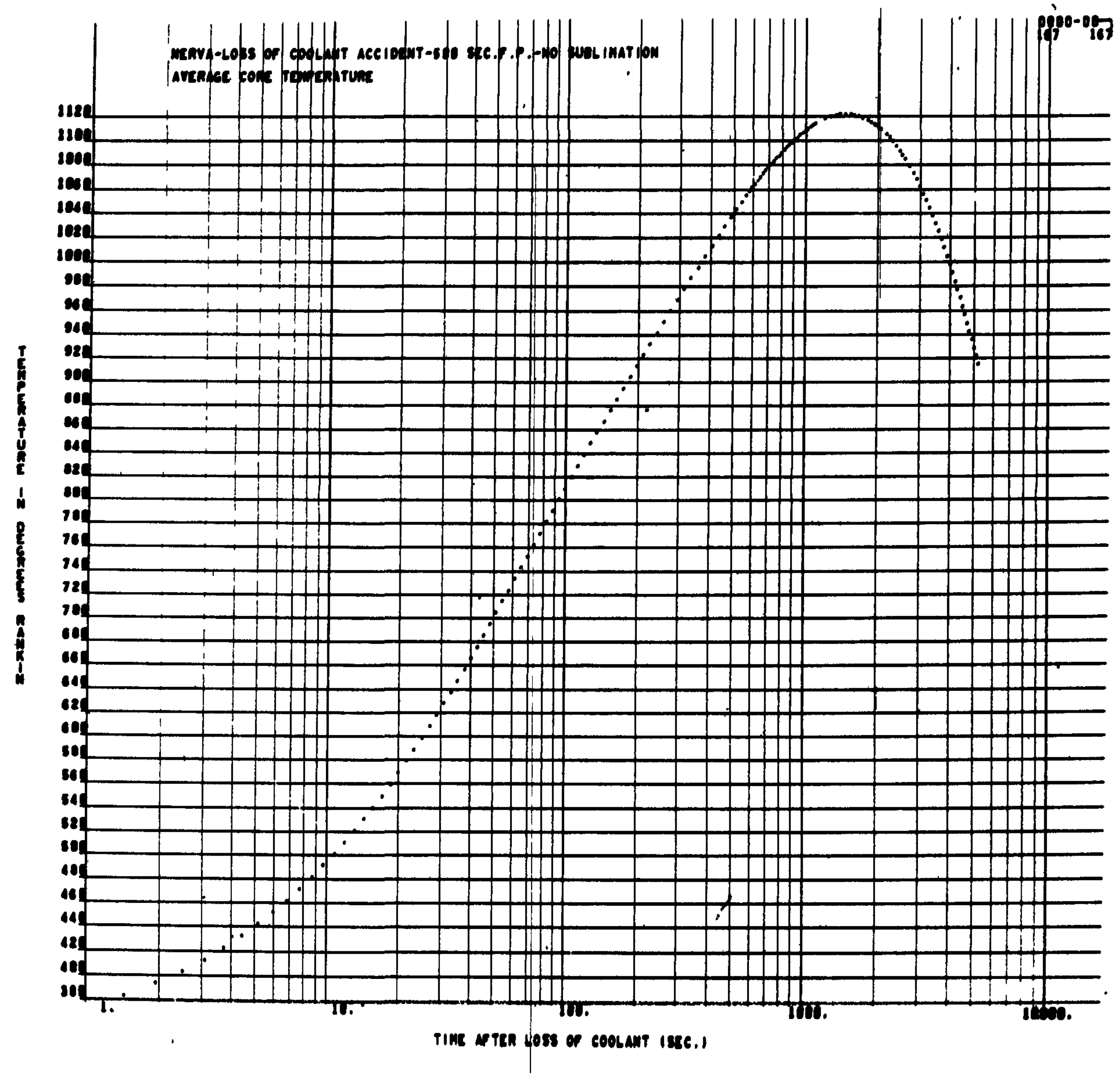

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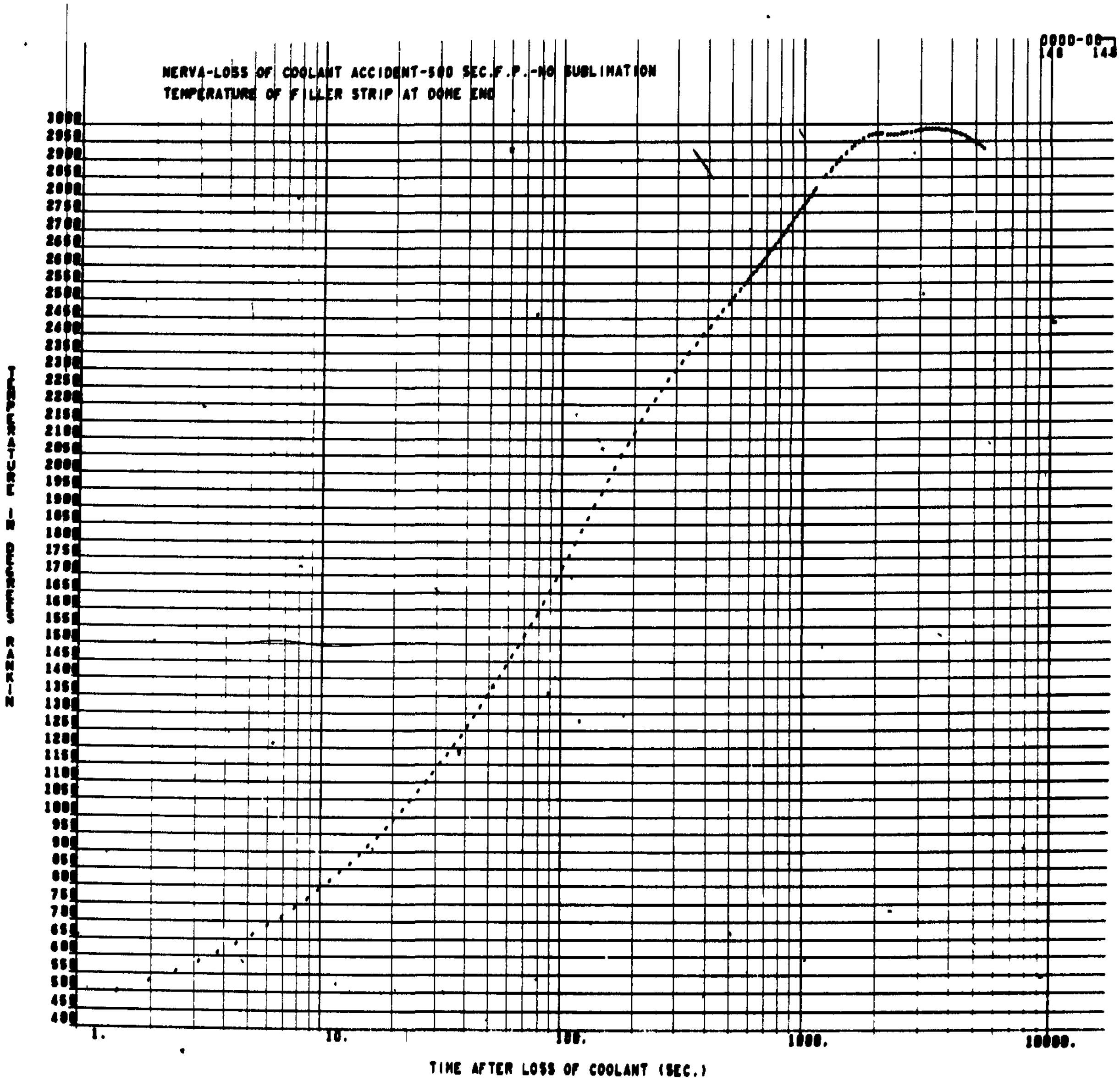

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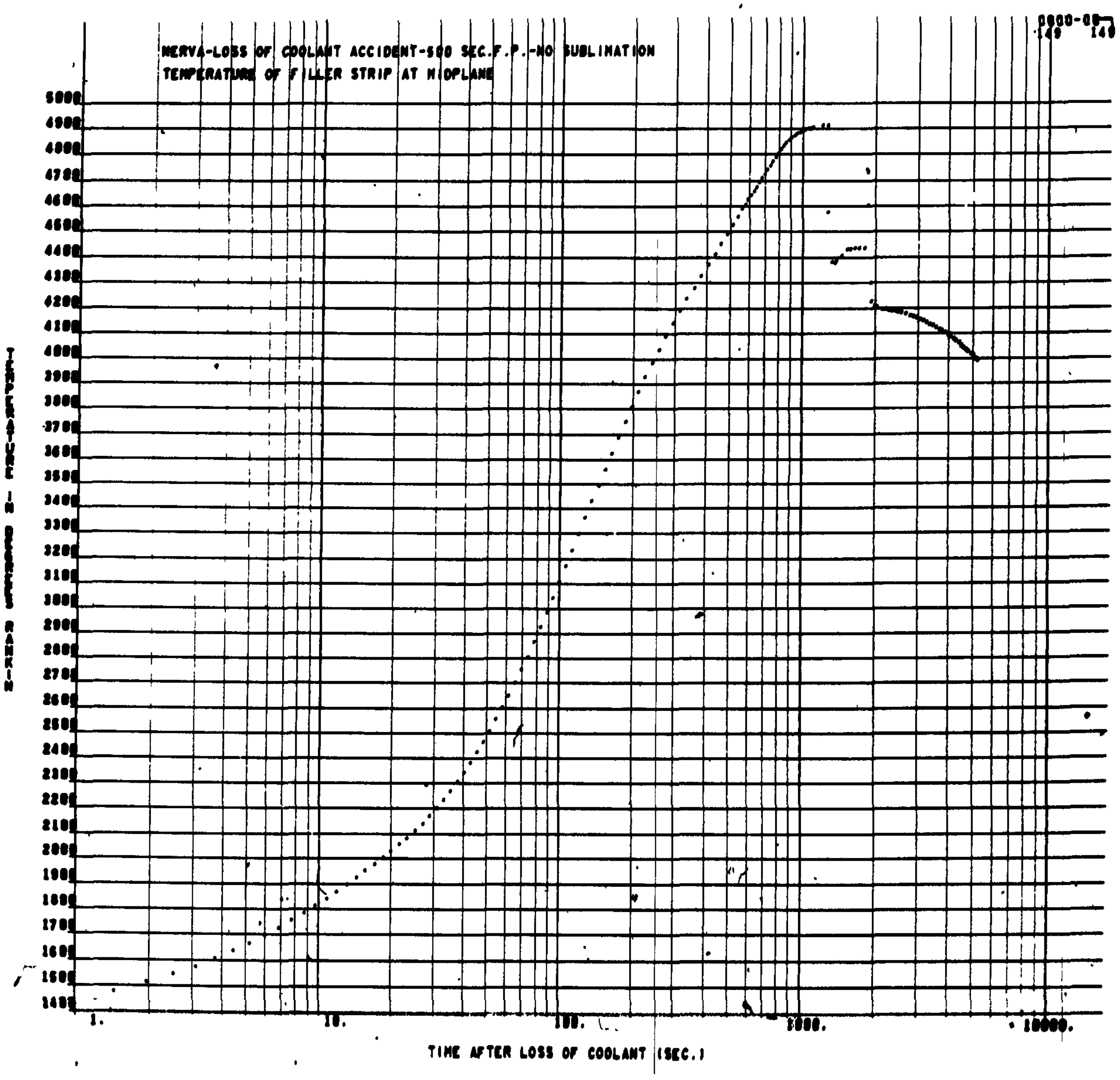

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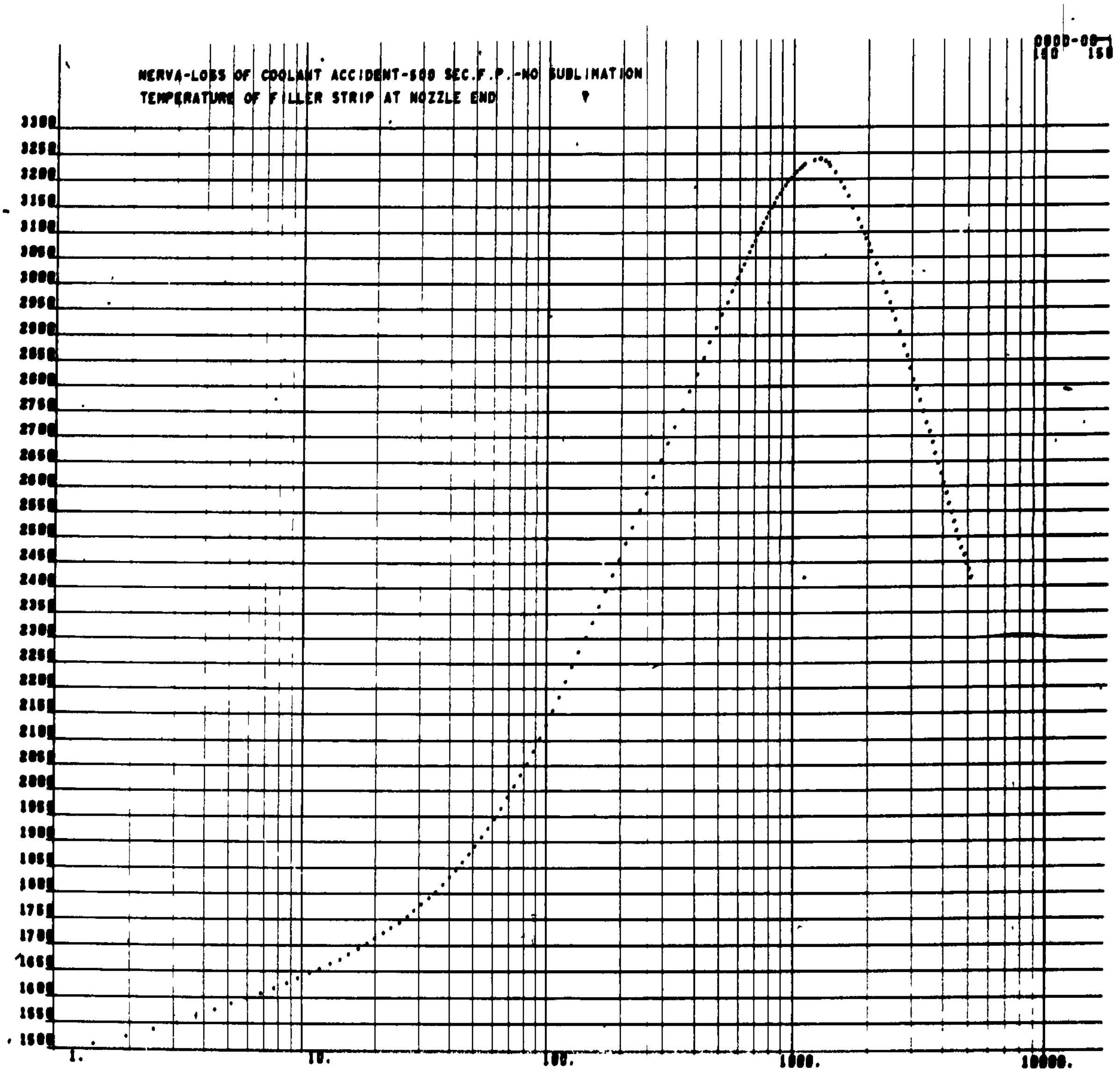

NERVA-LOSS OF COOLANT ACCIDENT-500 SEC.F.P.-NO SUBLIMATION
TEMPERATURE OF FILLER STRIP AT NOZZLE END

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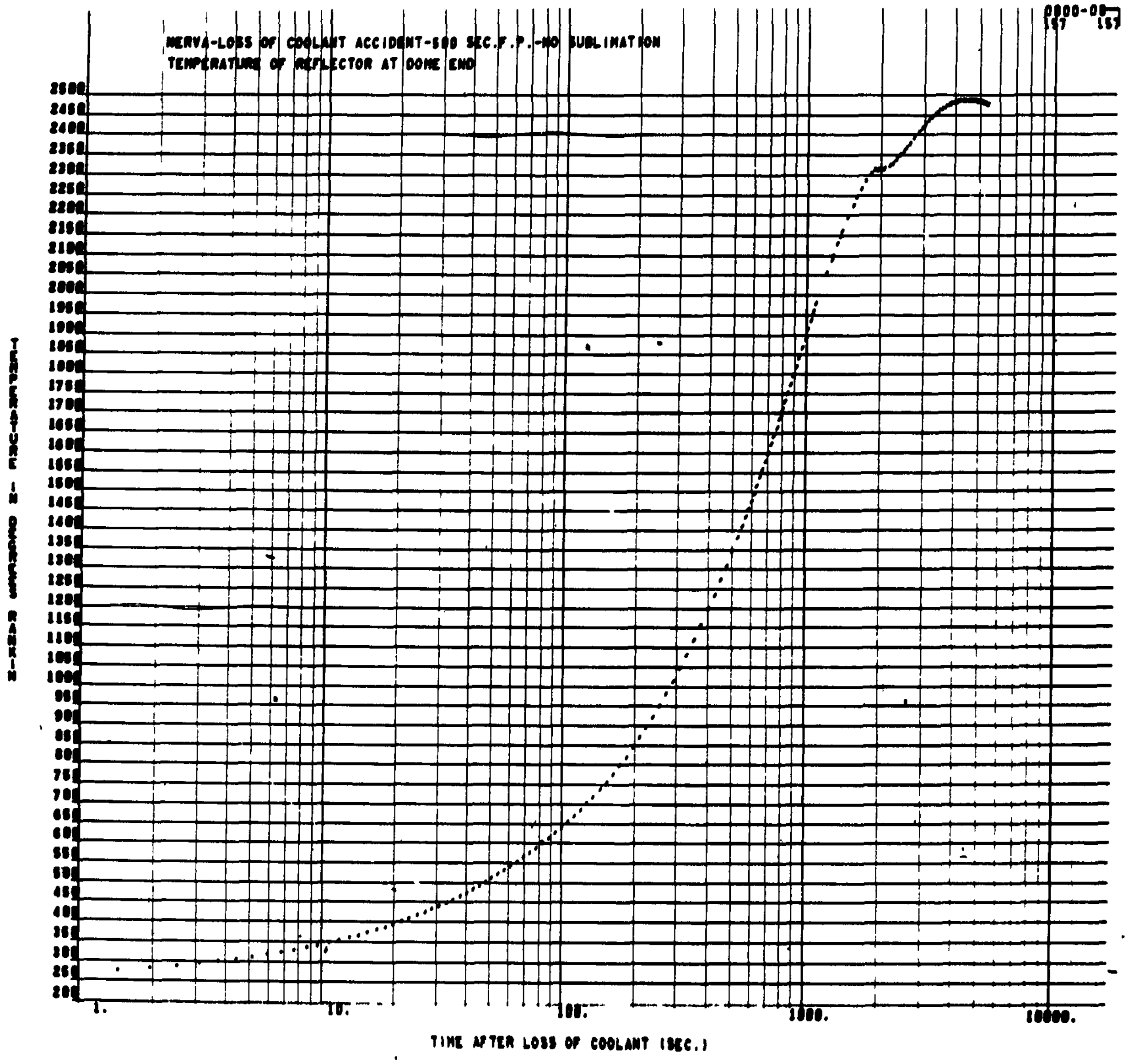

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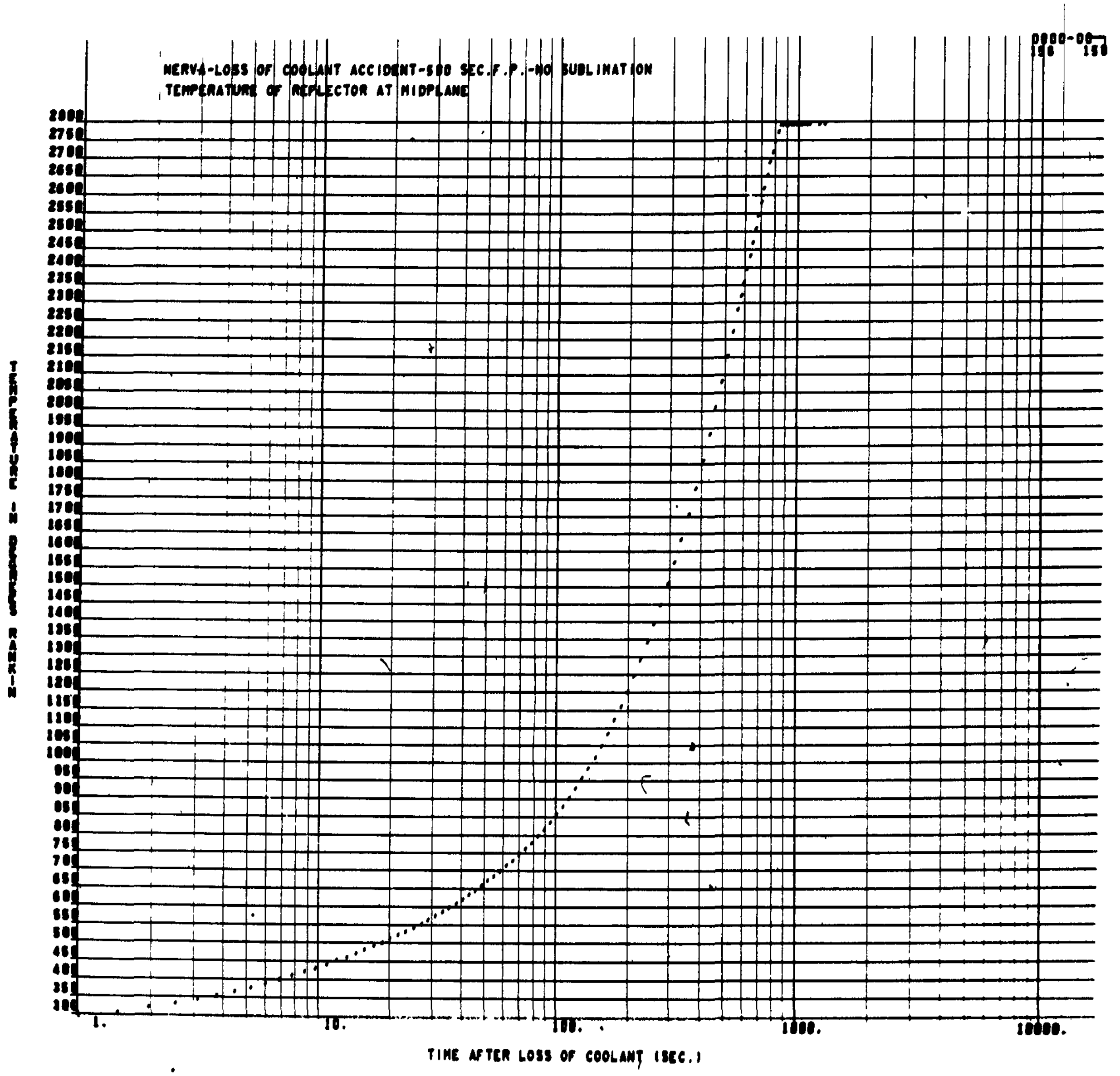
WANL-TME-1431



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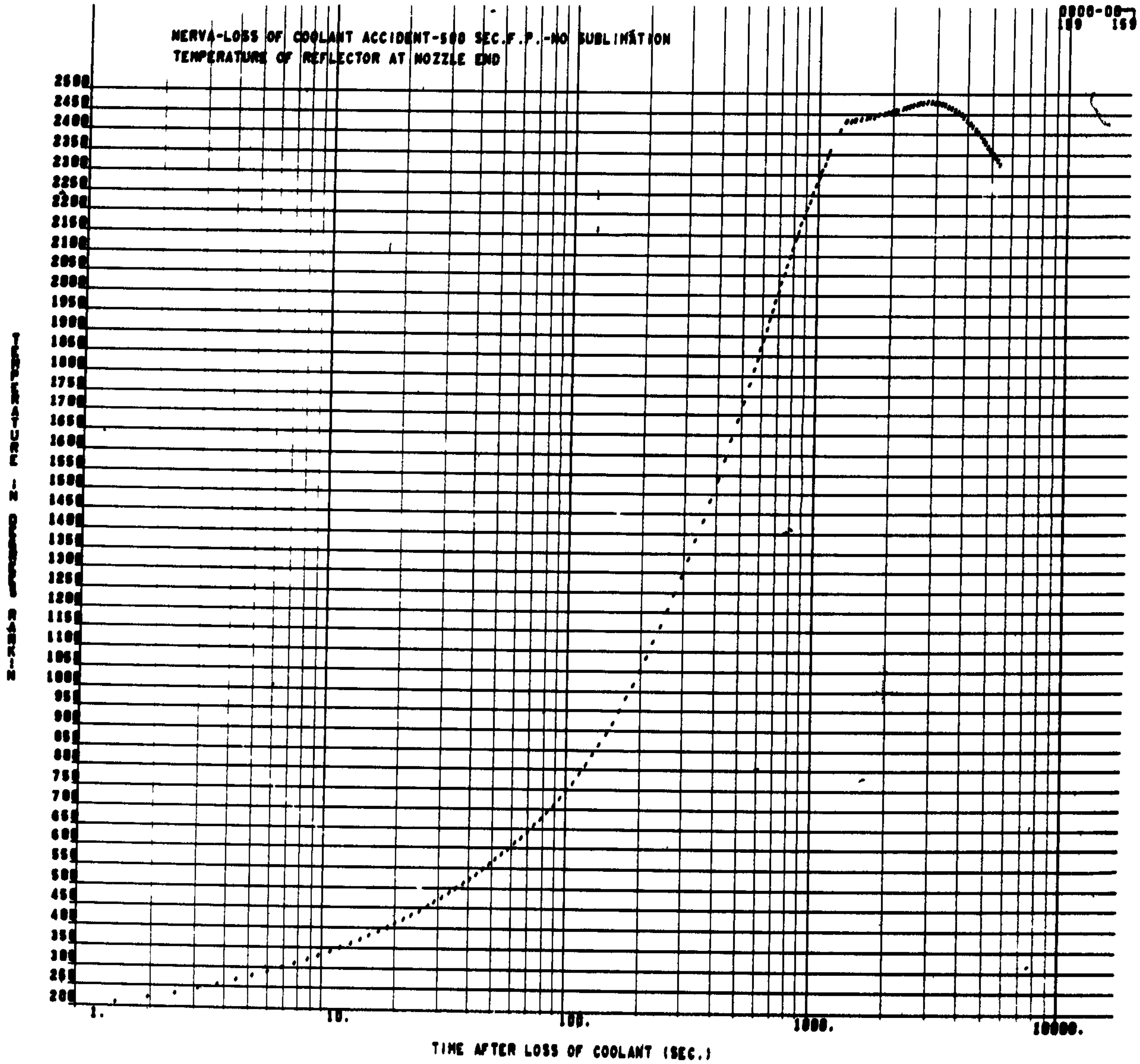

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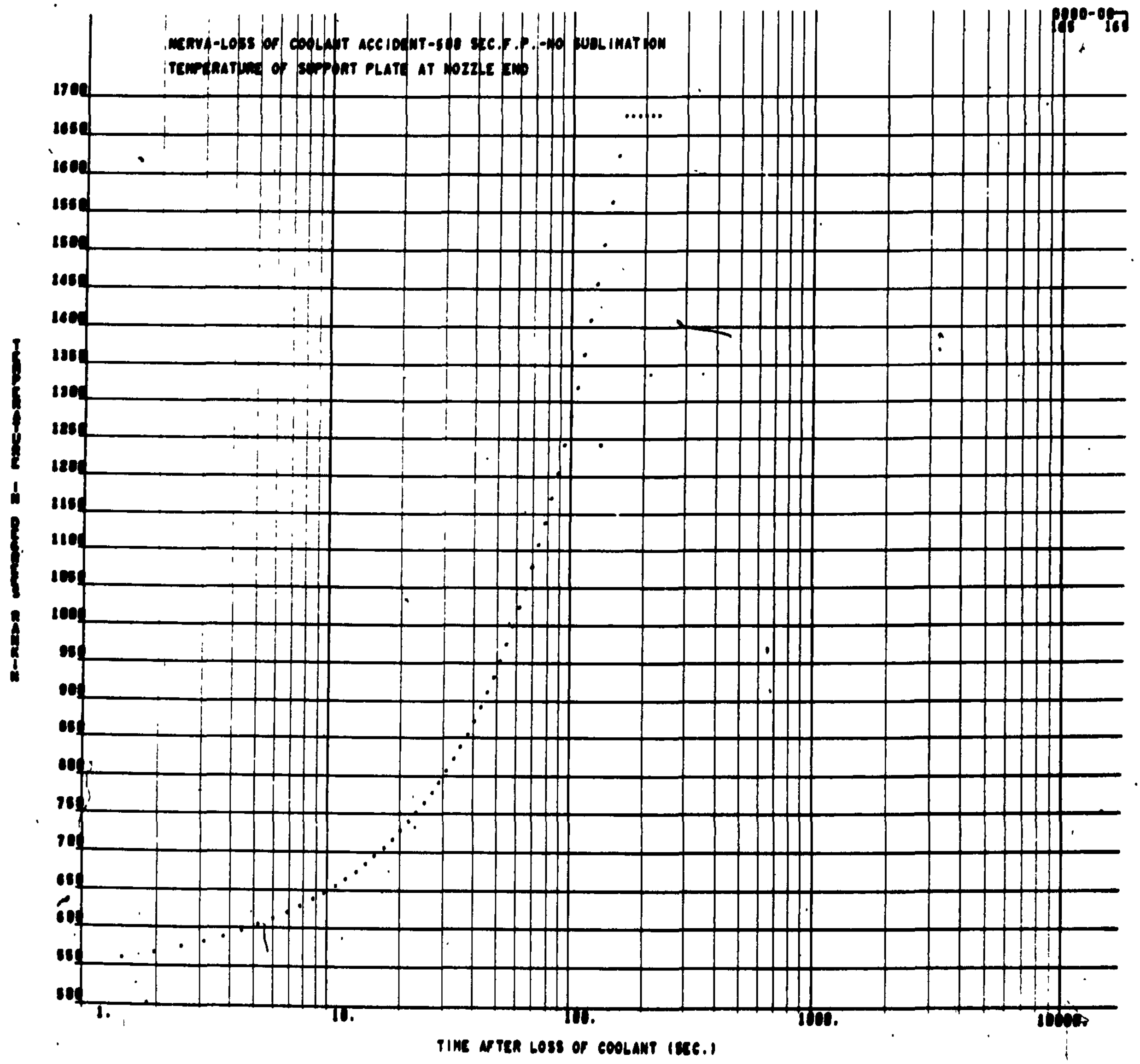

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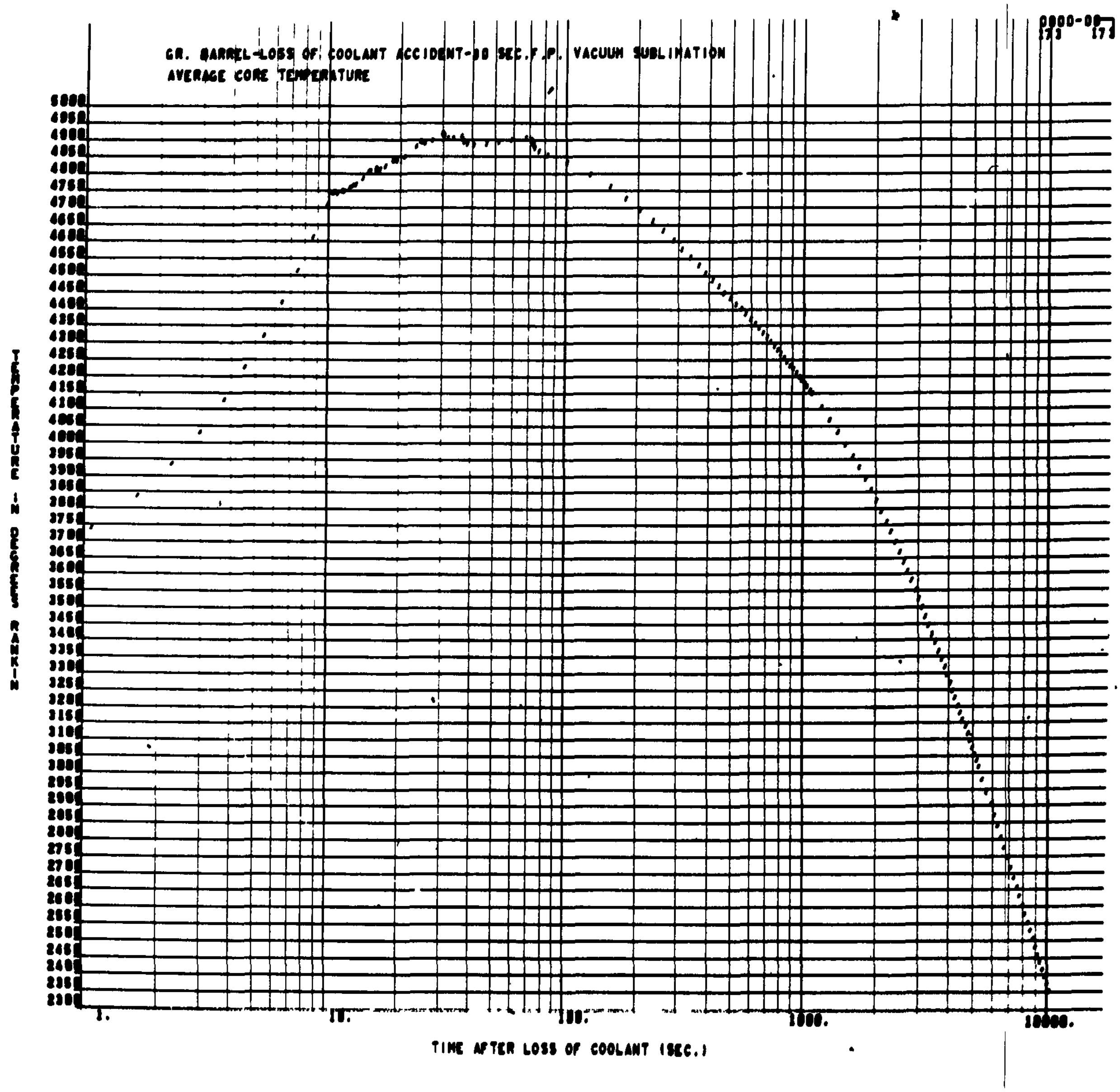

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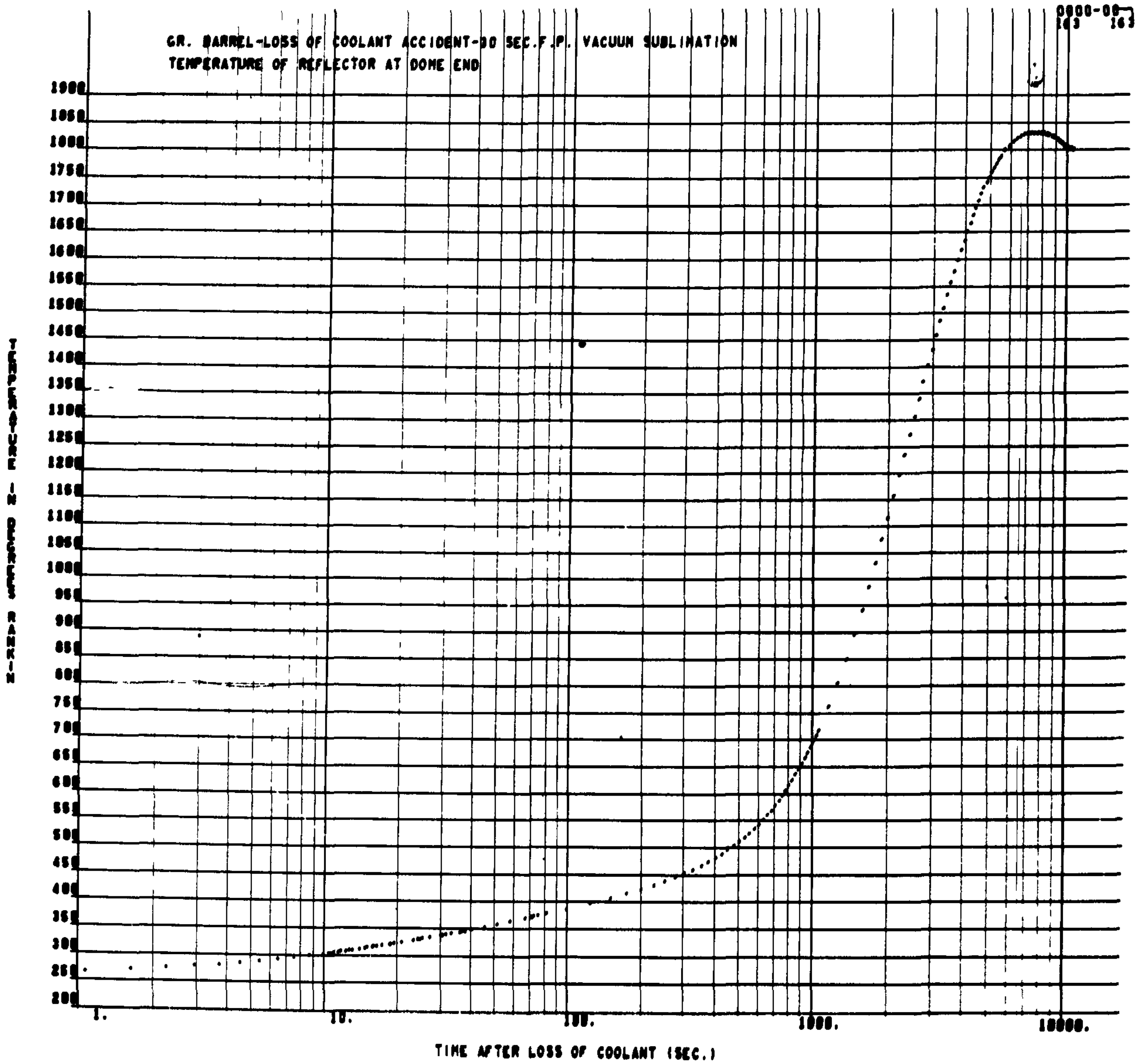

GR. BARREL-LOSS OF COOLANT ACCIDENT-30 SEC.F.P. VACUUM SUBLIMATION
TEMPERATURE OF REFLECTOR AT DOME END

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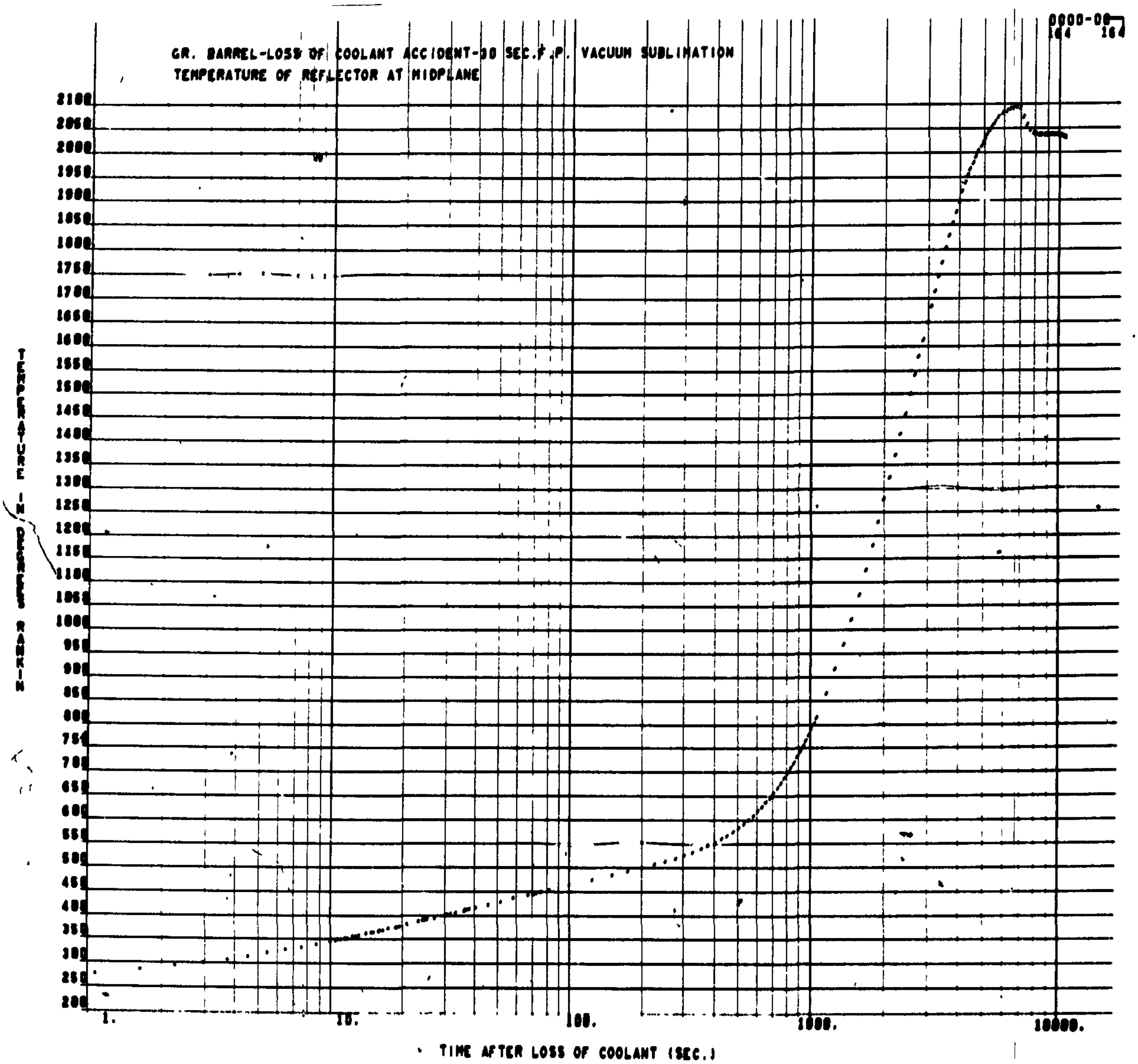

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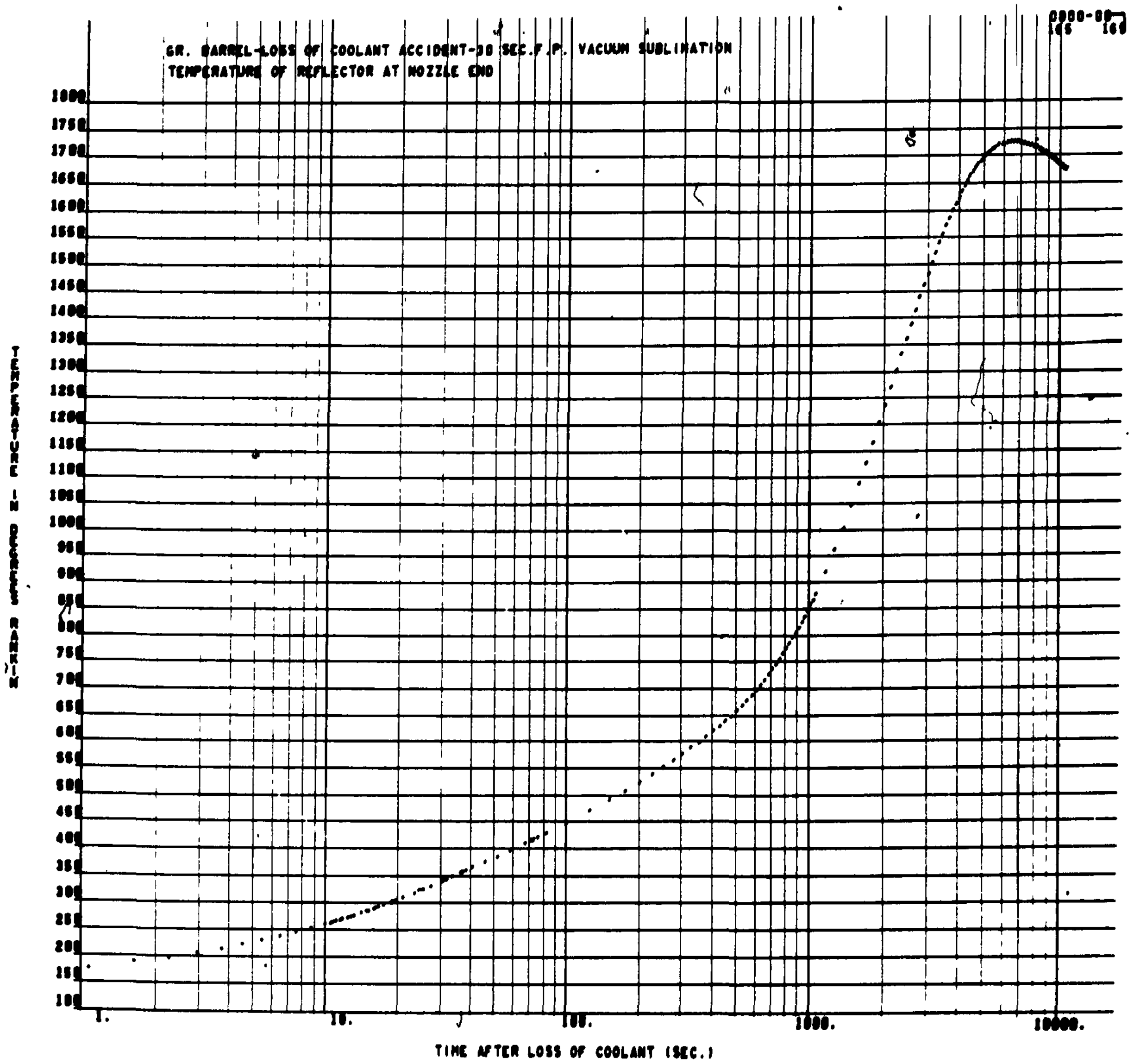

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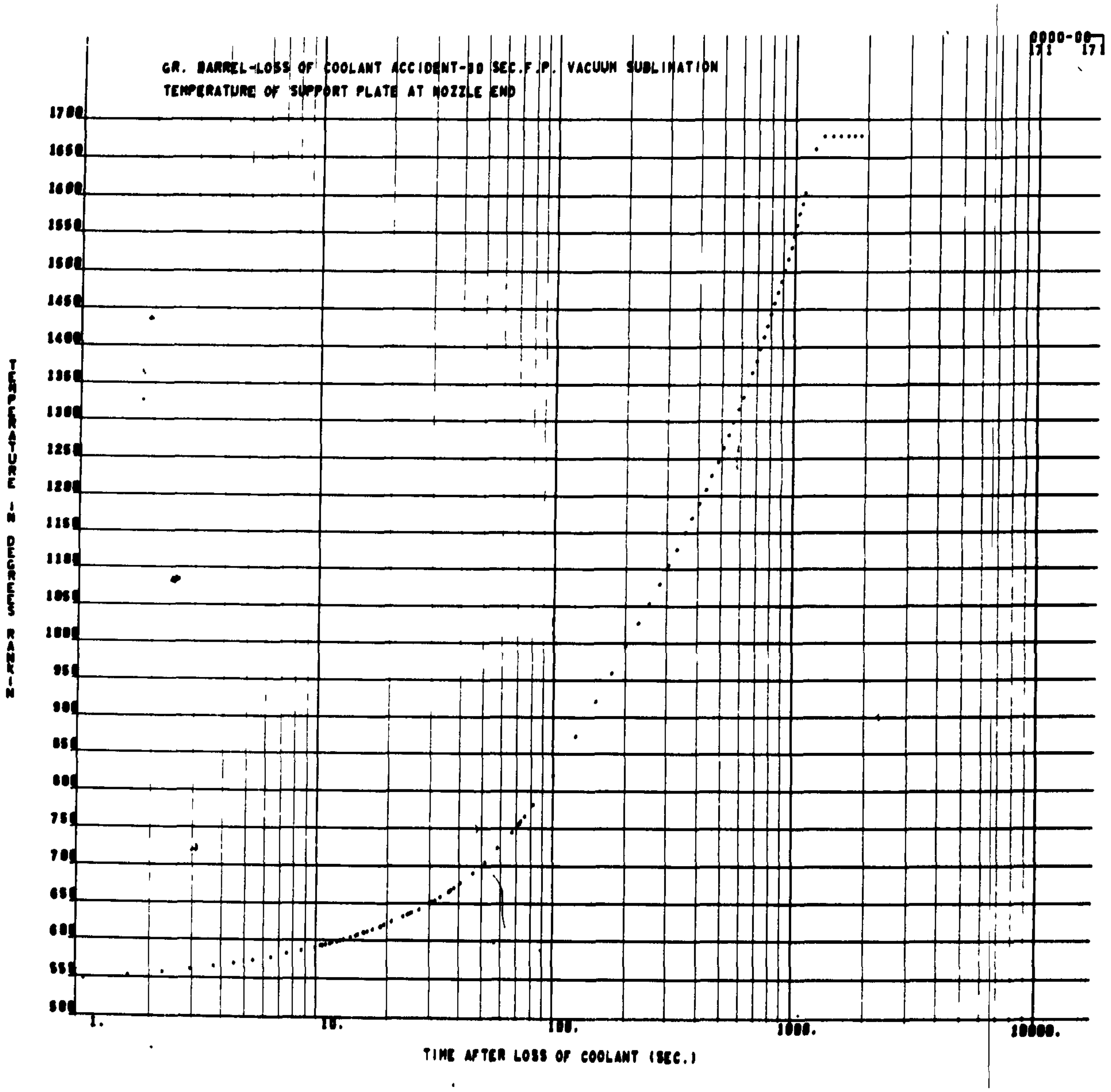

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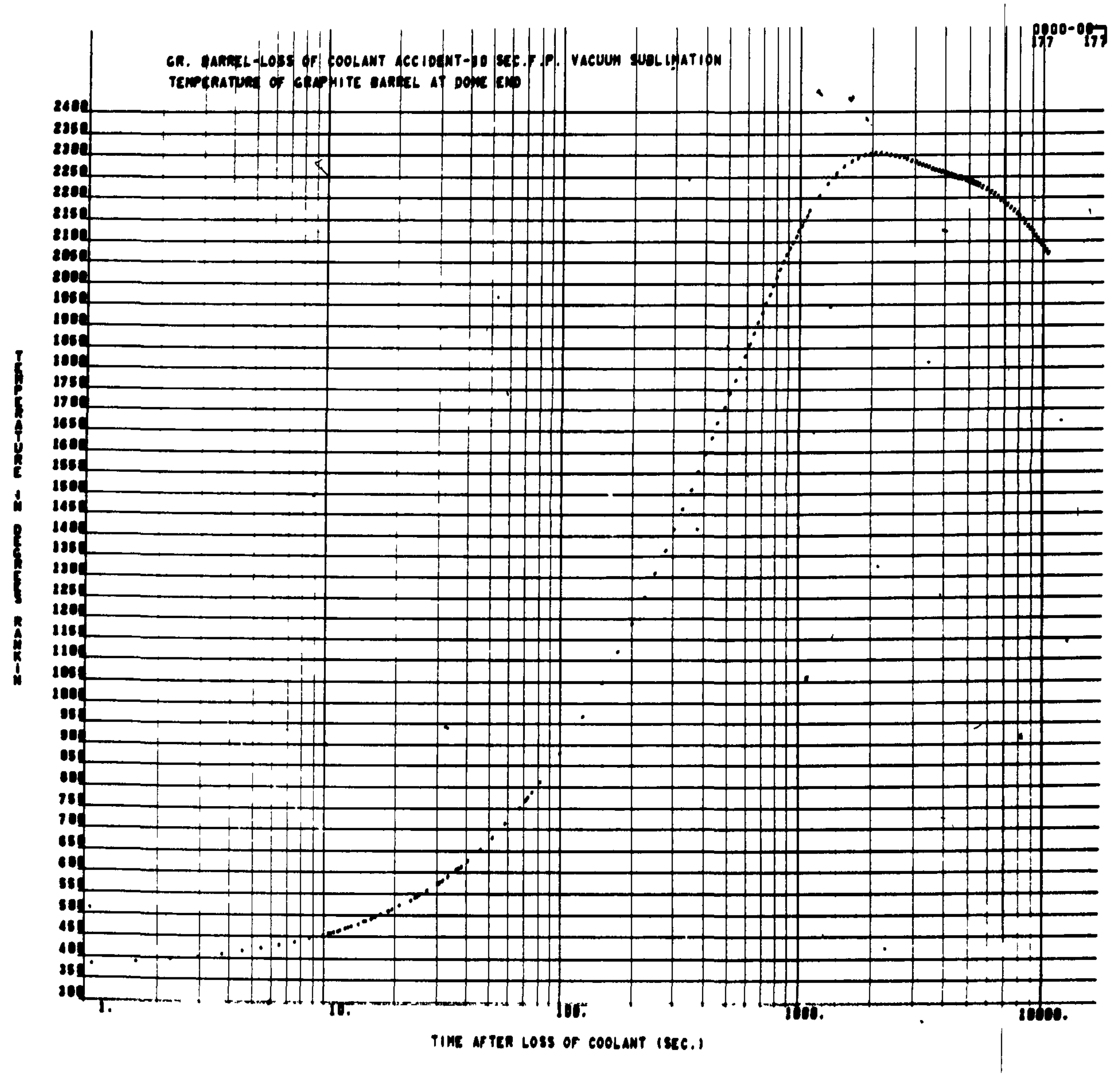
0000-00
177 177
GR. BARREL-LOSS OF COOLANT ACCIDENT-30 SEC.F.P. VACUUM SUBLIMATION
TEMPERATURE OF GRAPHITE BARREL AT DOME END
TEMPERATURE IN DEGREES RANKIN
2400
2350
2300
2250
2200
2150
2100
2050
2000
1950
1900
1850
1800
1750
1700
1650
1600
1550
1500
1450
1400
1350
1300
1250
1200
1150
1100
1050
1000
950
900
850
800
750
700
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450
400
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300
1.
10.
100.
1000.
10000.
TIME AFTER LOSS OF COOLANT (SEC.)

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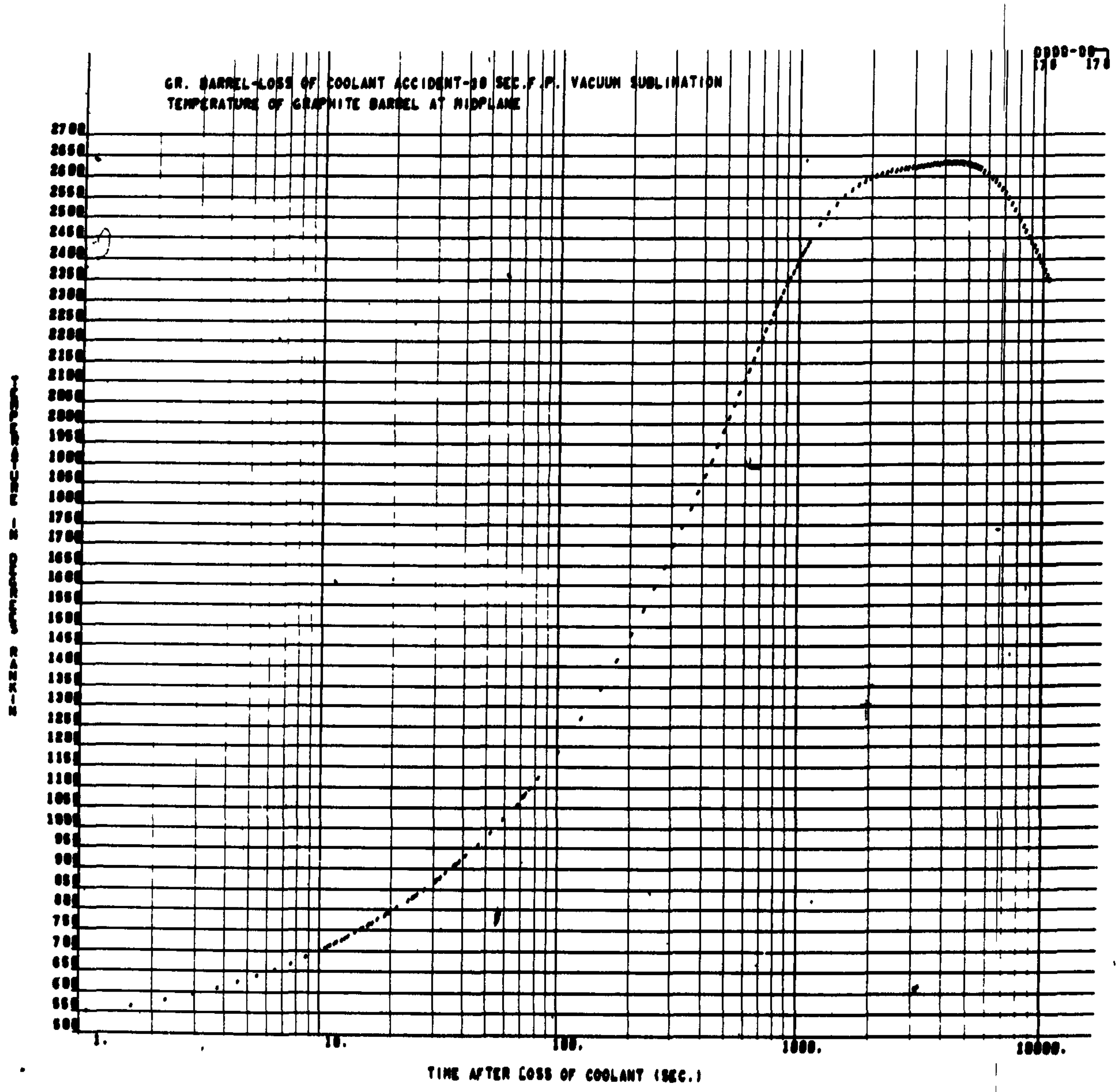

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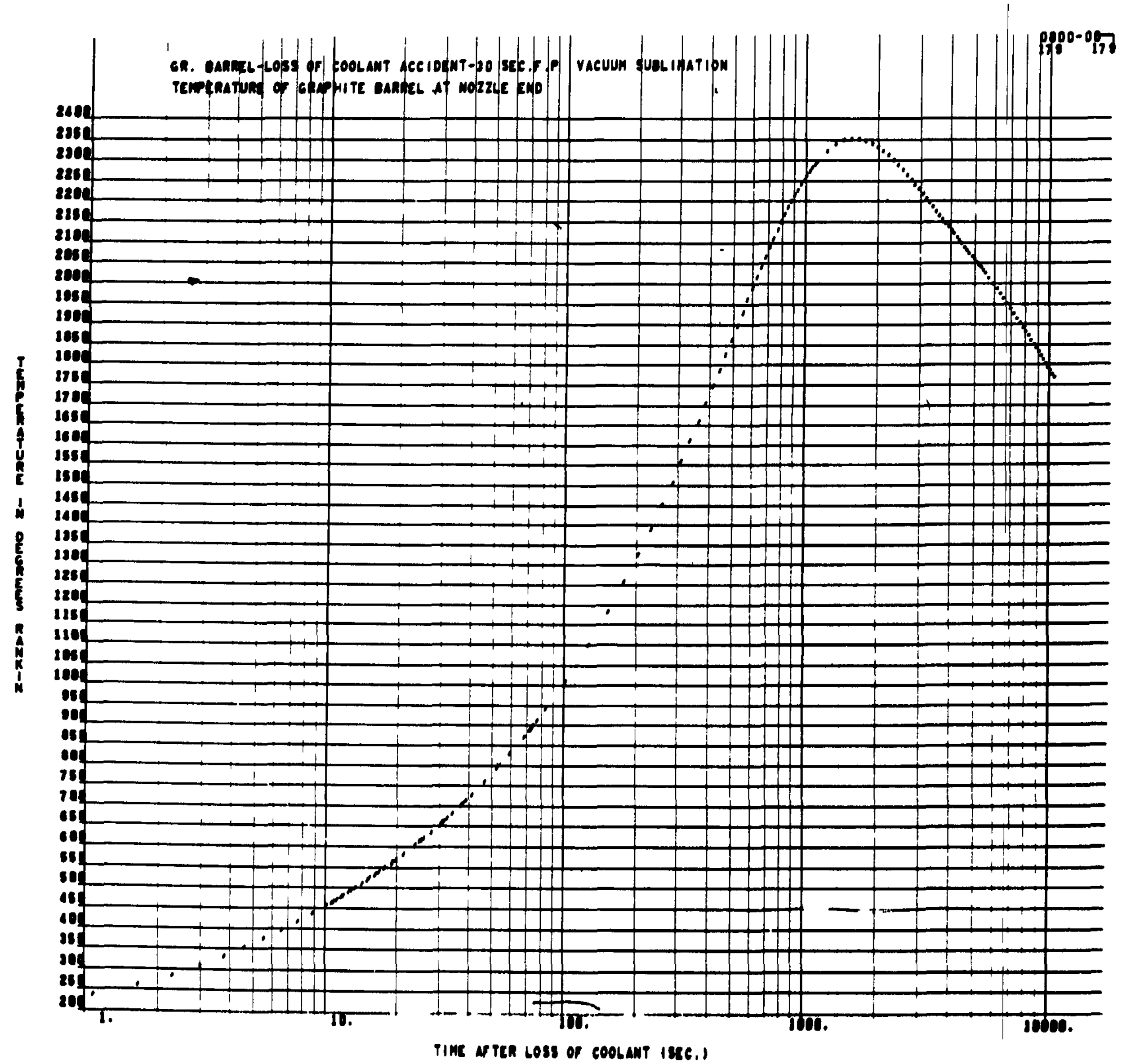

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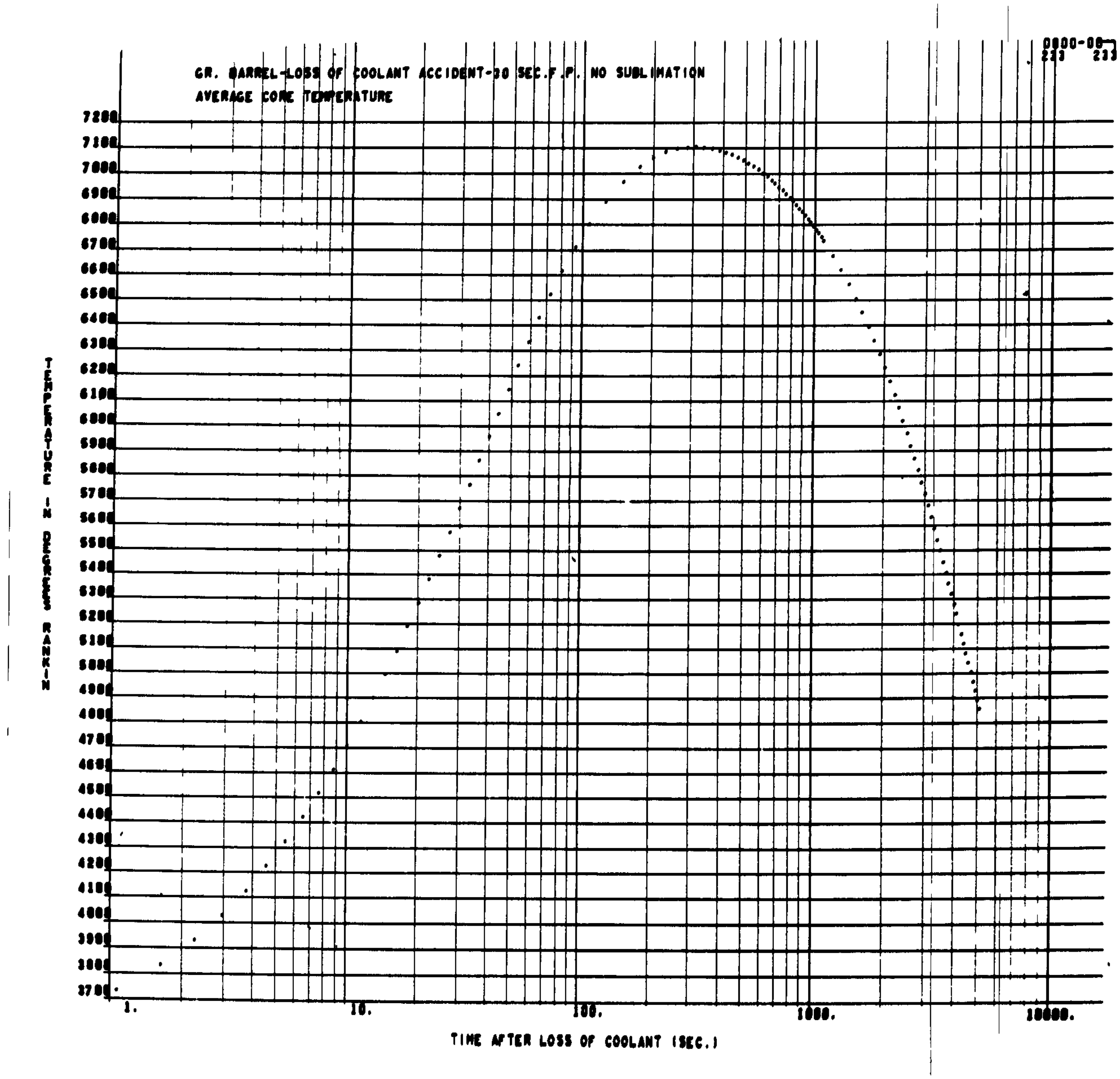

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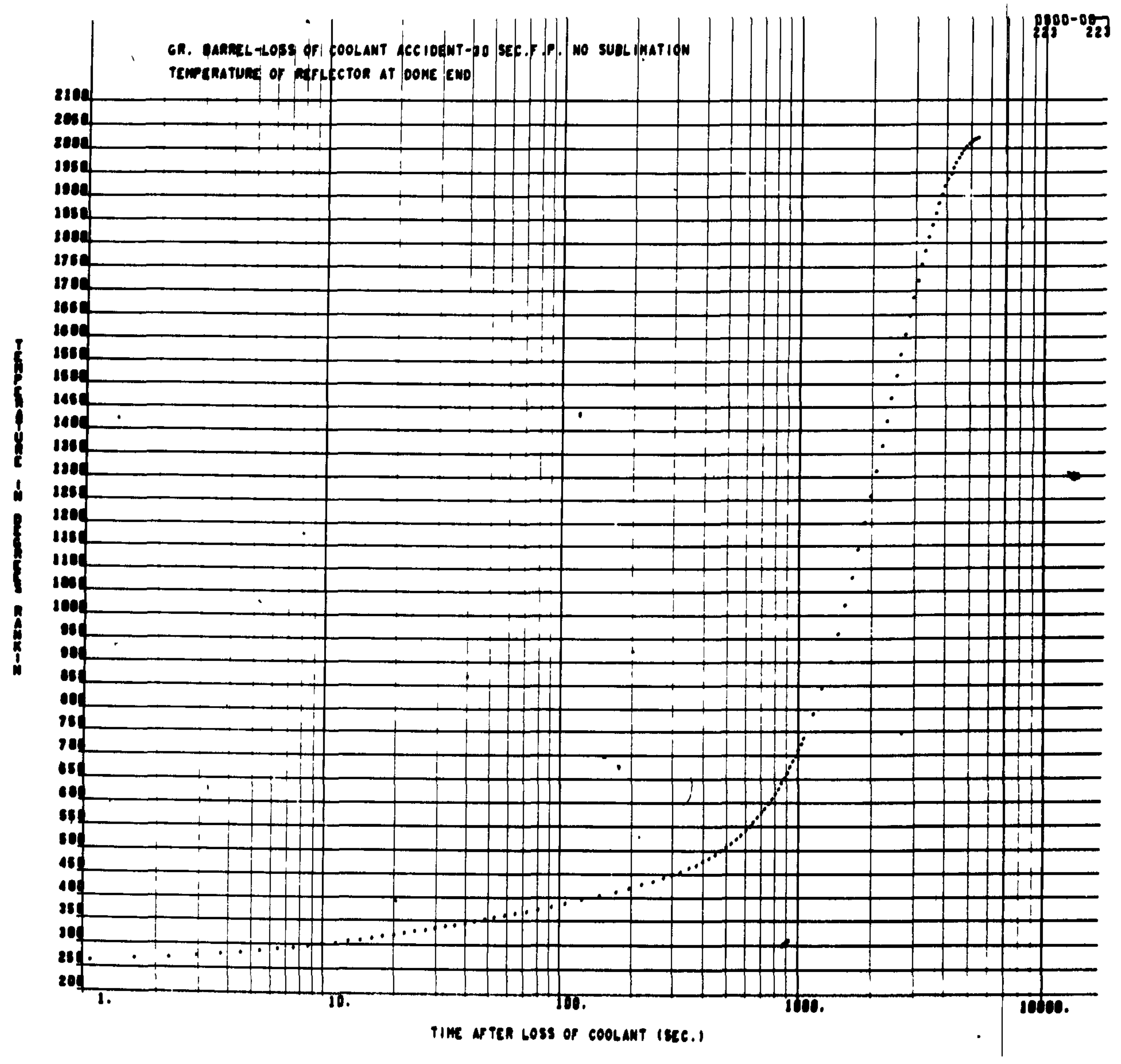

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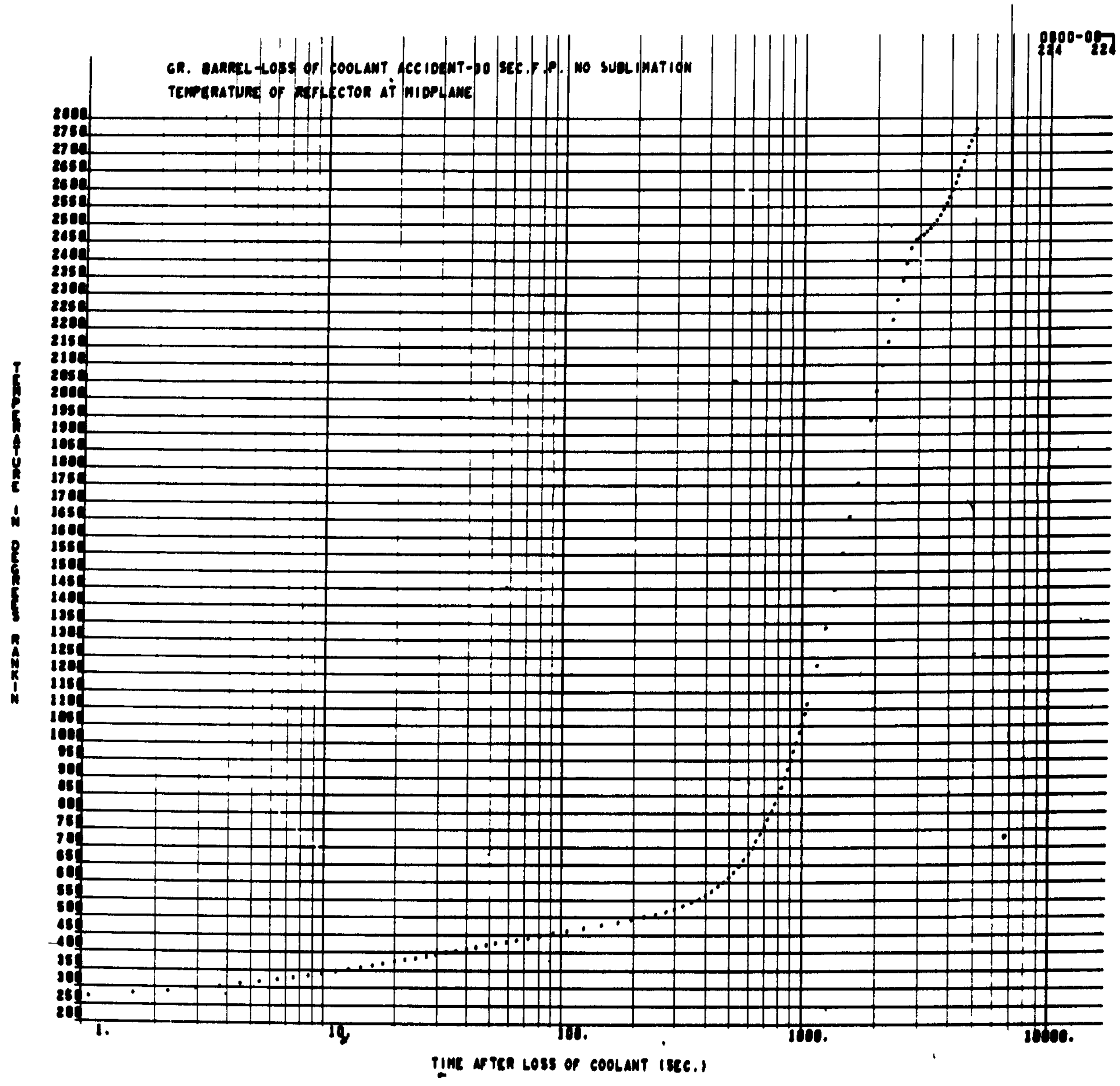

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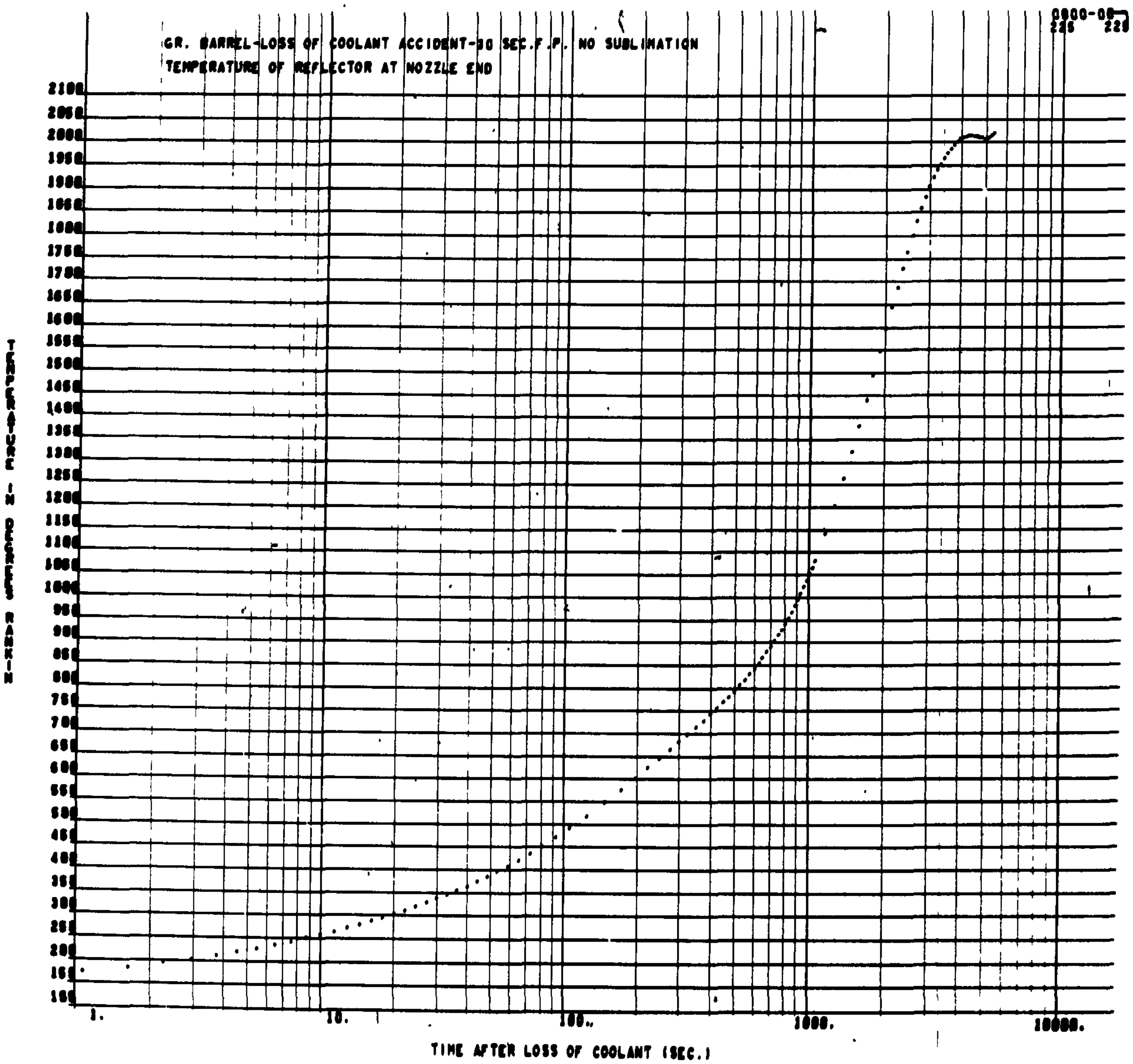

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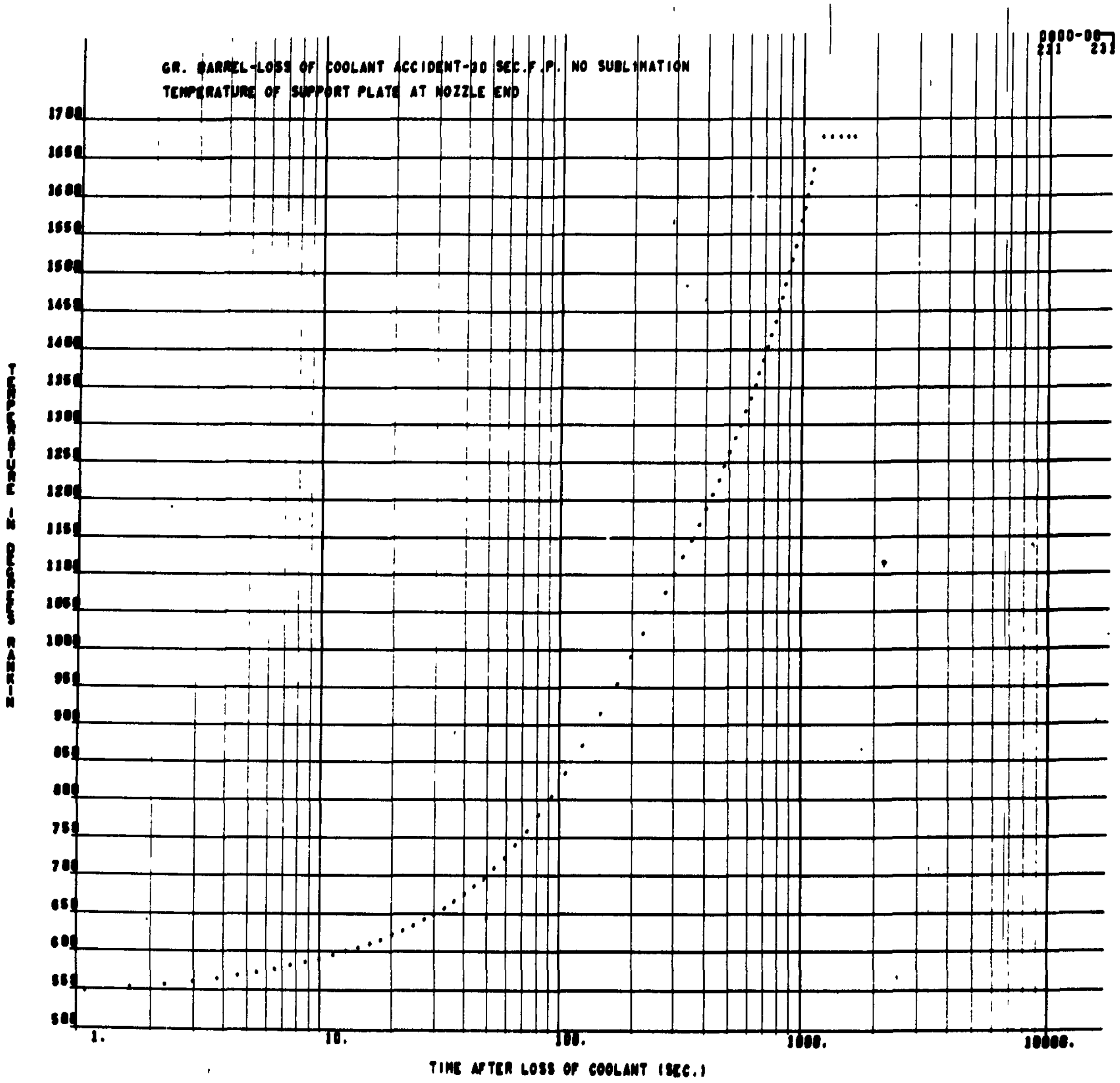

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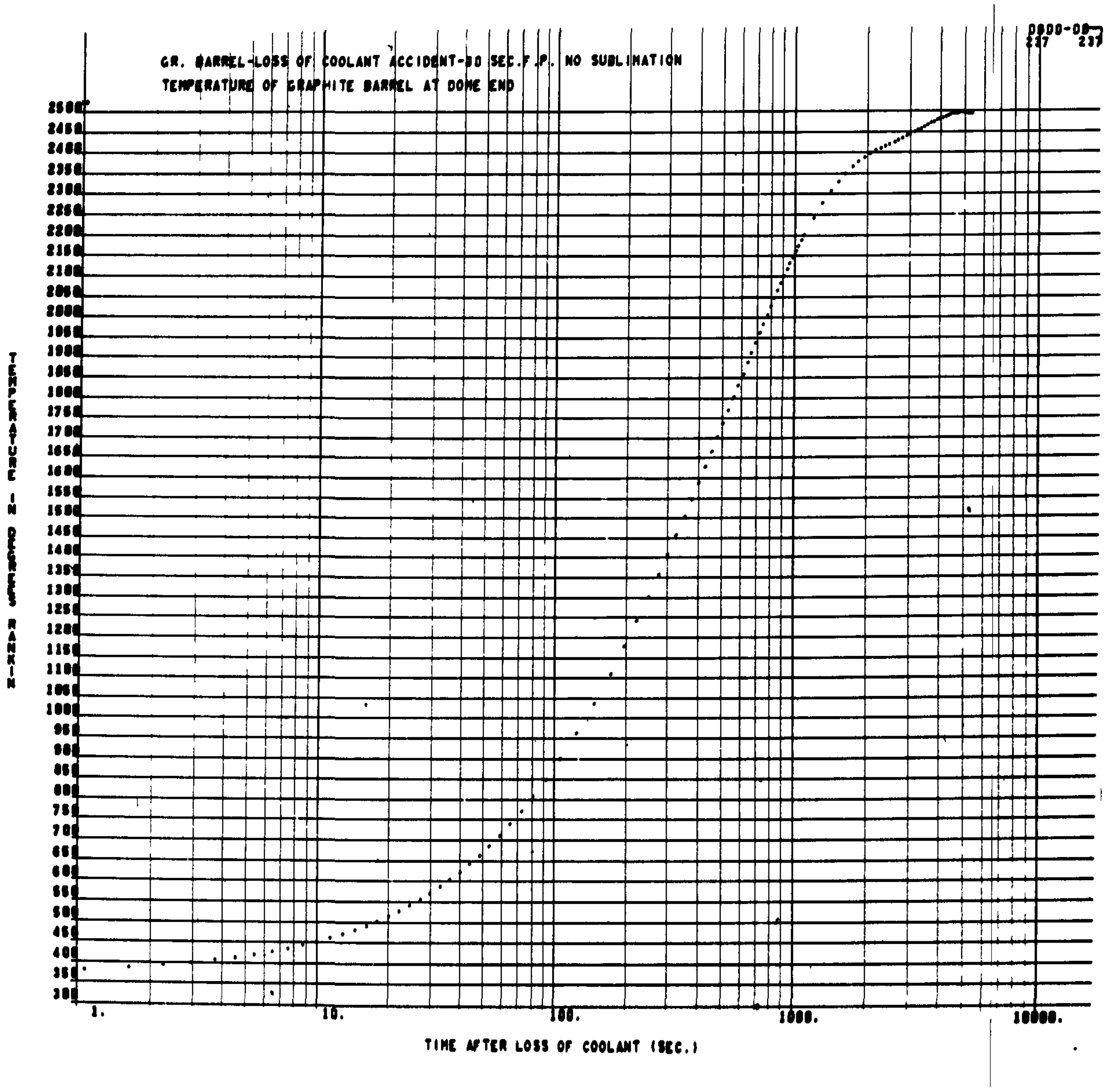

GR. BARREL-LOSS OF COOLANT ACCIDENT-30 SEC.F.P. NO SUBLIMATION
TEMPERATURE OF GRAPHITE BARREL AT DOME END

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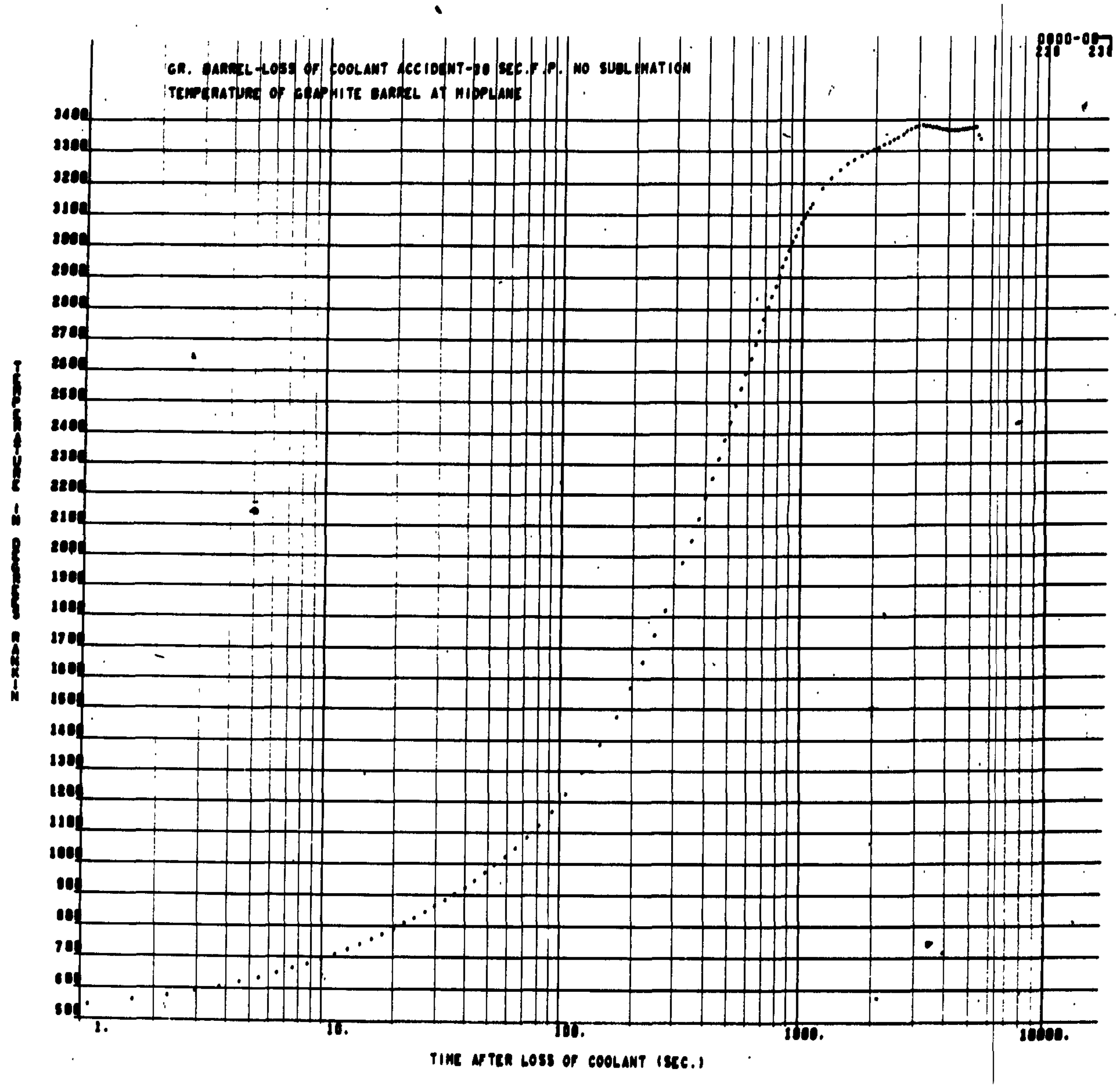

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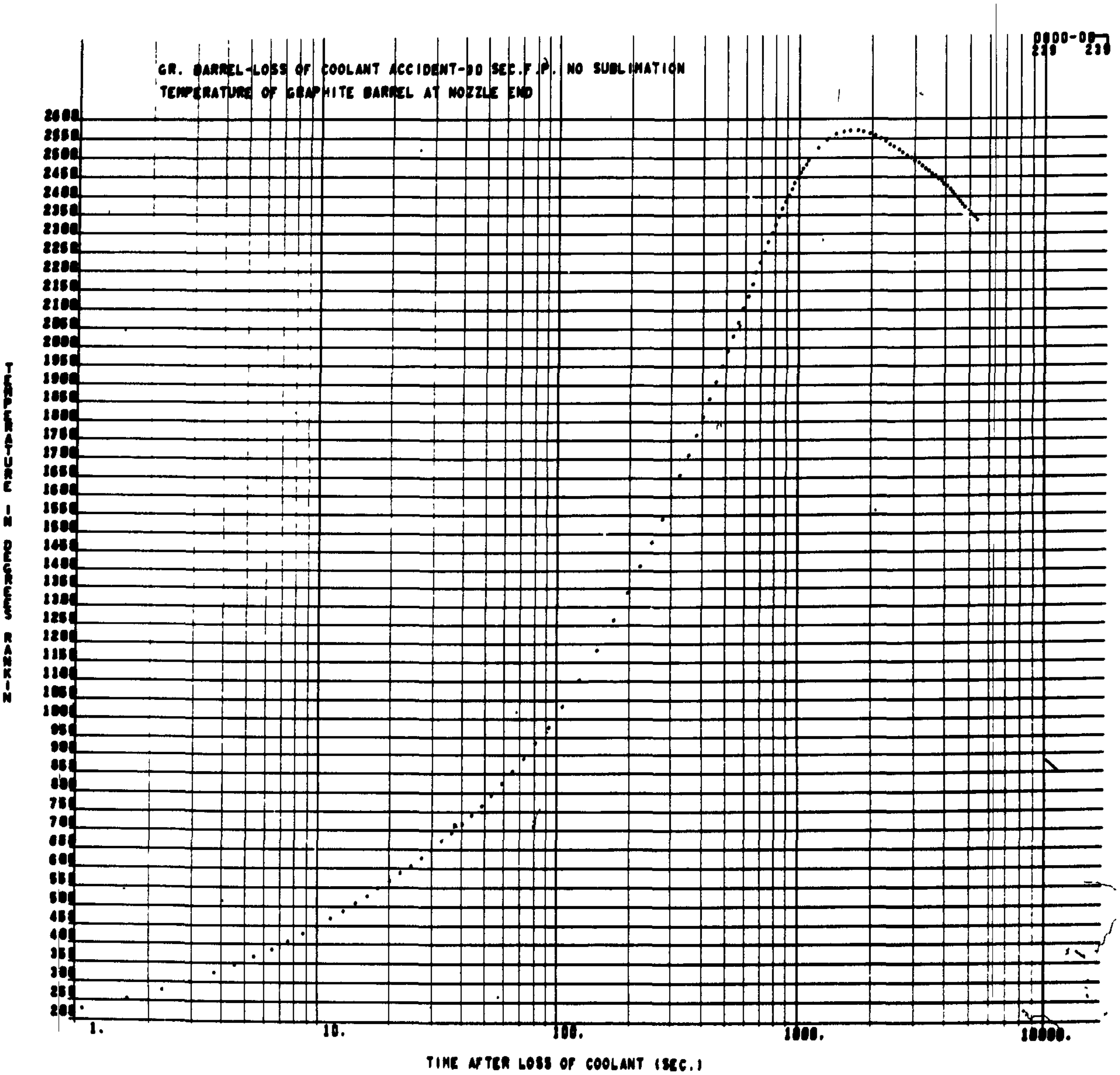

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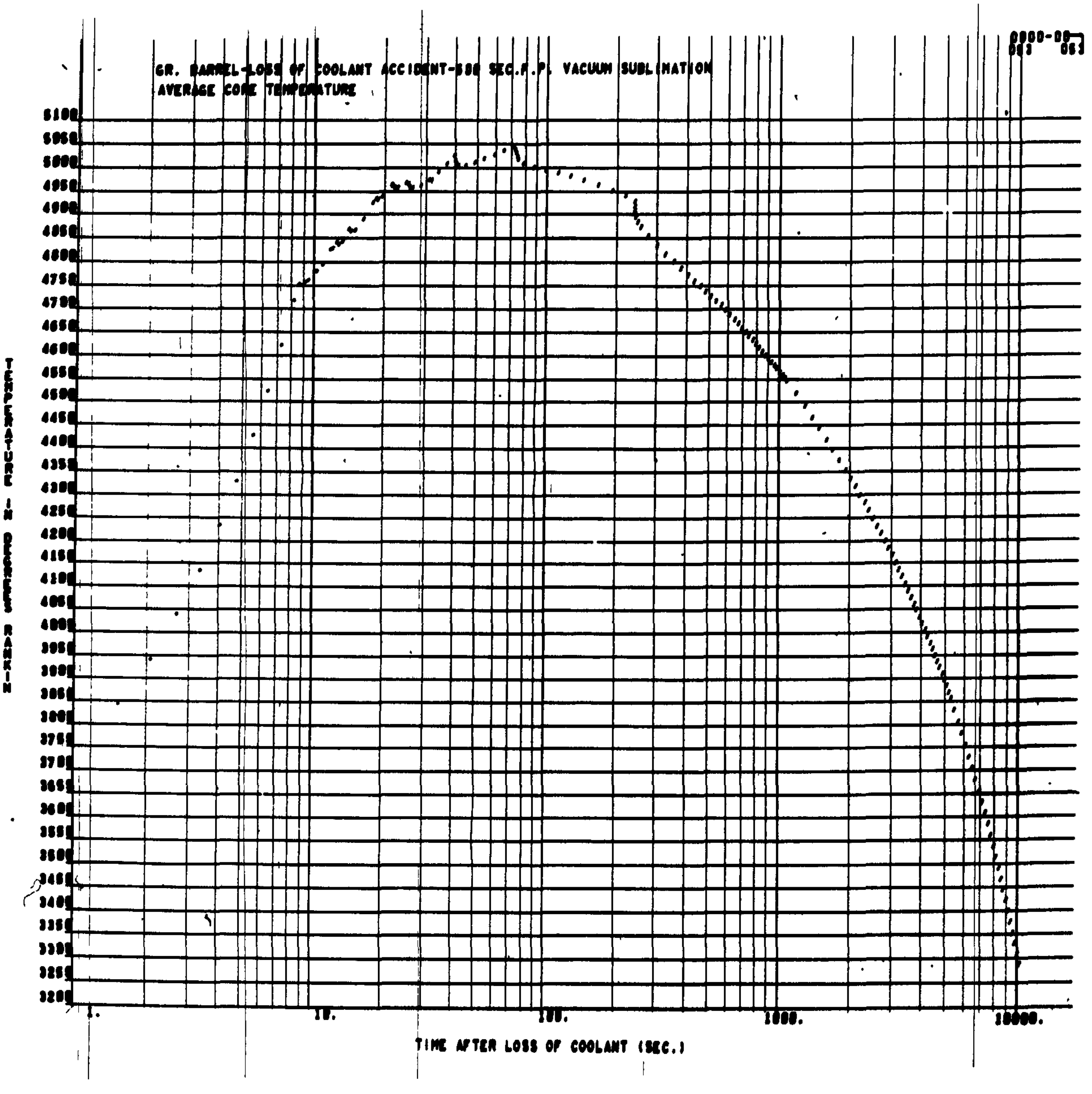

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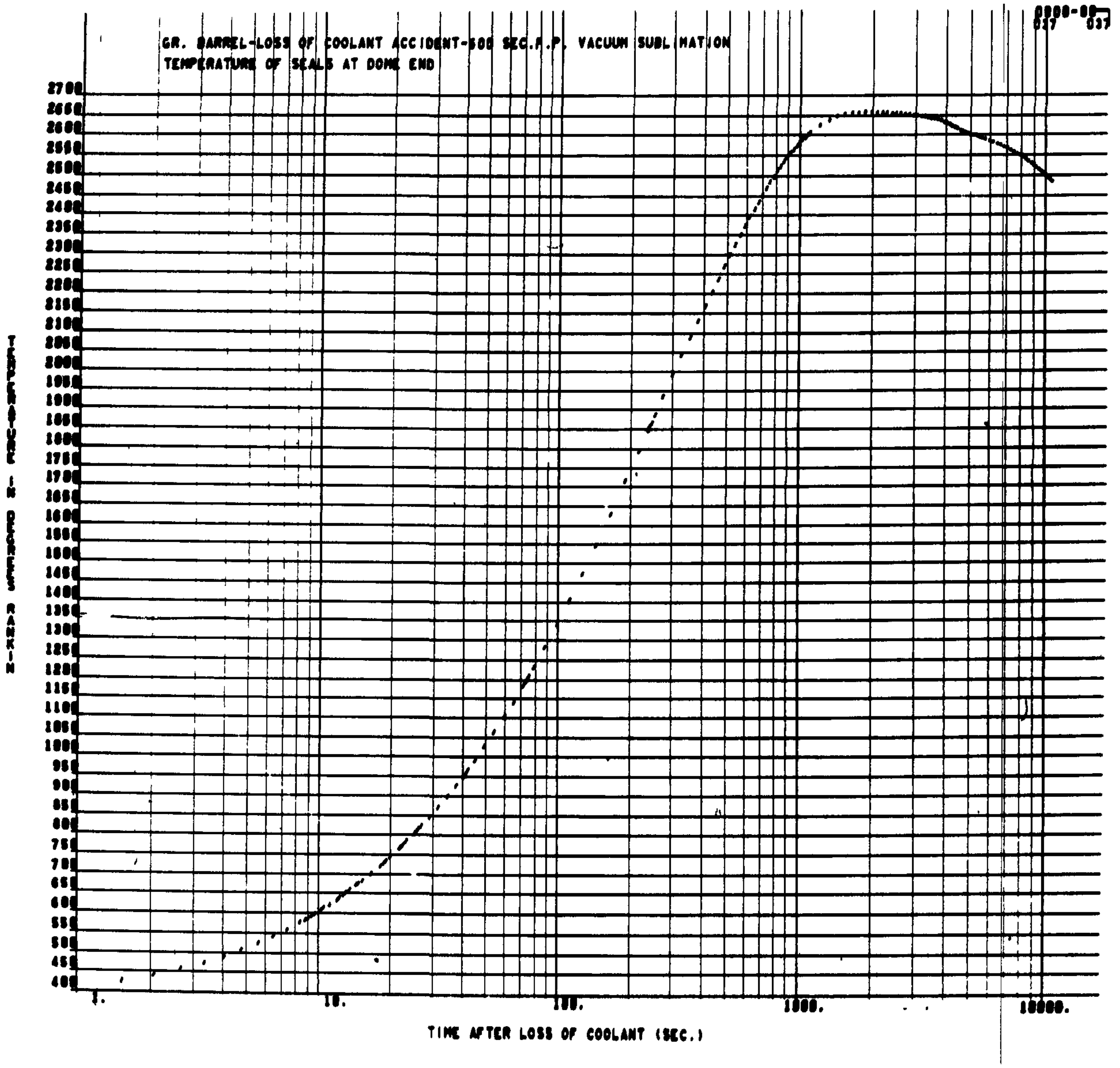

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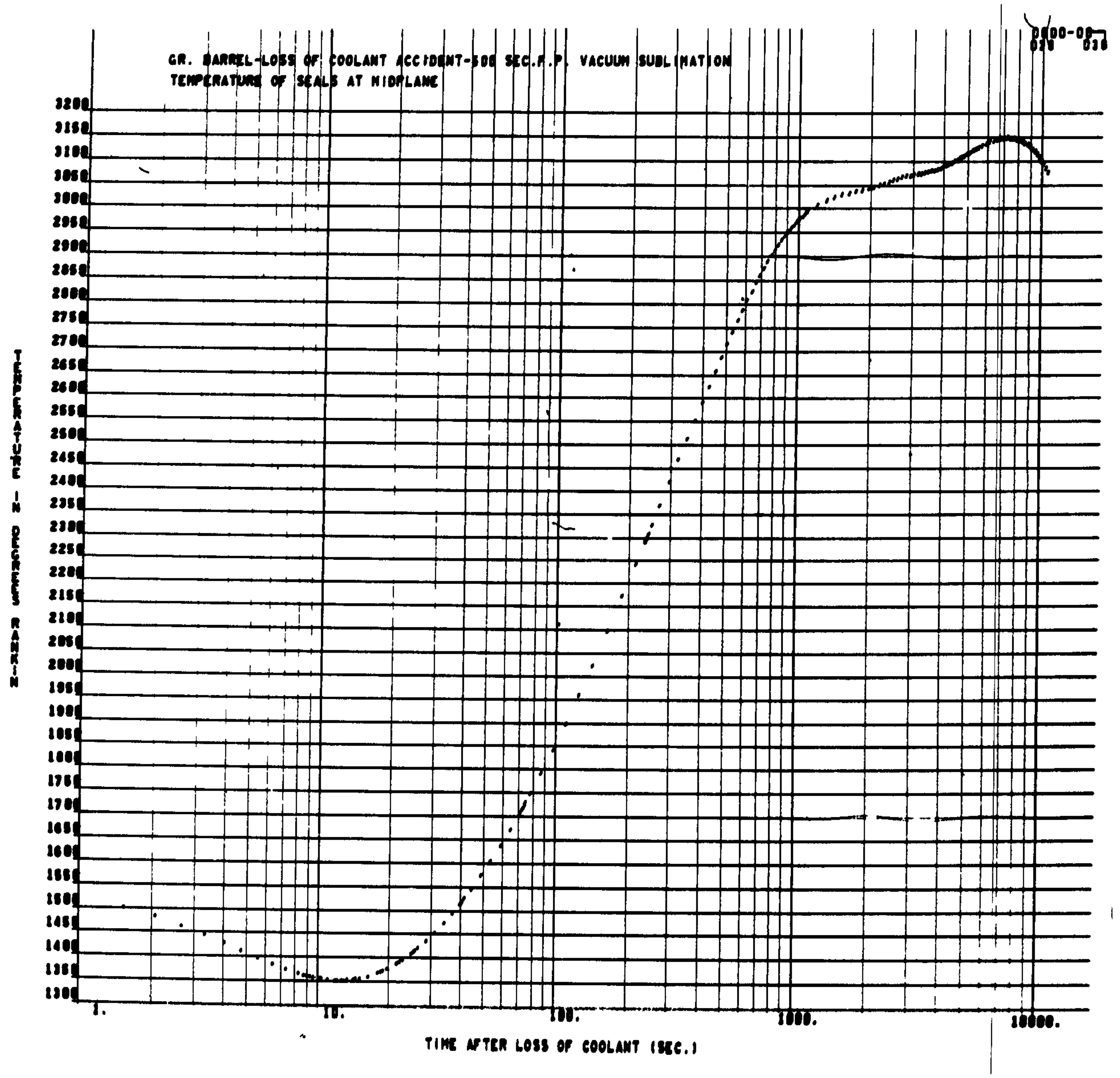

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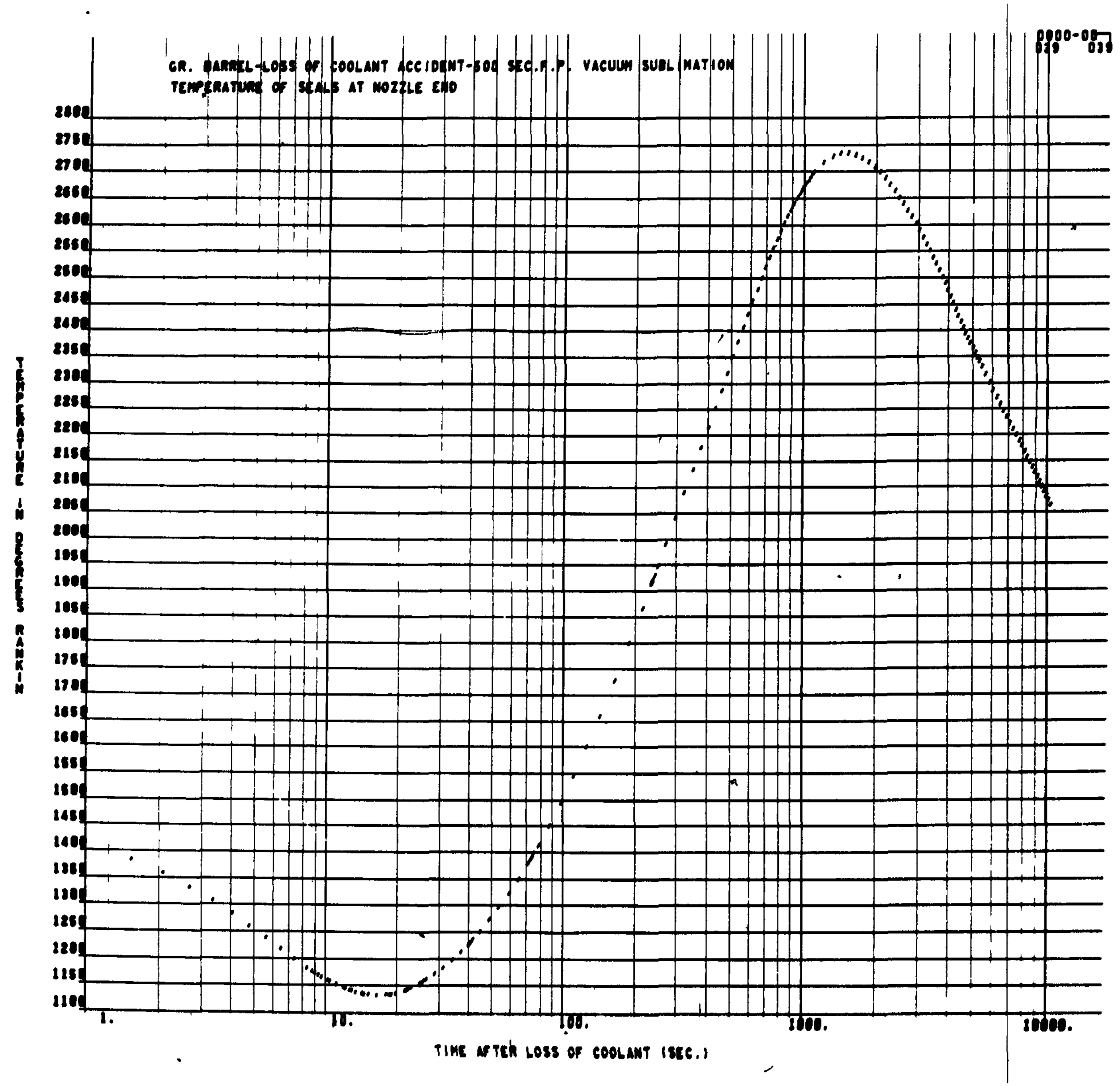

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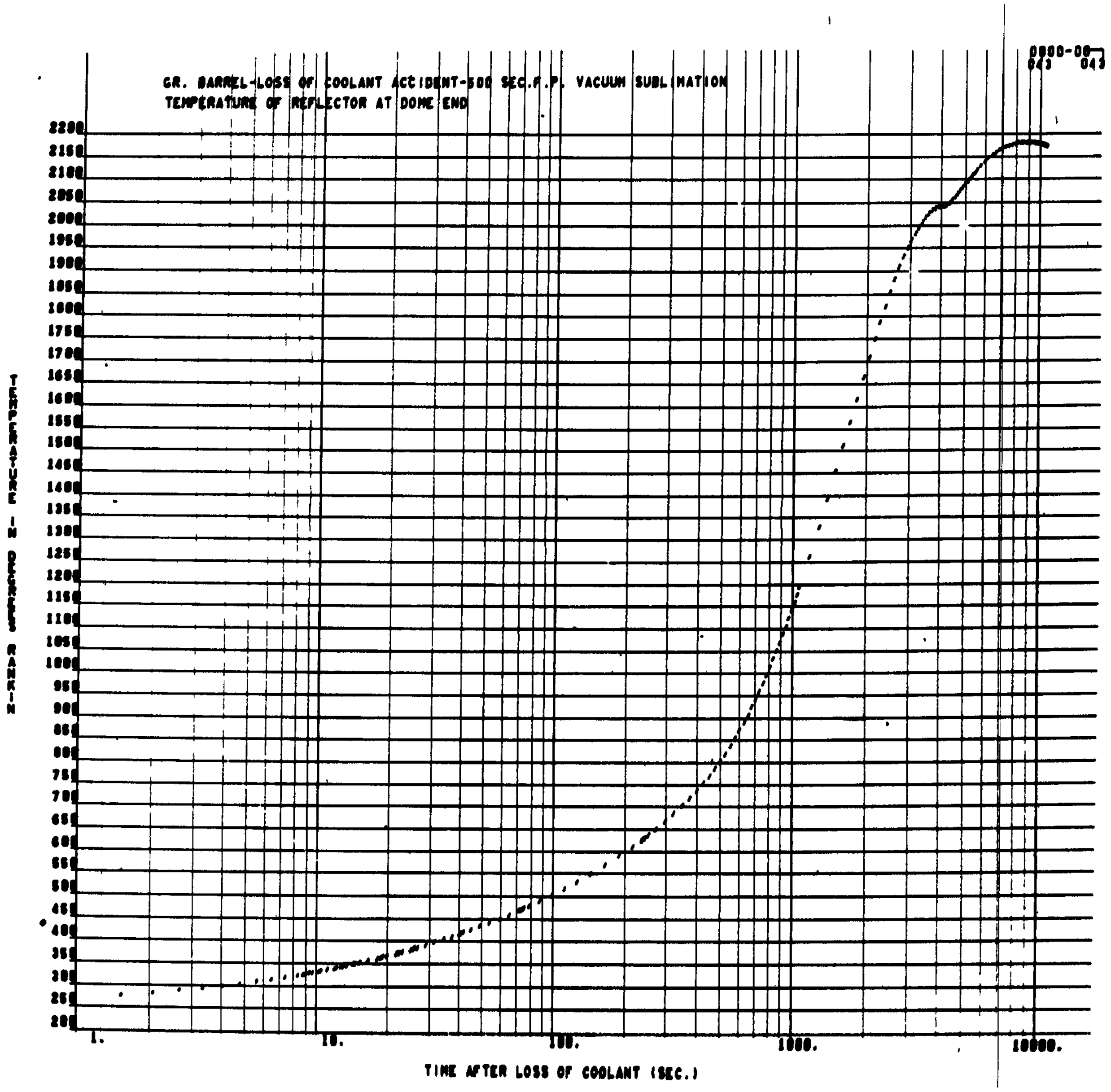

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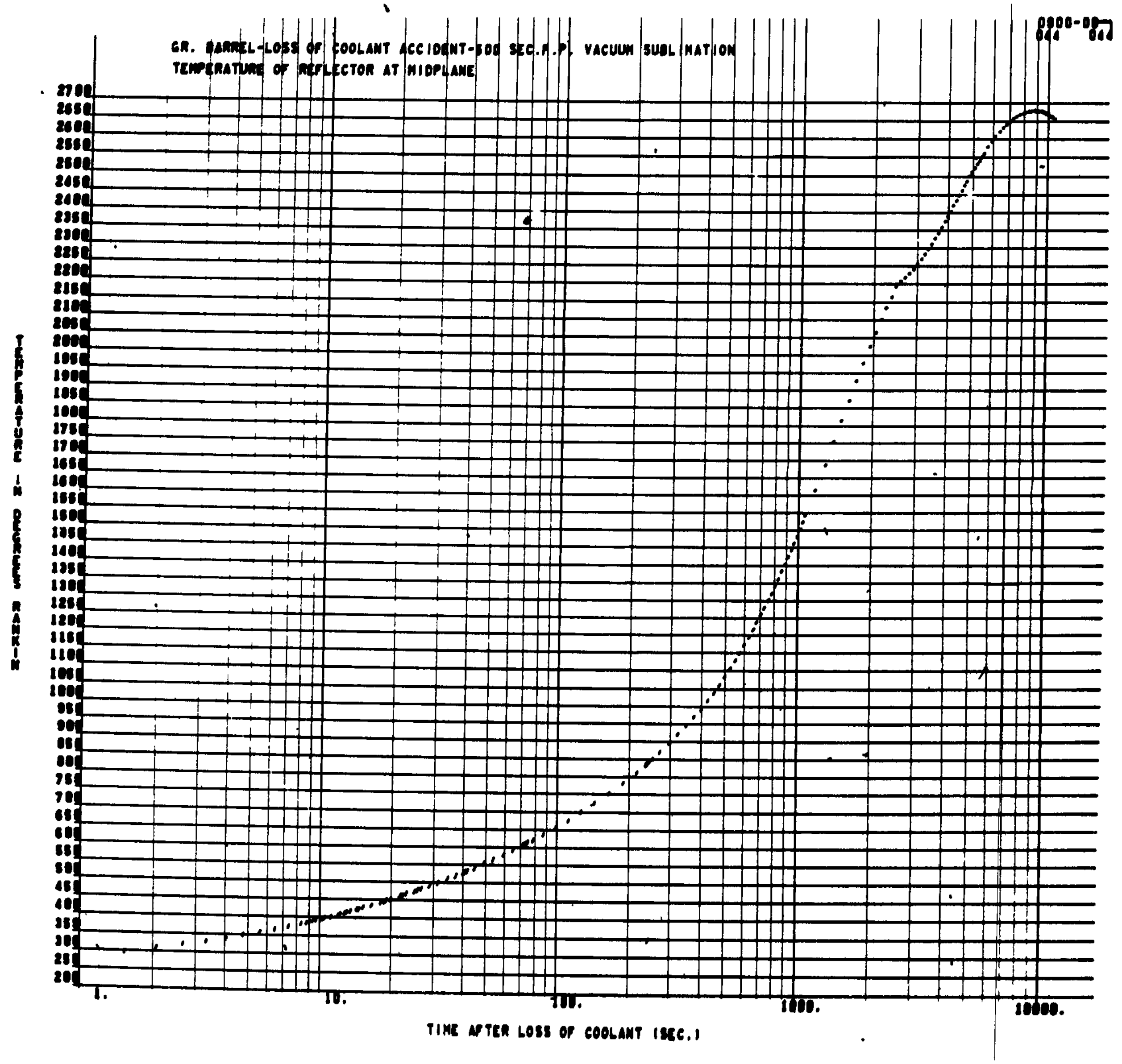

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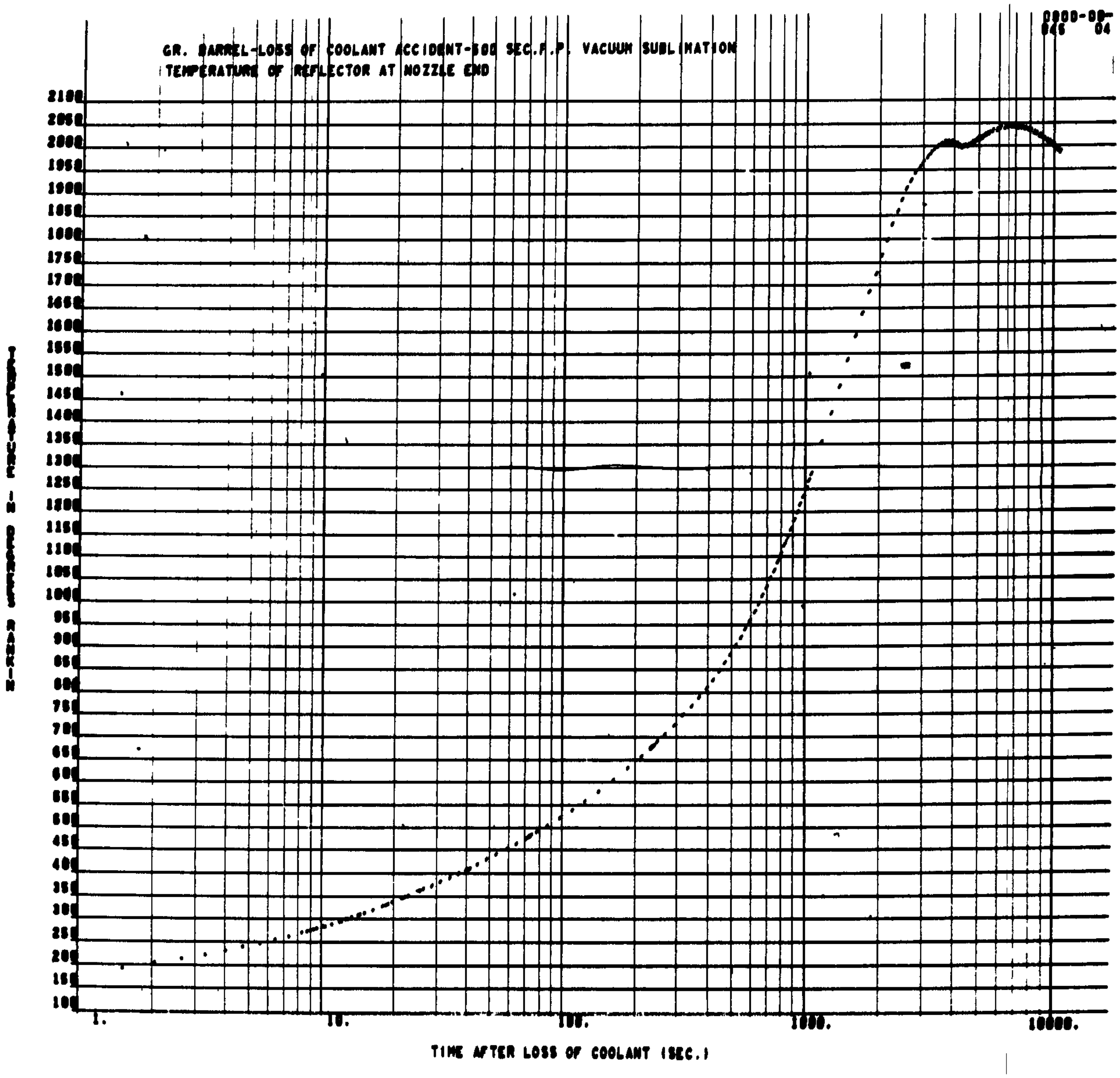

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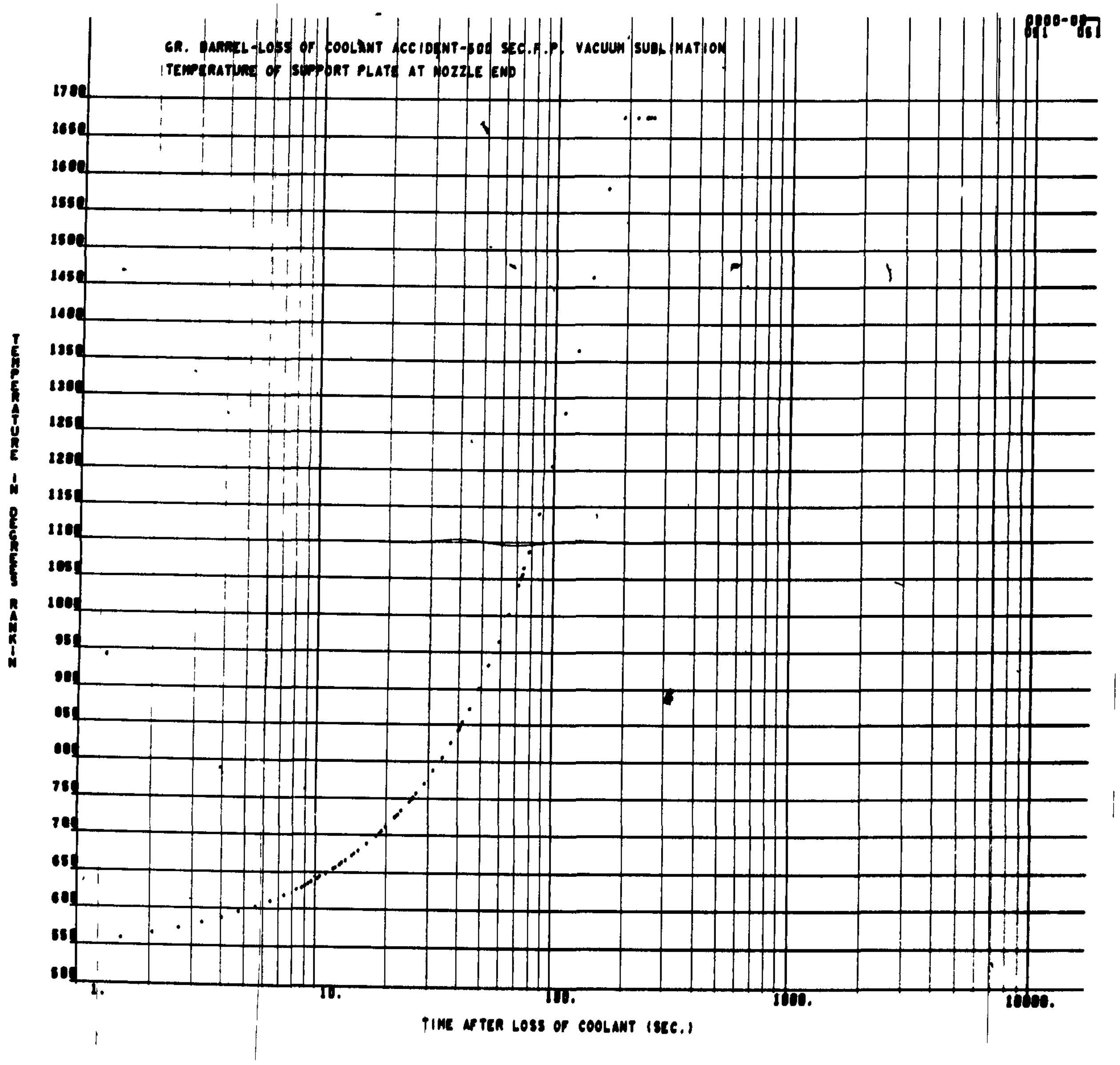

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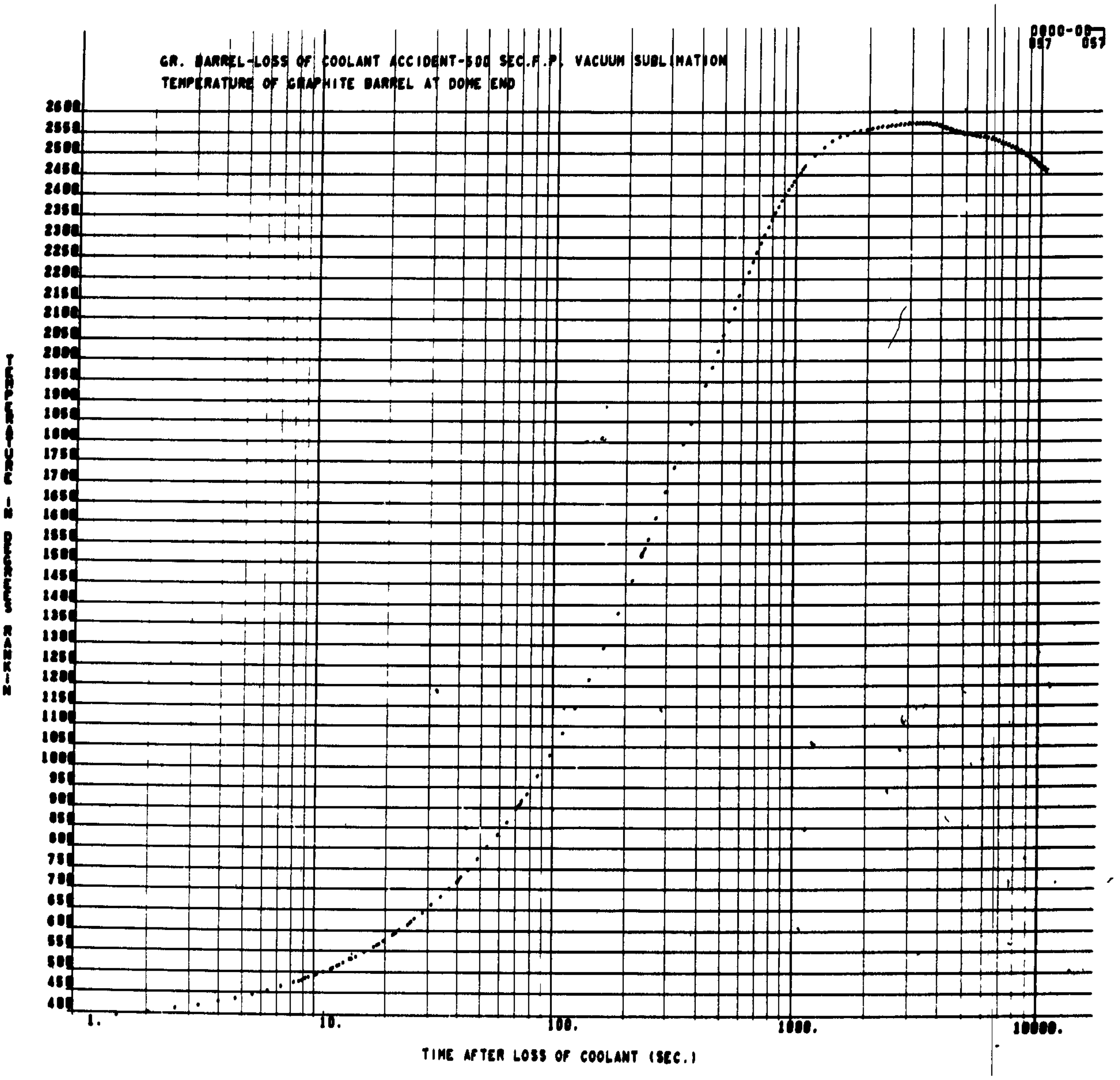

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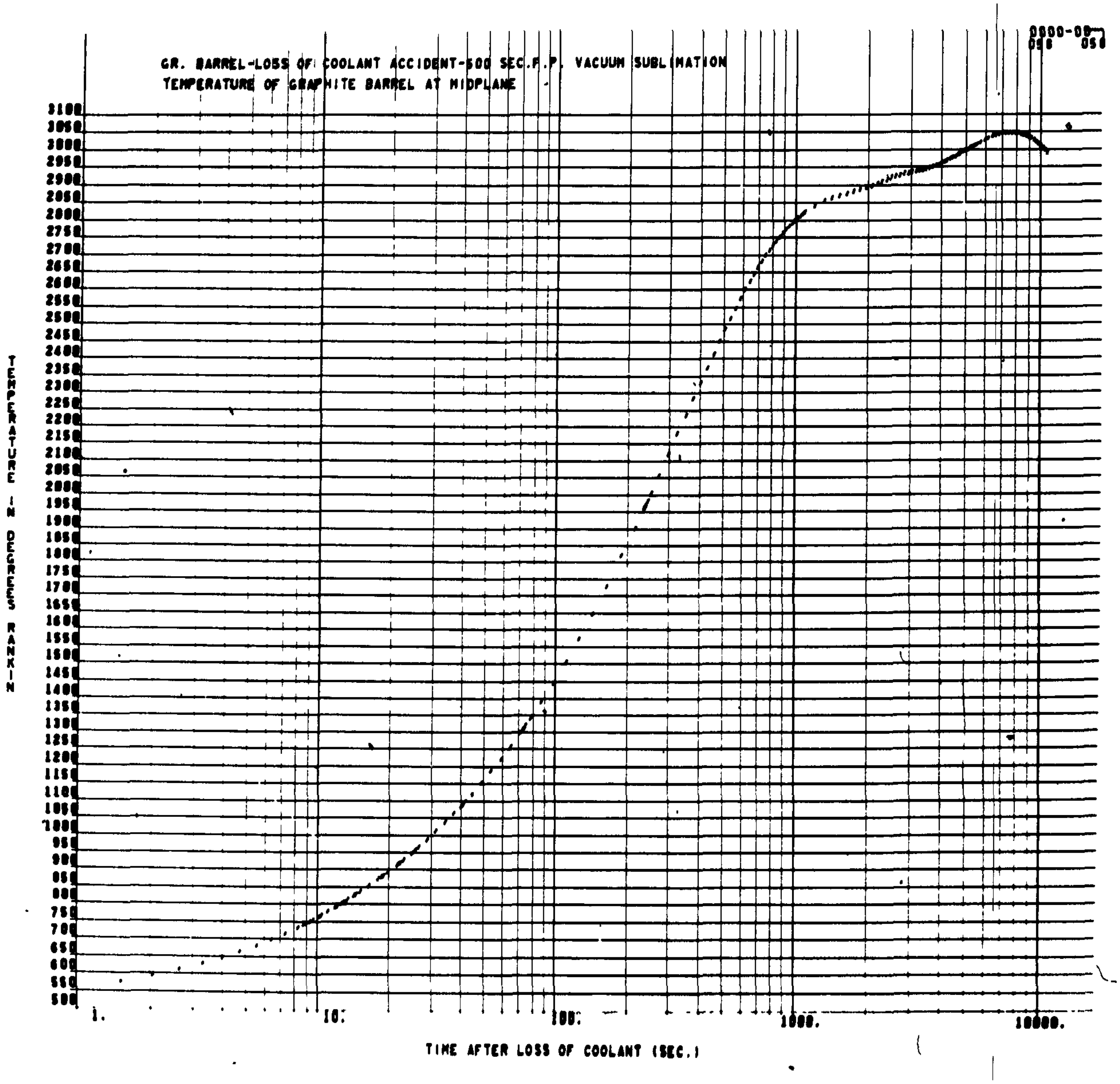

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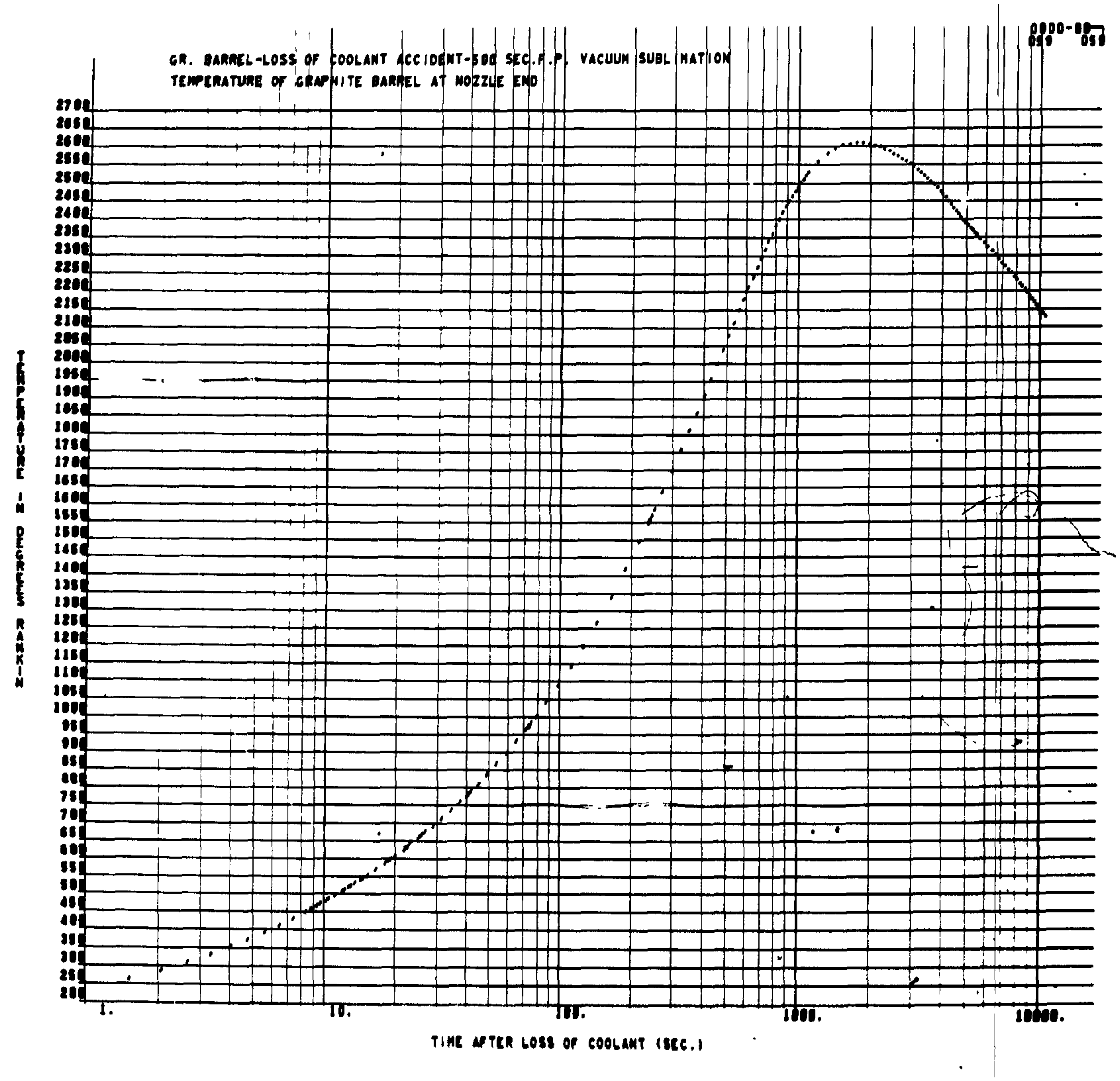

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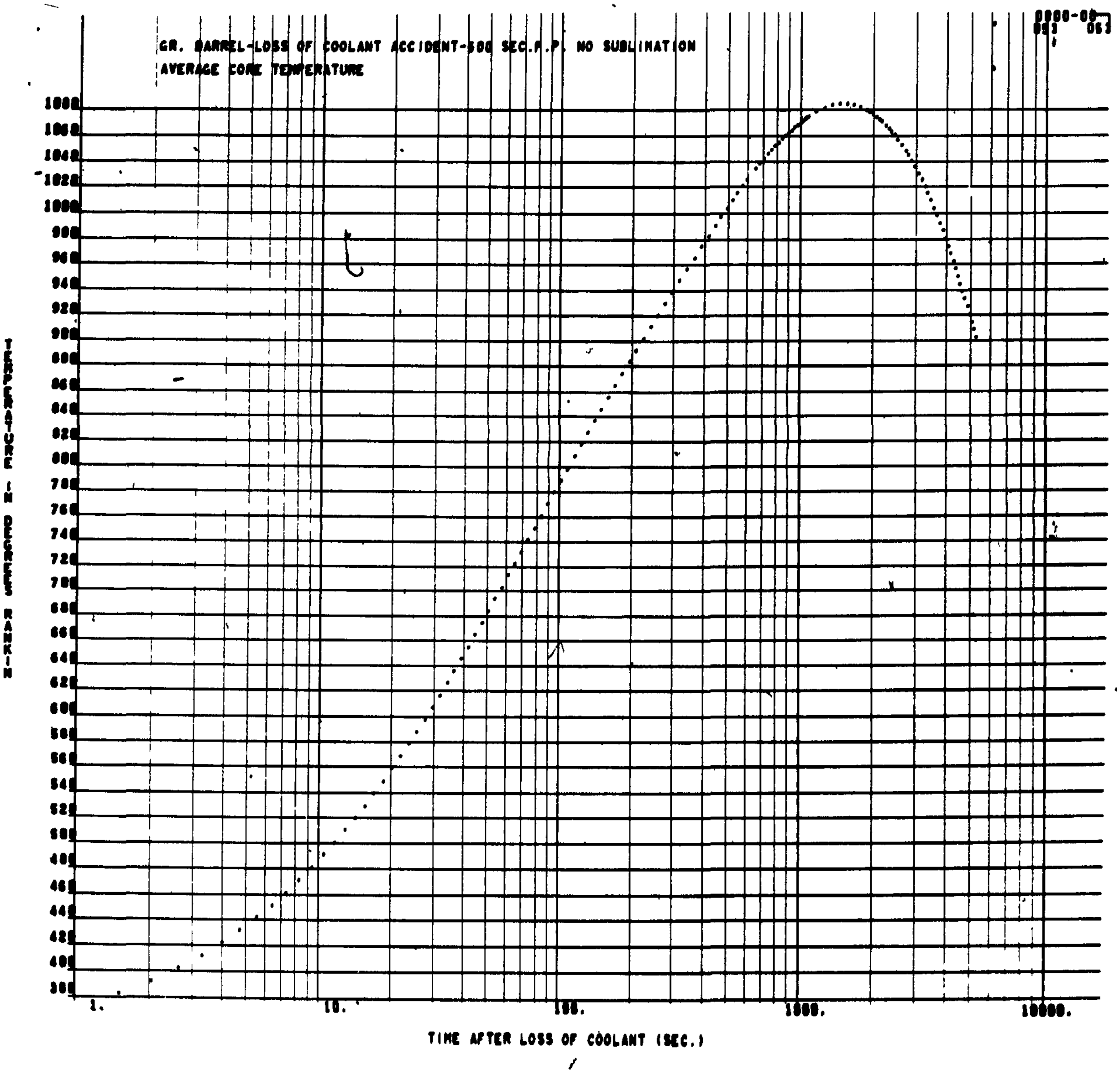

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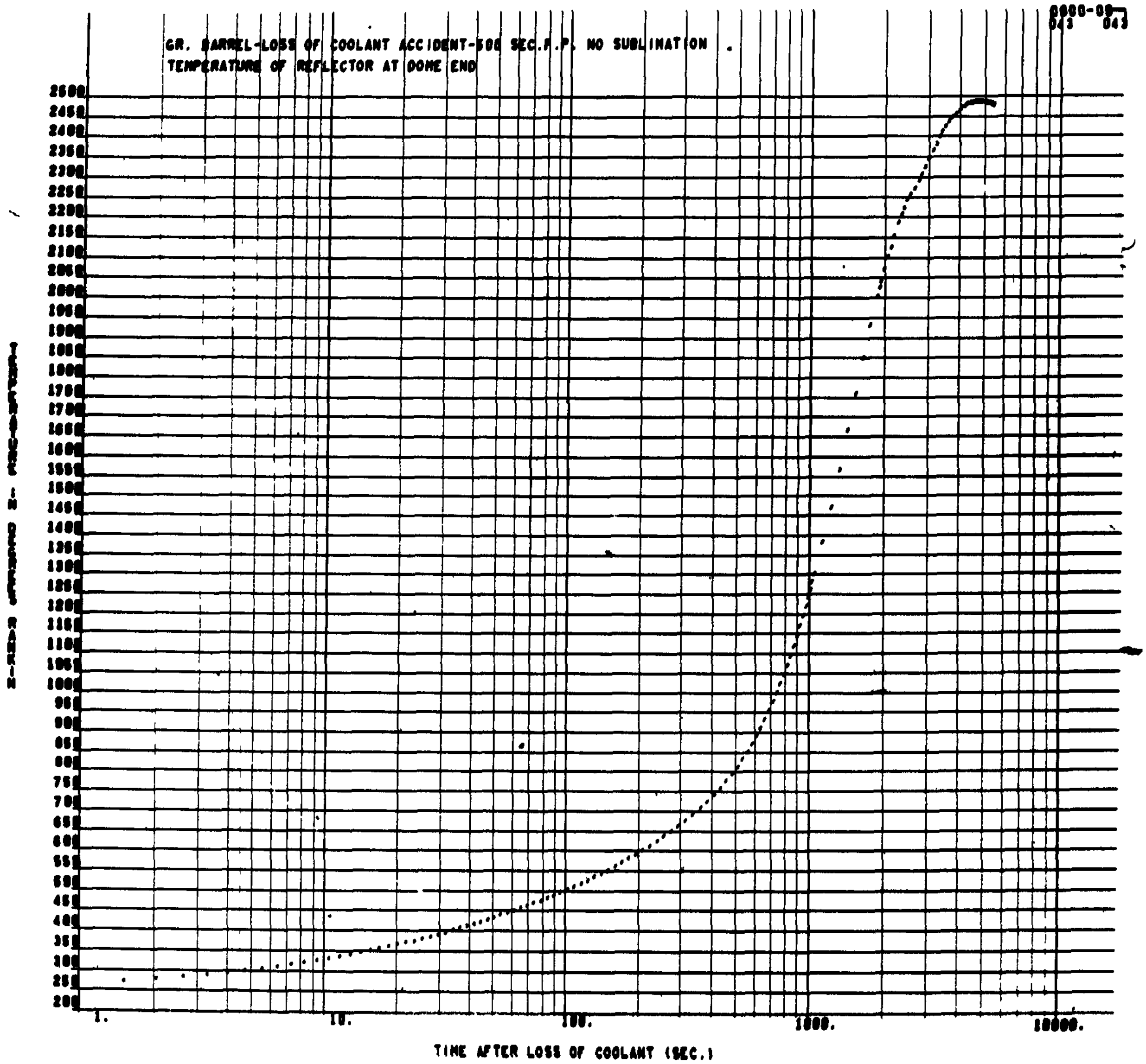
Astronuclear Laboratory
WANL-TME-1431



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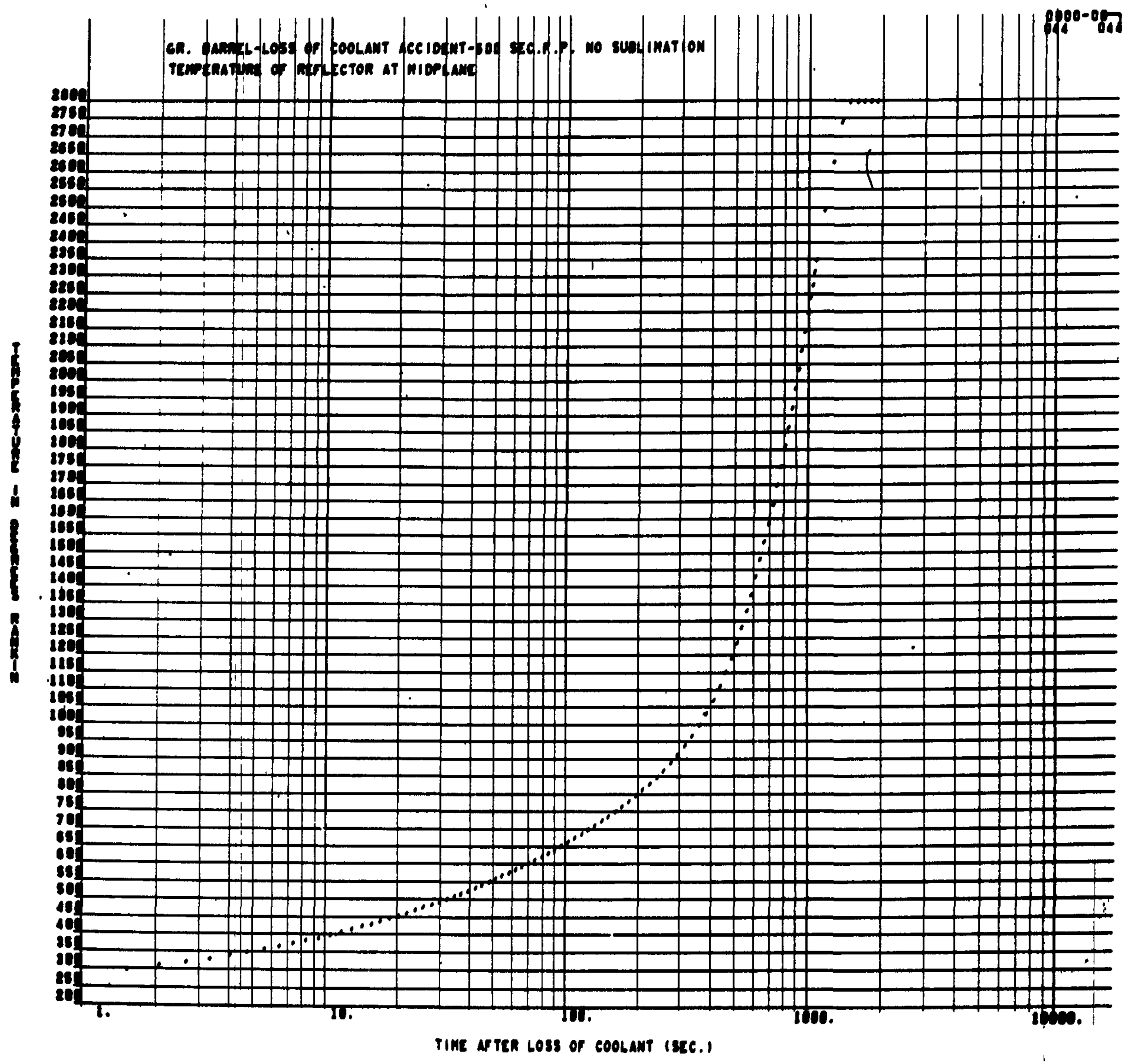

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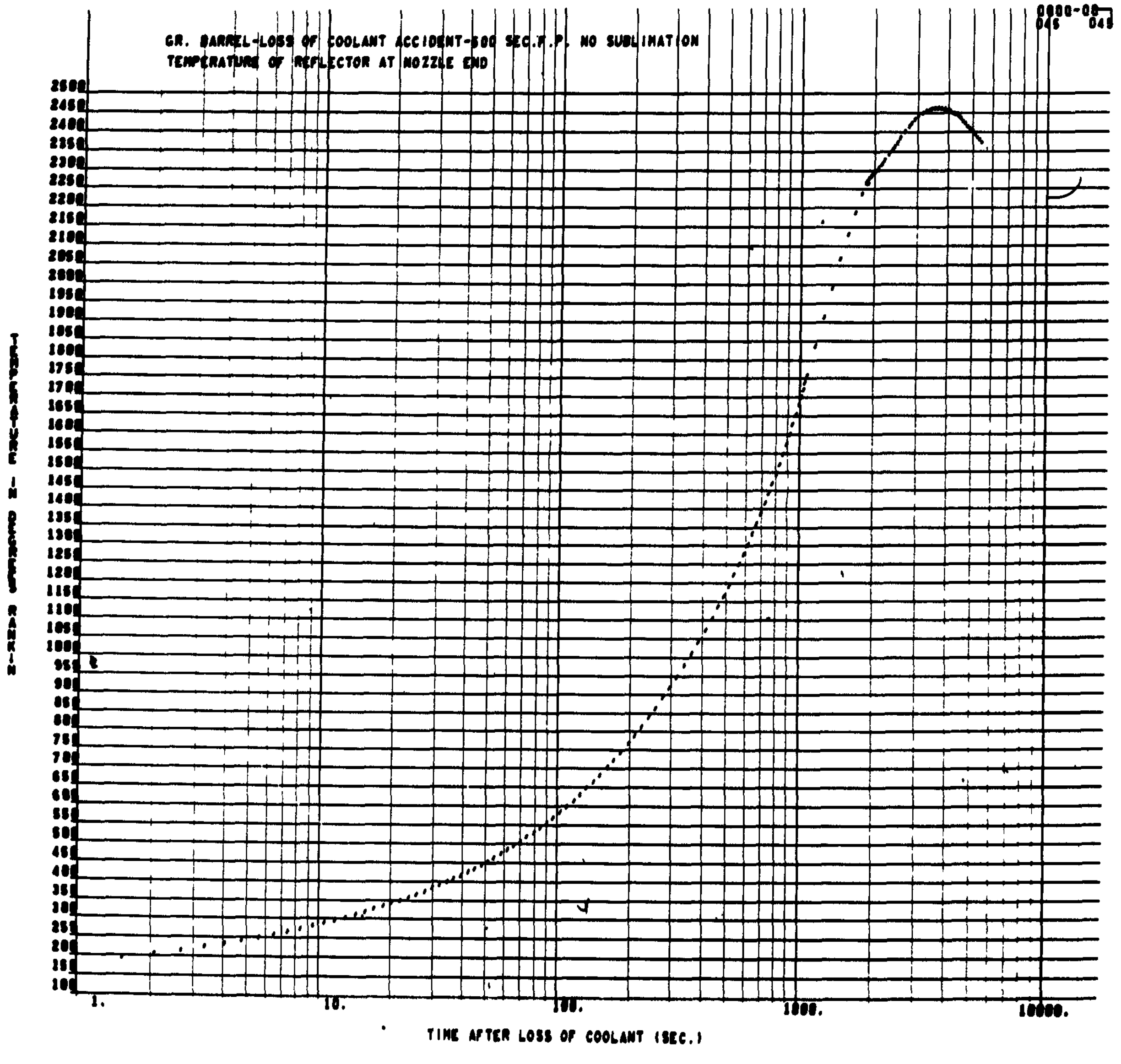

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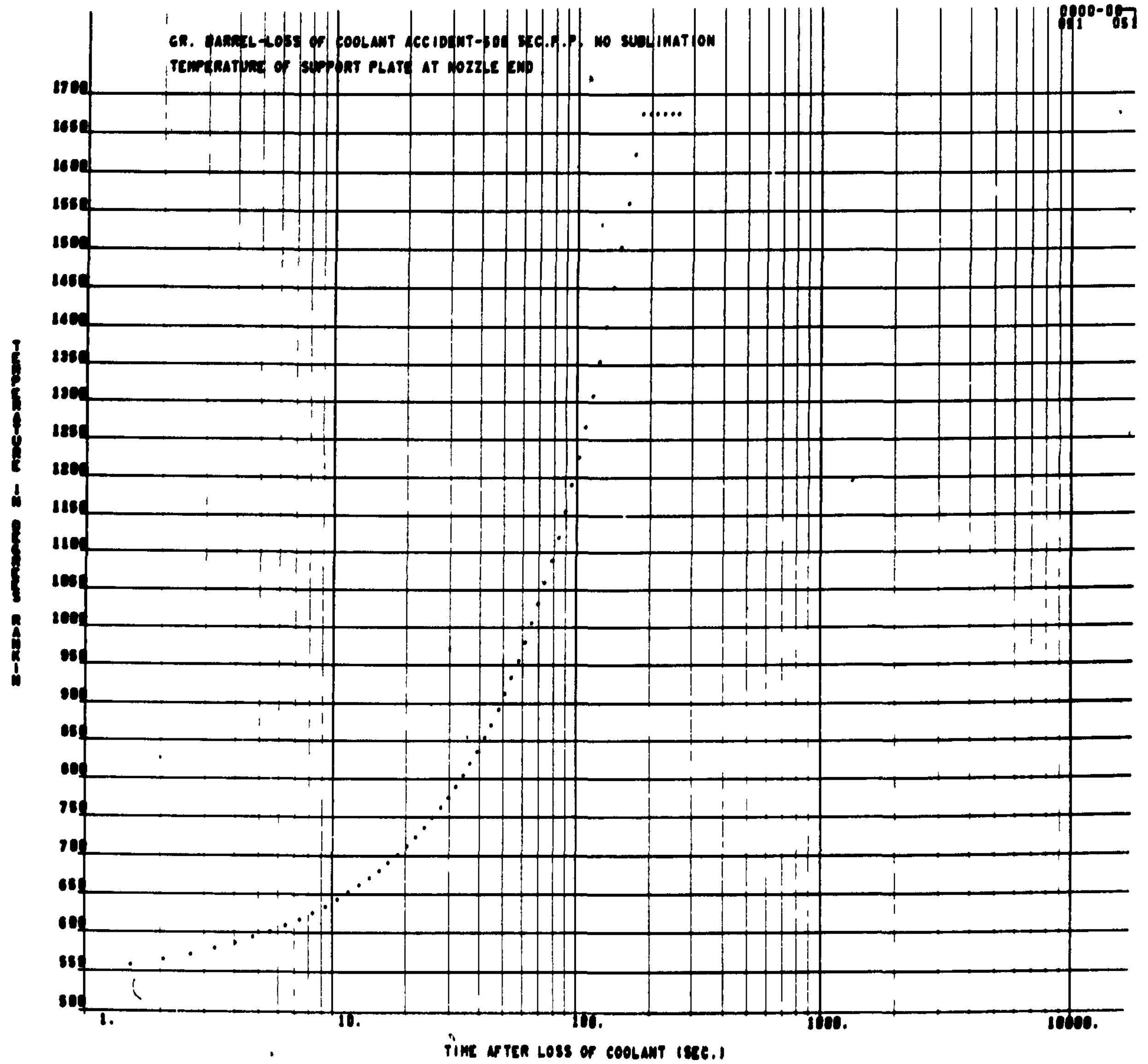

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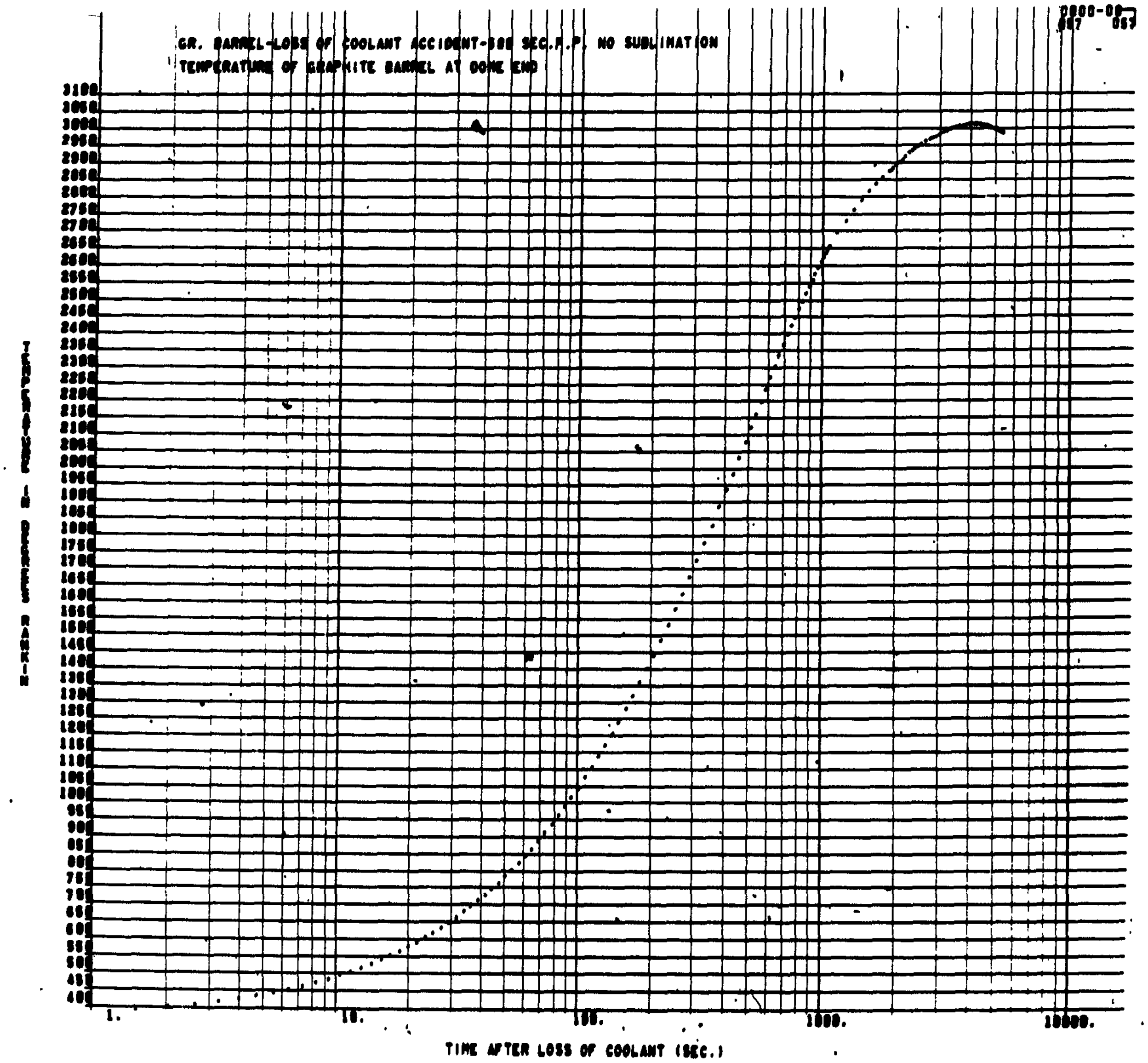

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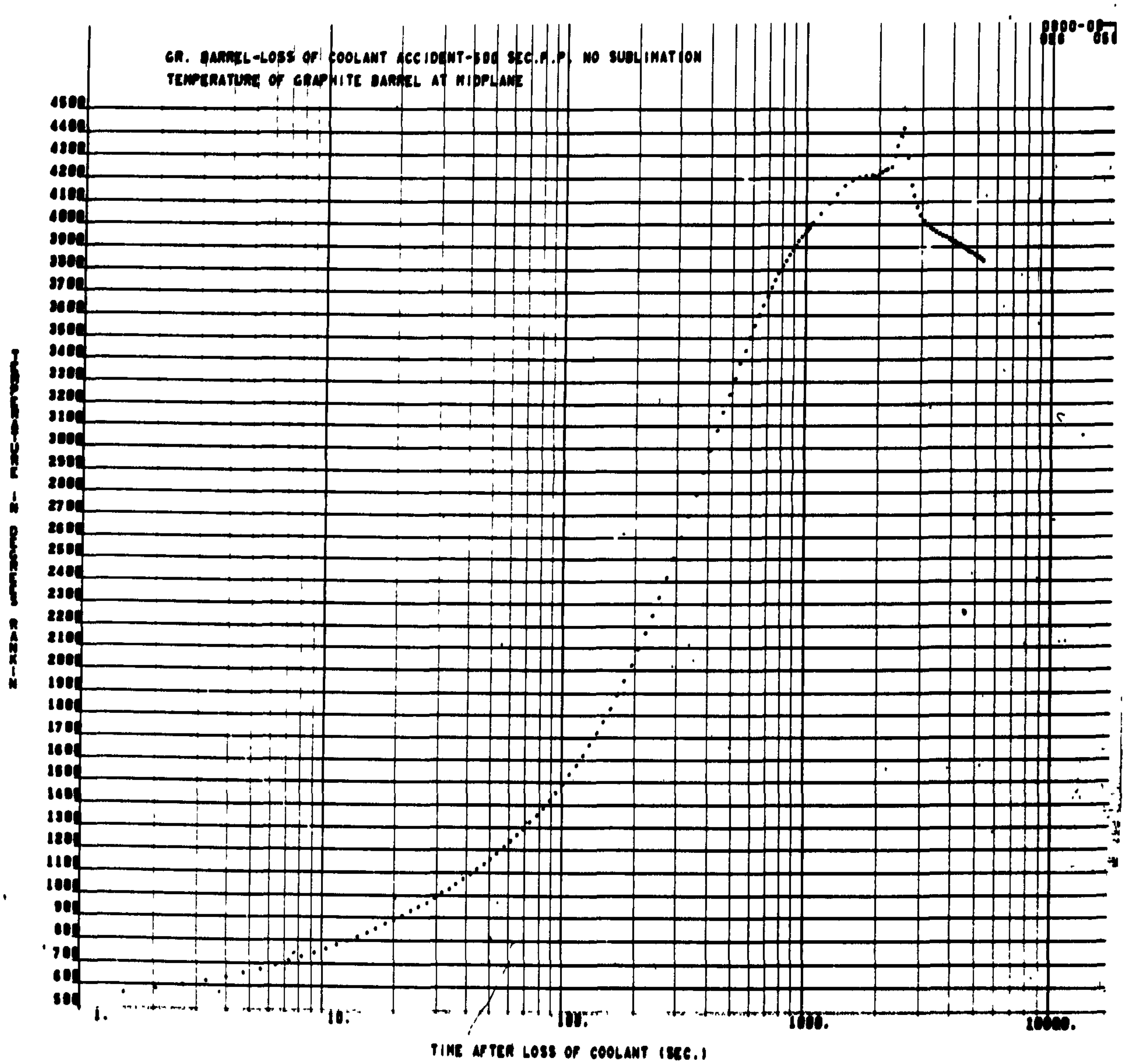

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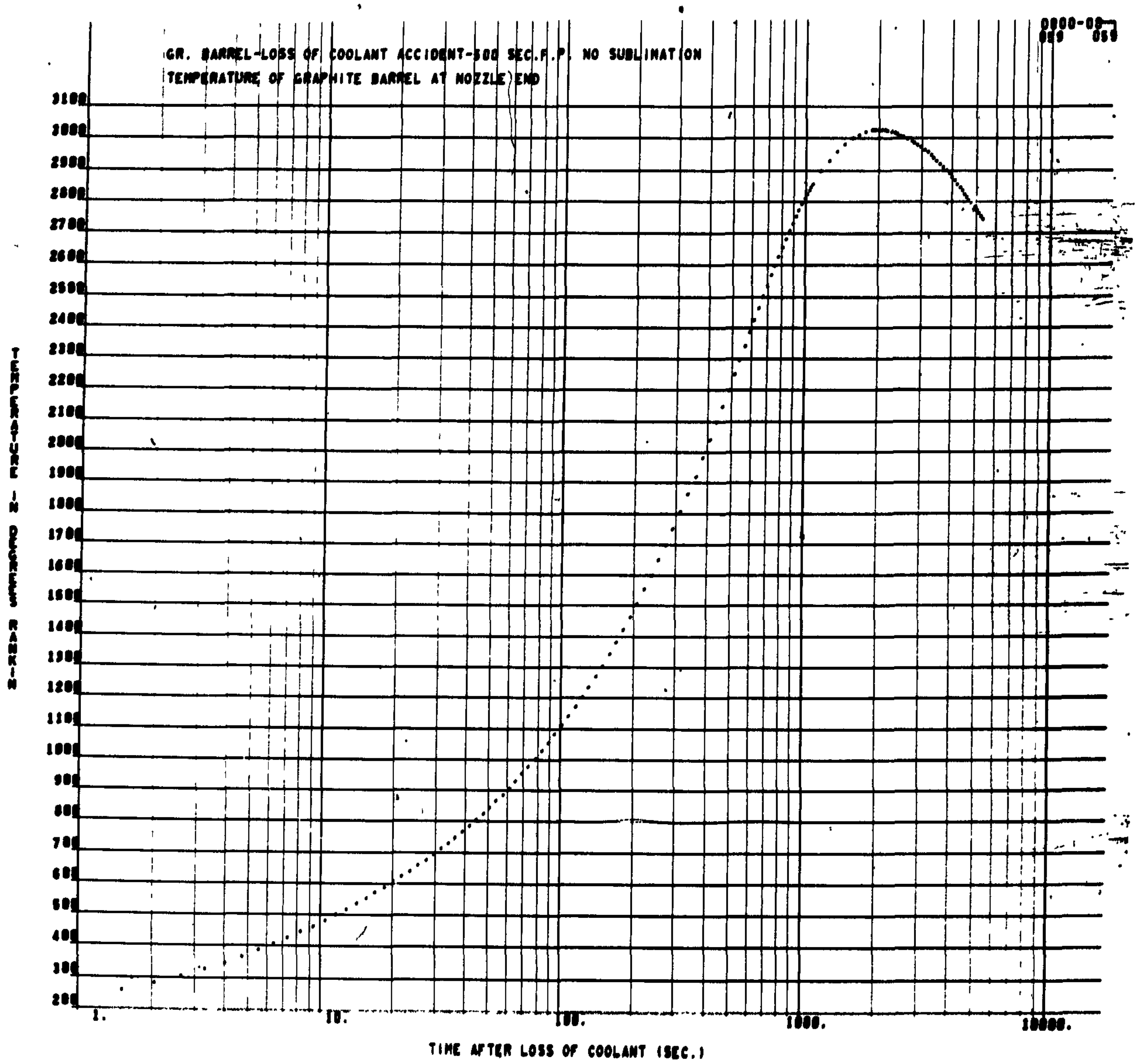

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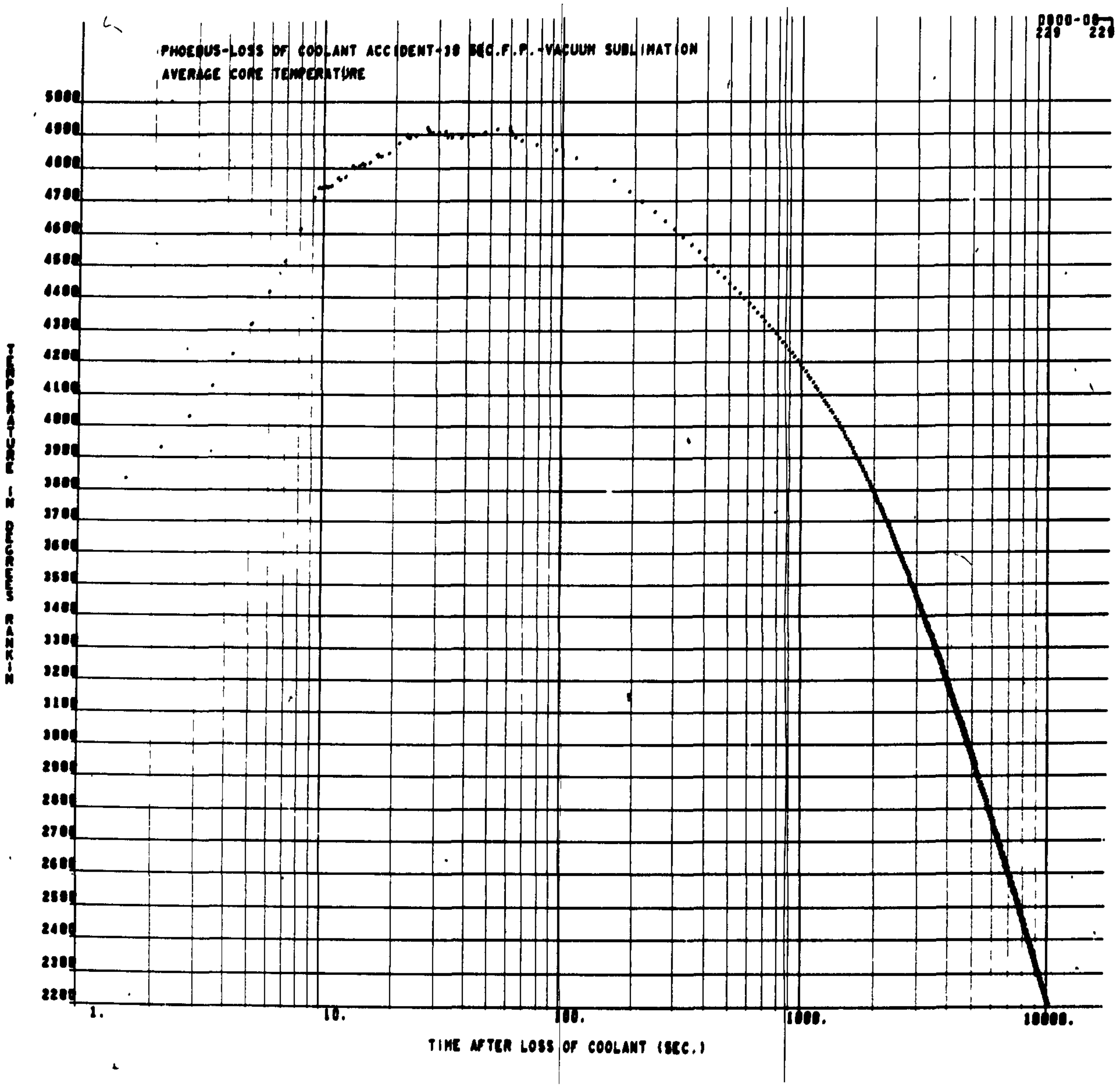

PHOEBUS-LOSS OF COOLANT ACCIDENT-30 SEC.F.P.-VACUUM SUBLIMATION
AVERAGE CORE TEMPERATURE

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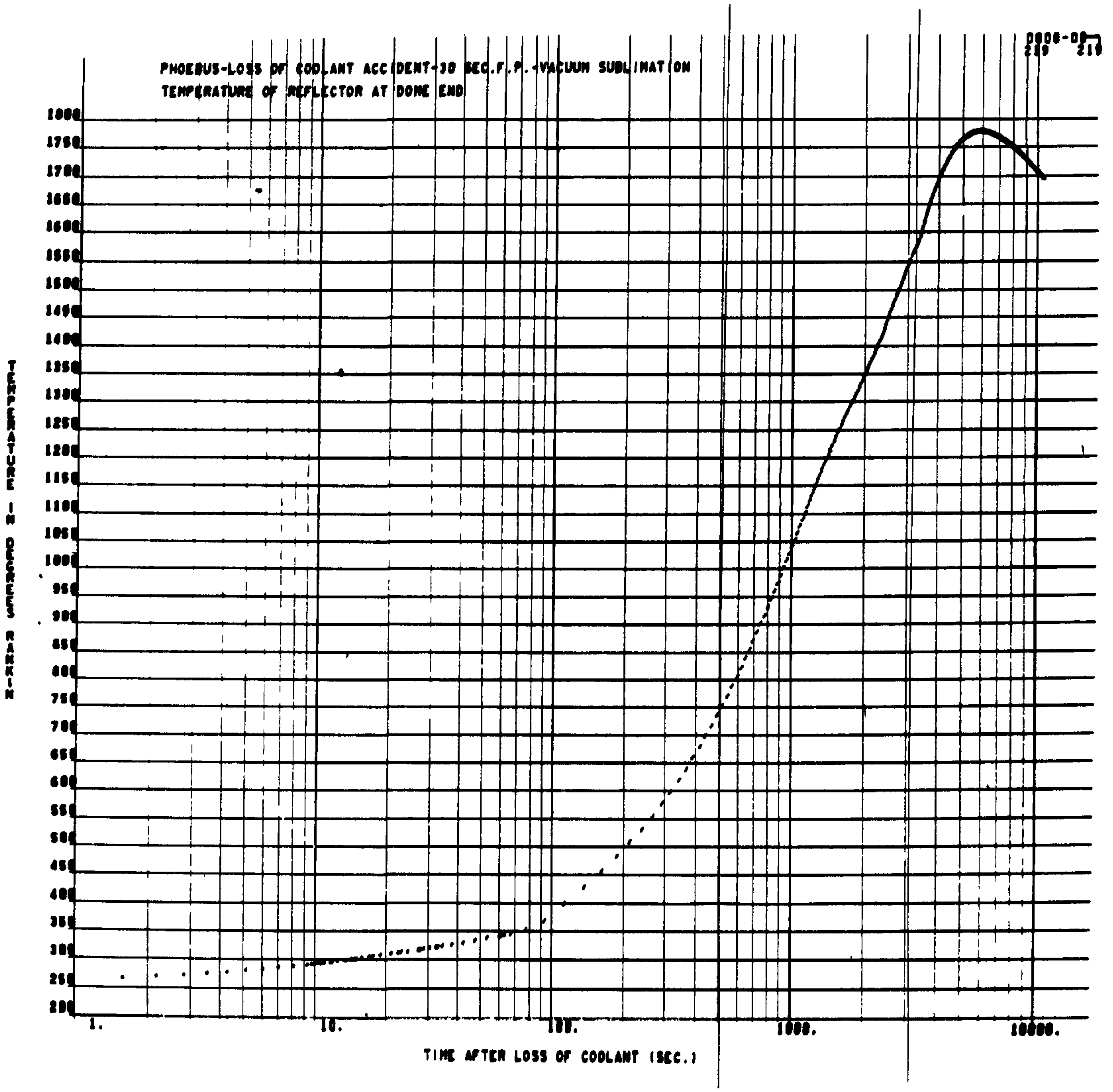

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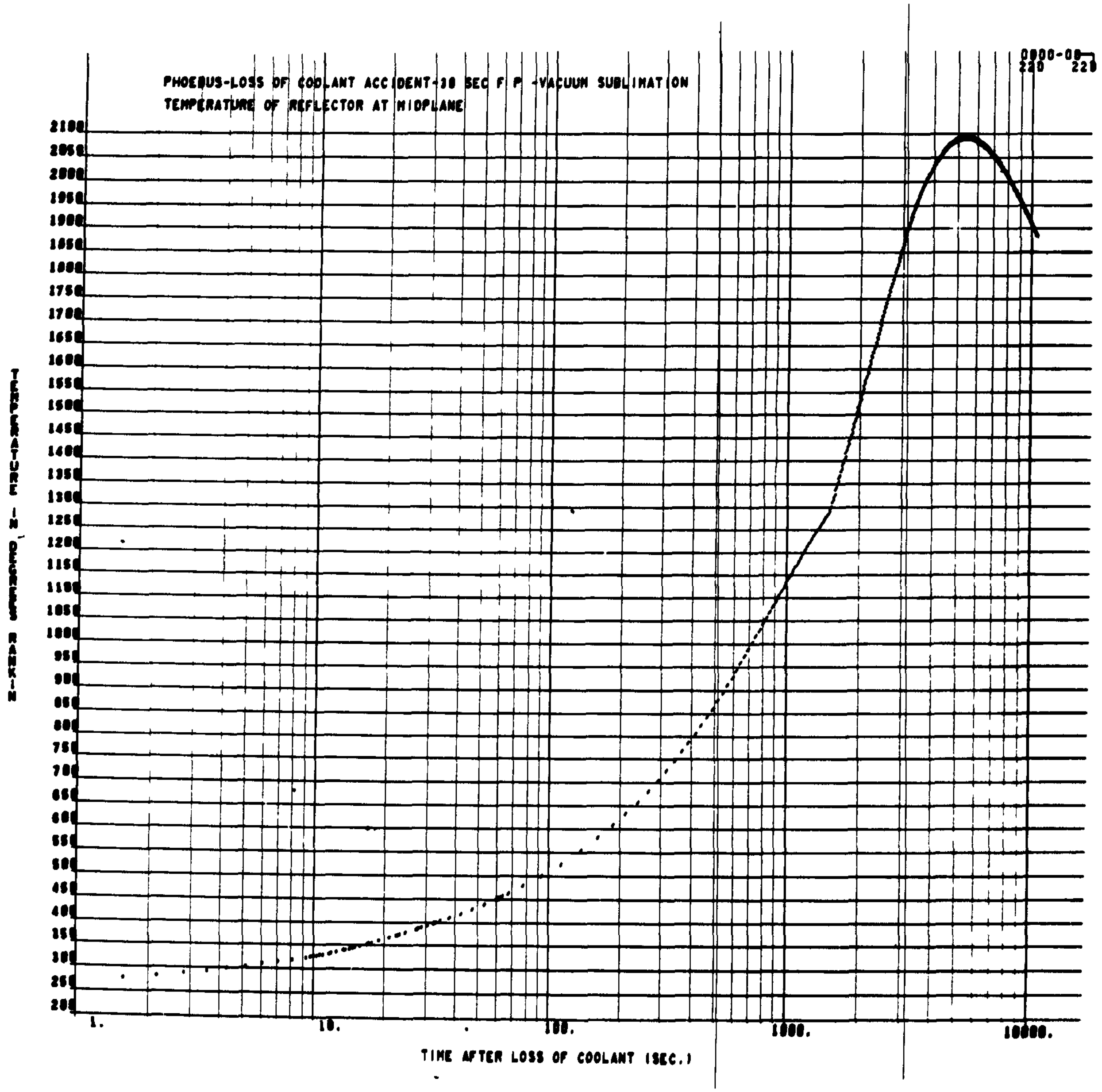

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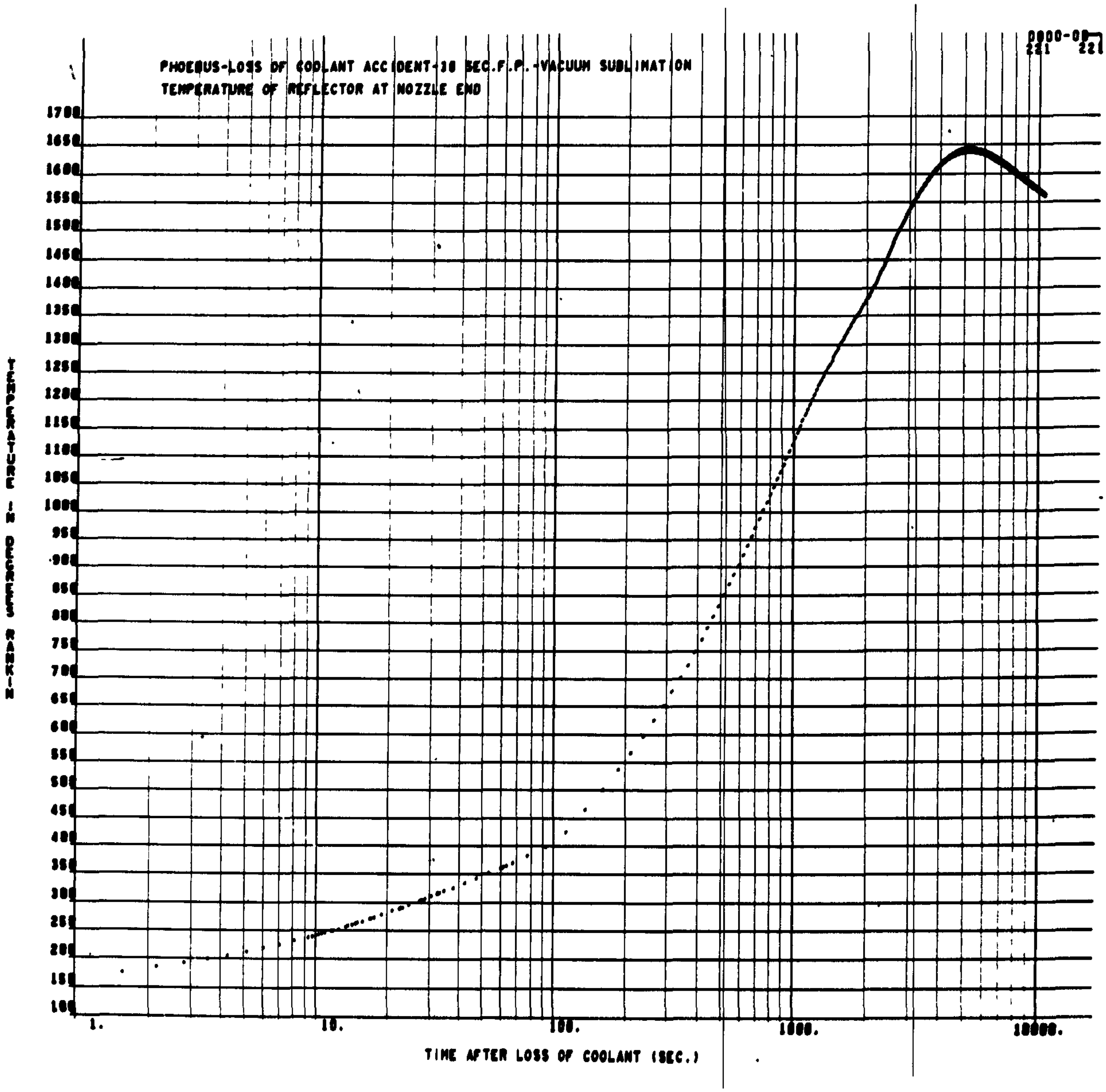

PHOEBUS-LOSS OF COOLANT ACCIDENT-30 SEC.F.P.-VACUUM SUBLIMATION
TEMPERATURE OF REFLECTOR AT NOZZLE END

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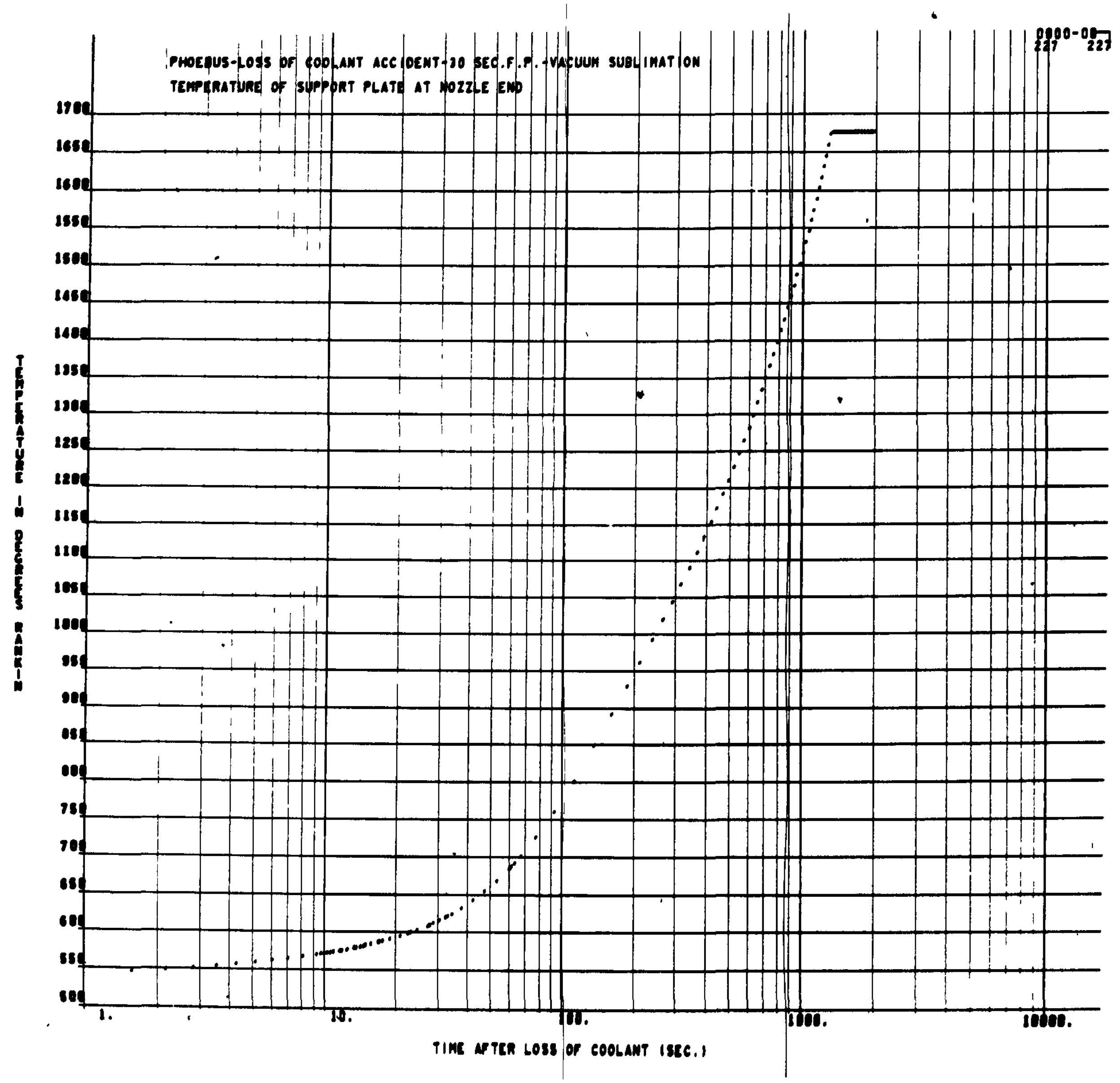

PHOEBUS-LOSS OF COOLANT ACCIDENT-30 SEC.F.P.-VACUUM SUBLIMATION
TEMPERATURE OF SUPPORT PLATE AT NOZZLE END

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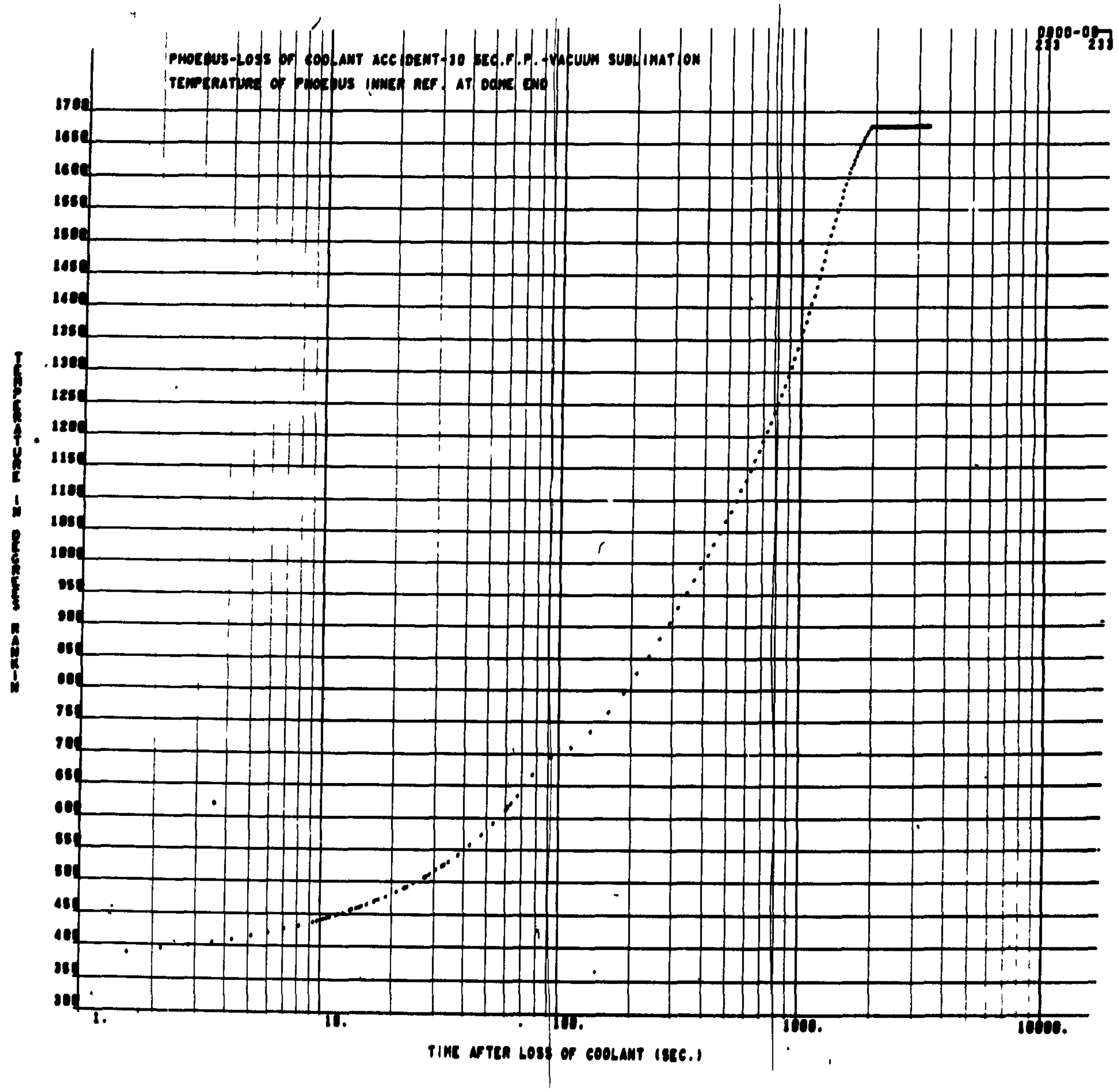

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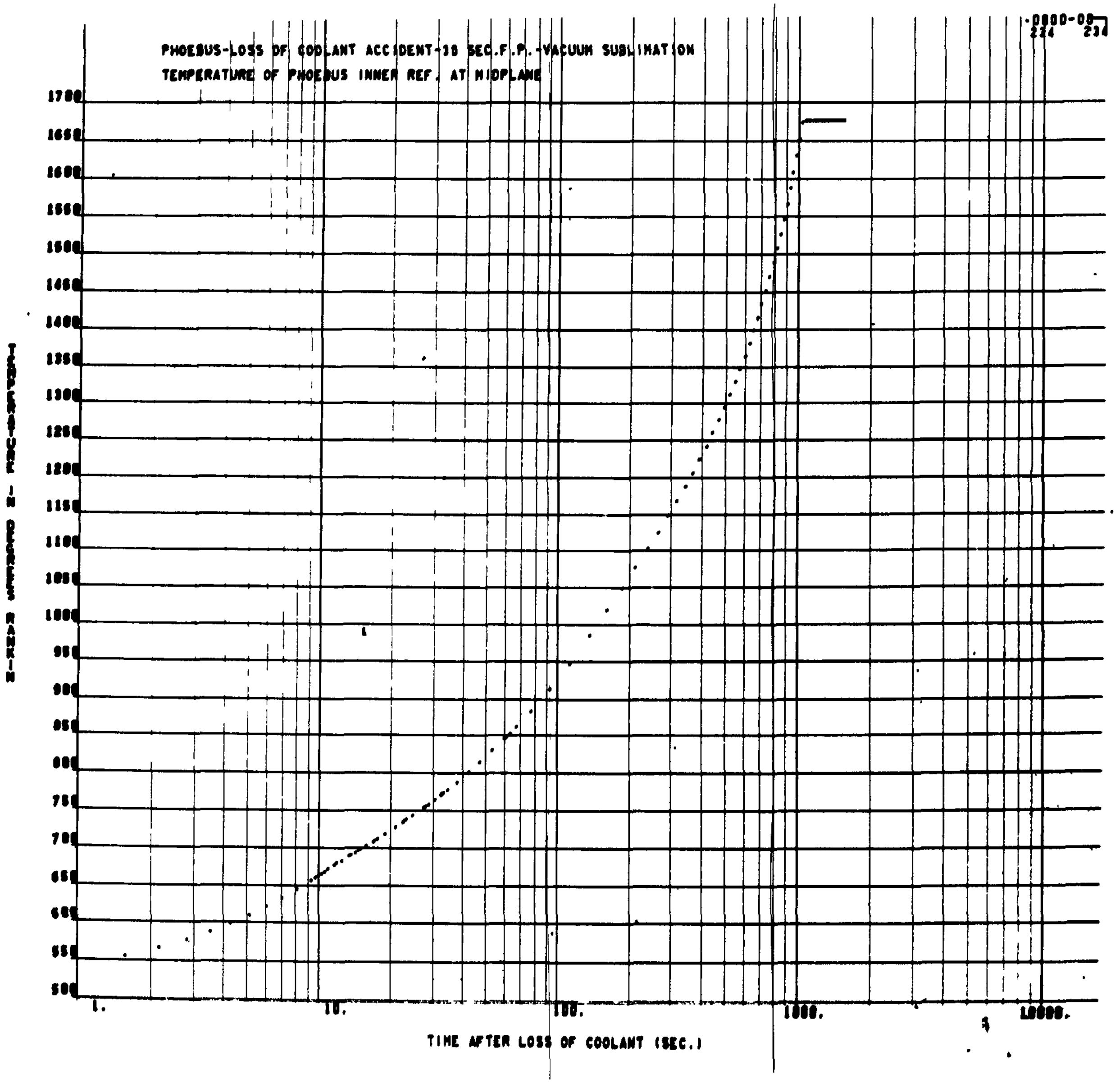

PHOEBUS-LOSS OF COOLANT ACCIDENT-30 SEC.F.P.-VACUUM SUBLIMATION
TEMPERATURE OF PHOEBUS INNER REF. AT MIDPLANE

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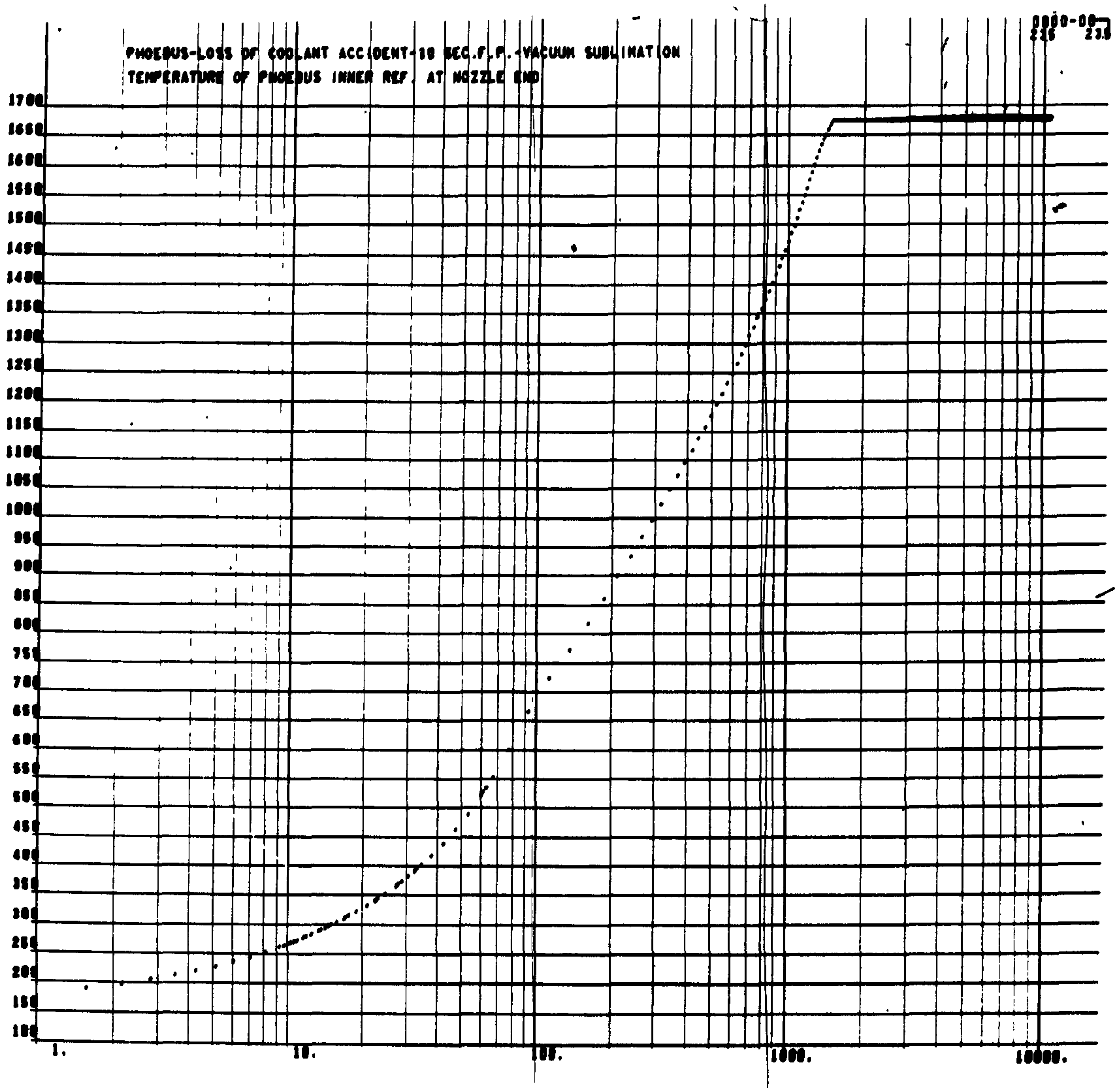

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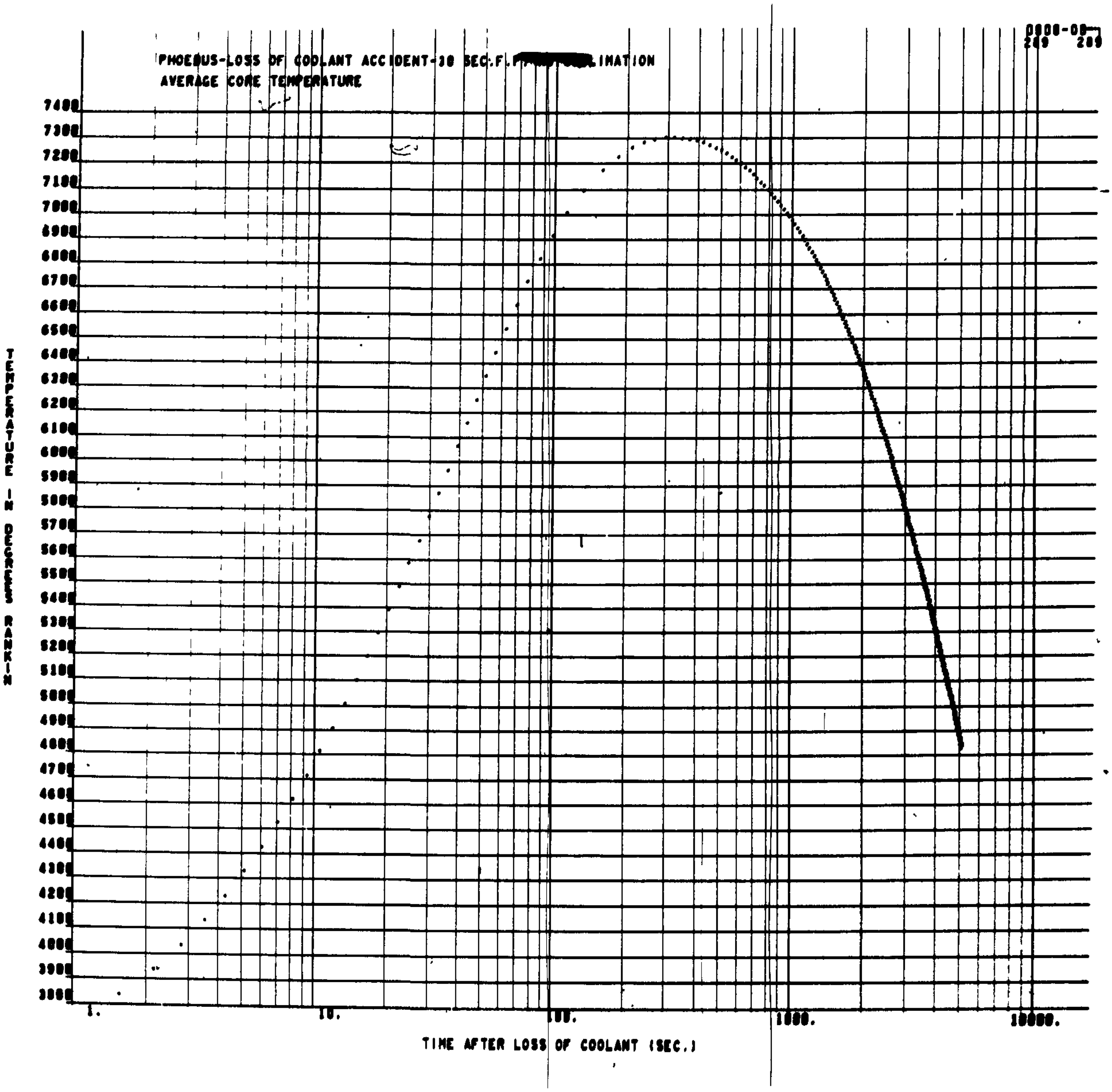

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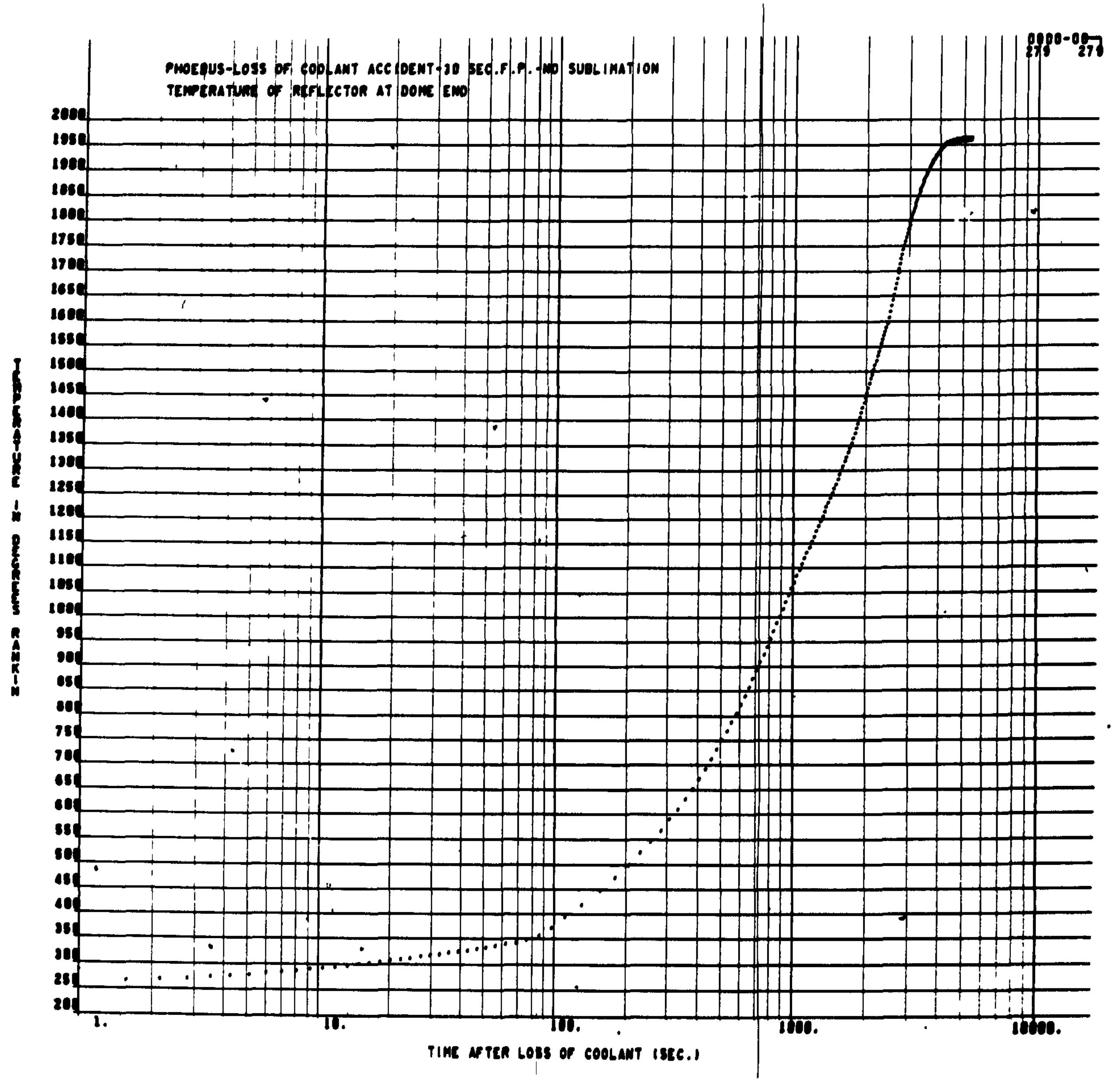

PHOEBUS-LOSS OF COOLANT ACCIDENT-30 SEC.F.P.-NO SUBLIMATION
TEMPERATURE OF REFLECTOR AT DOME END

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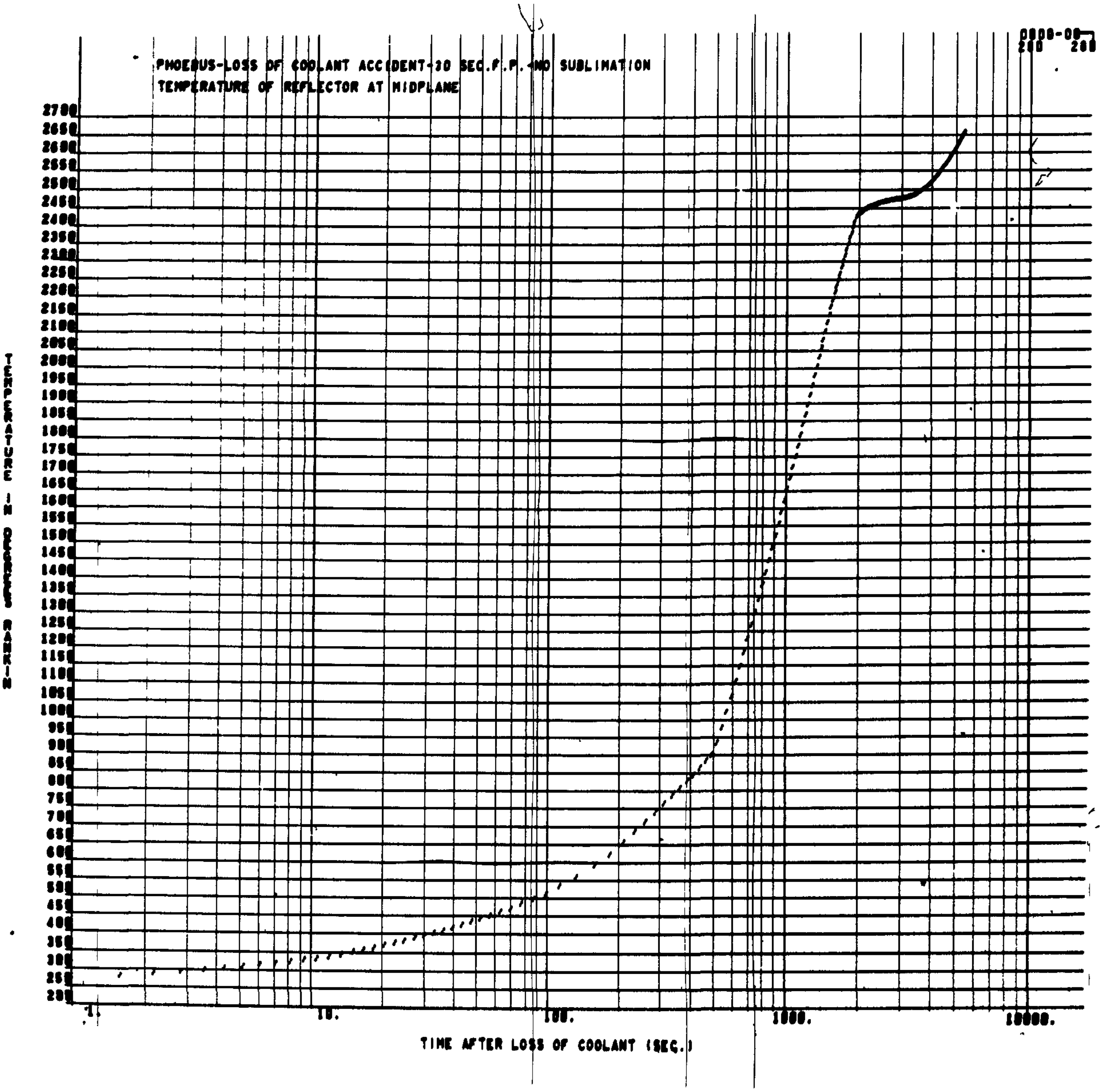

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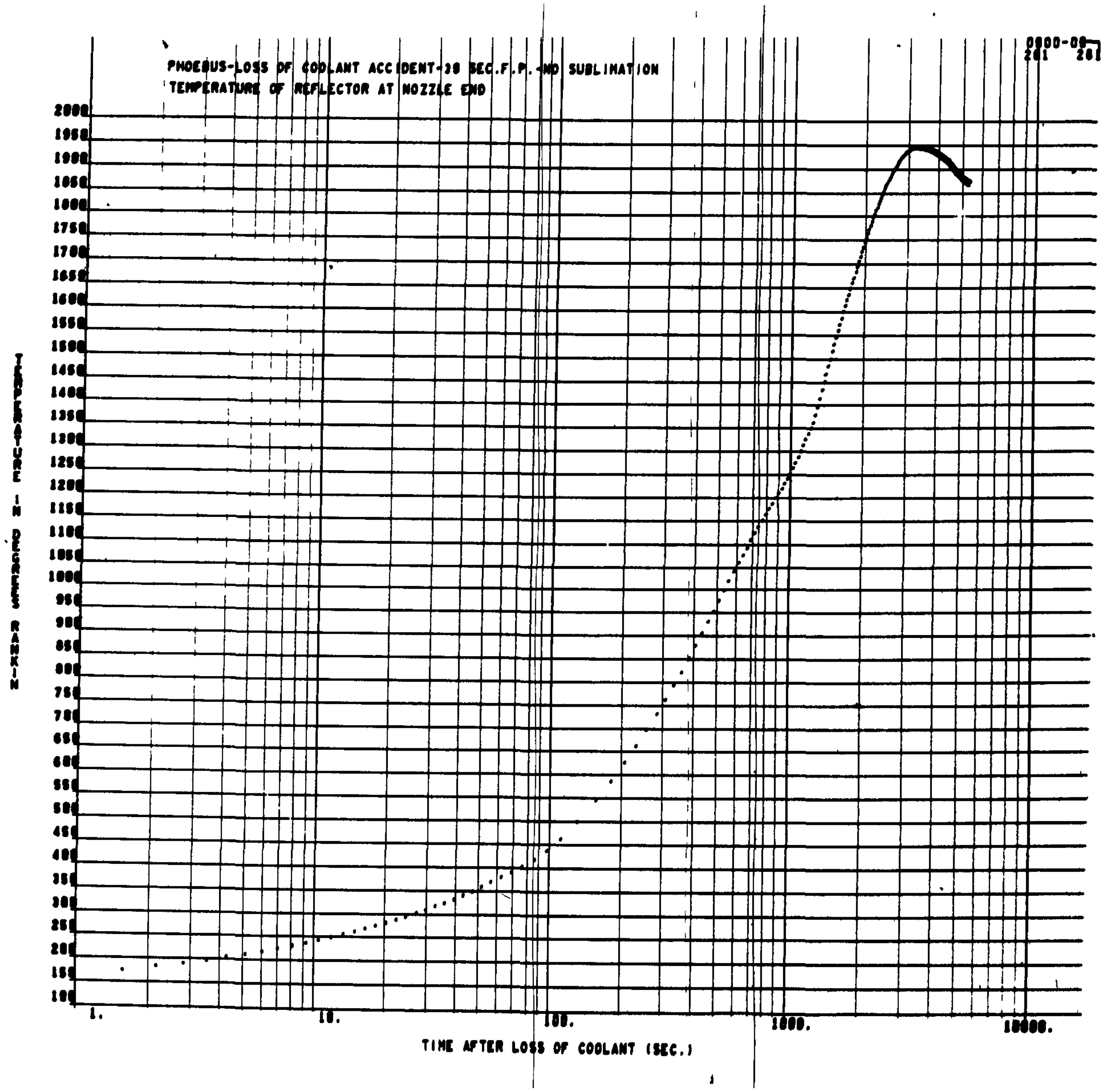

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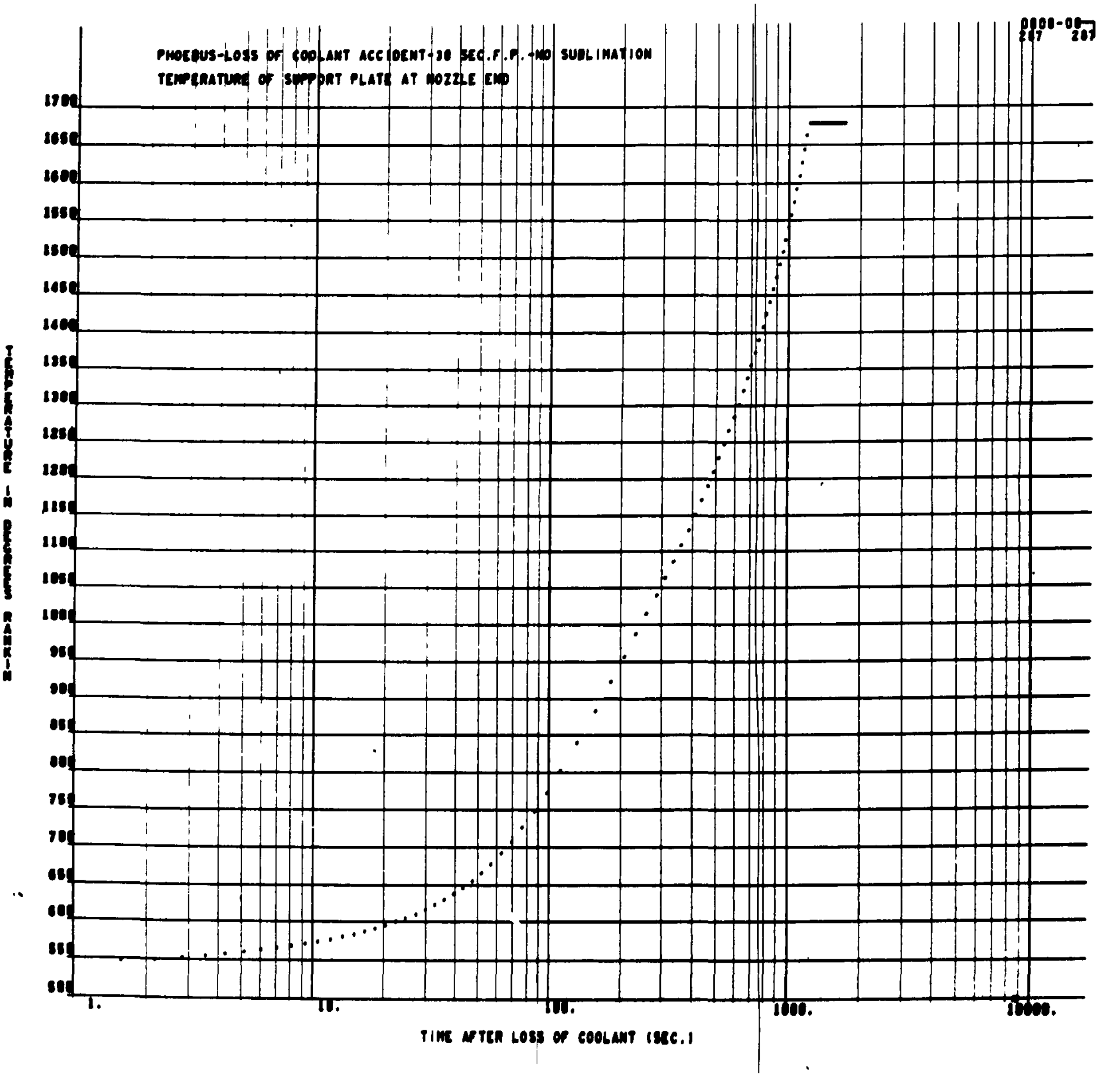

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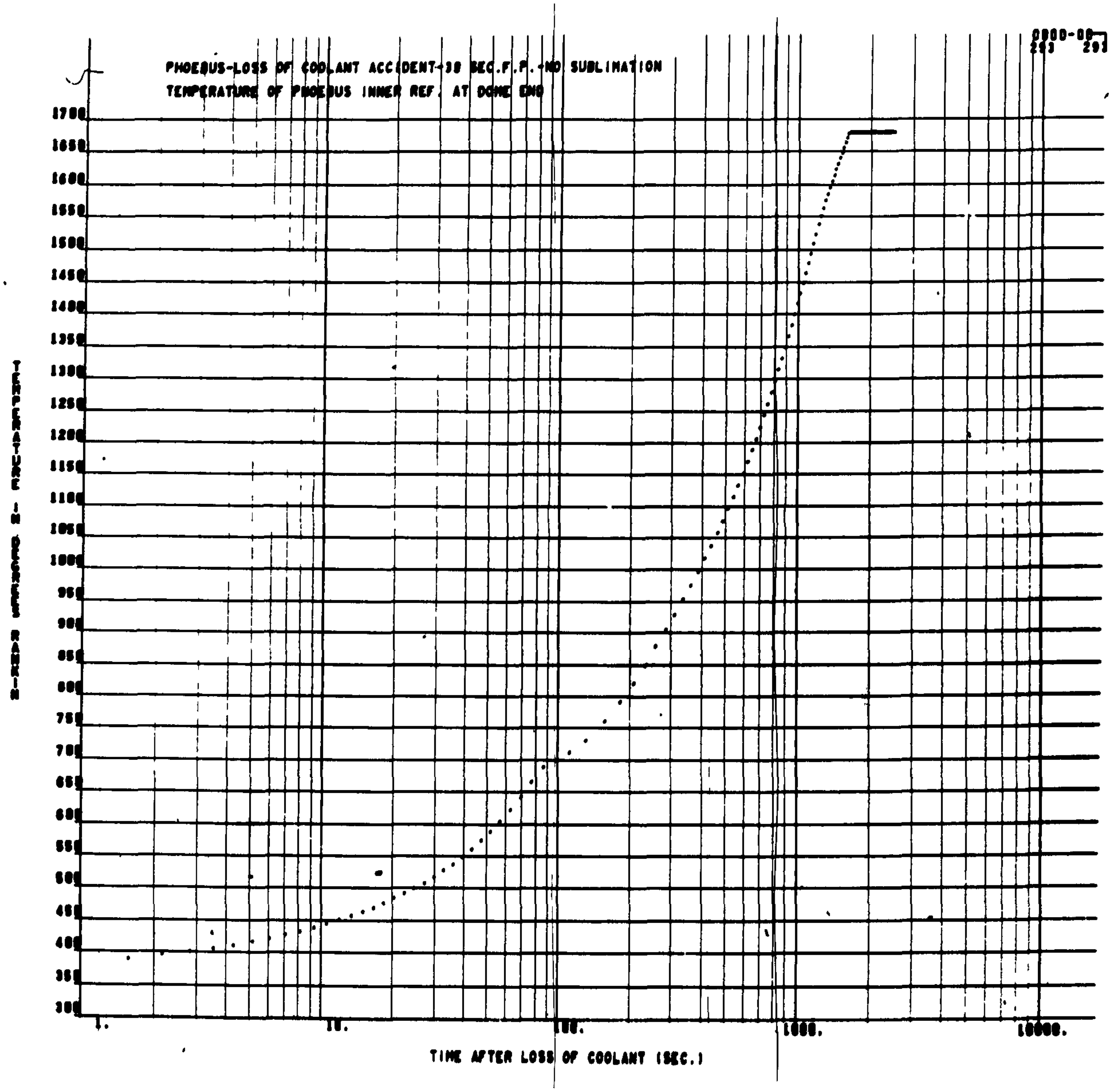

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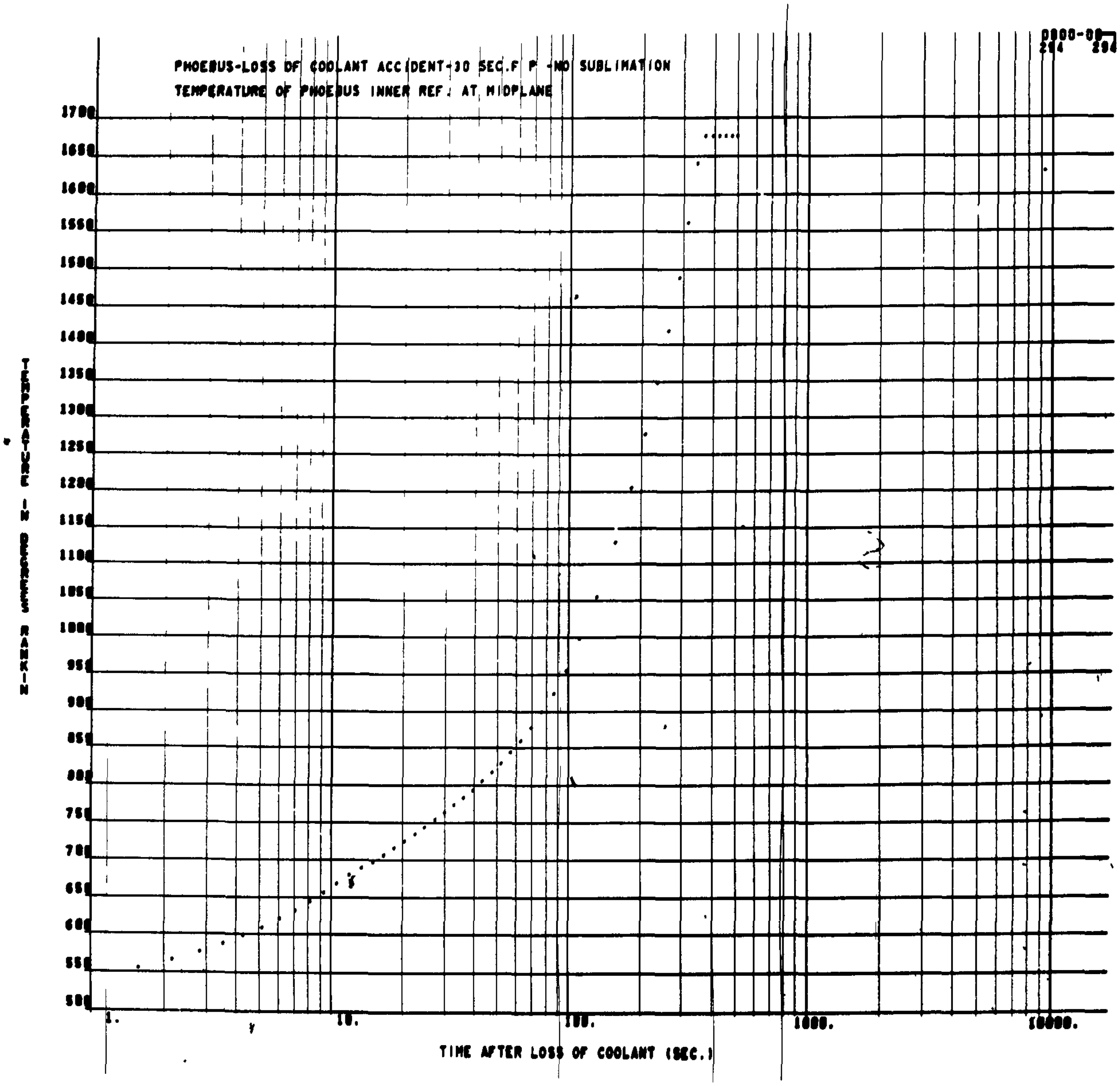

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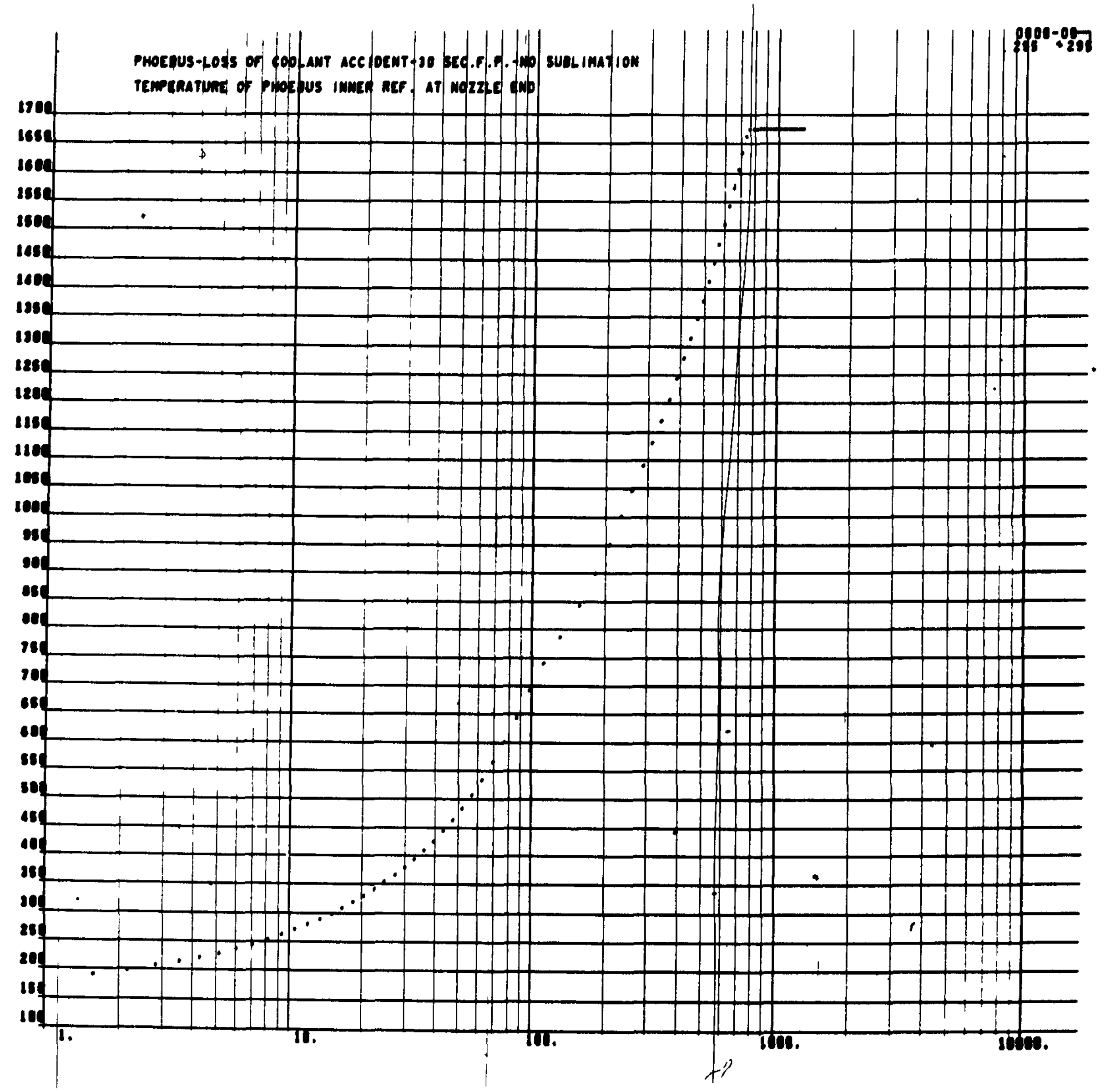

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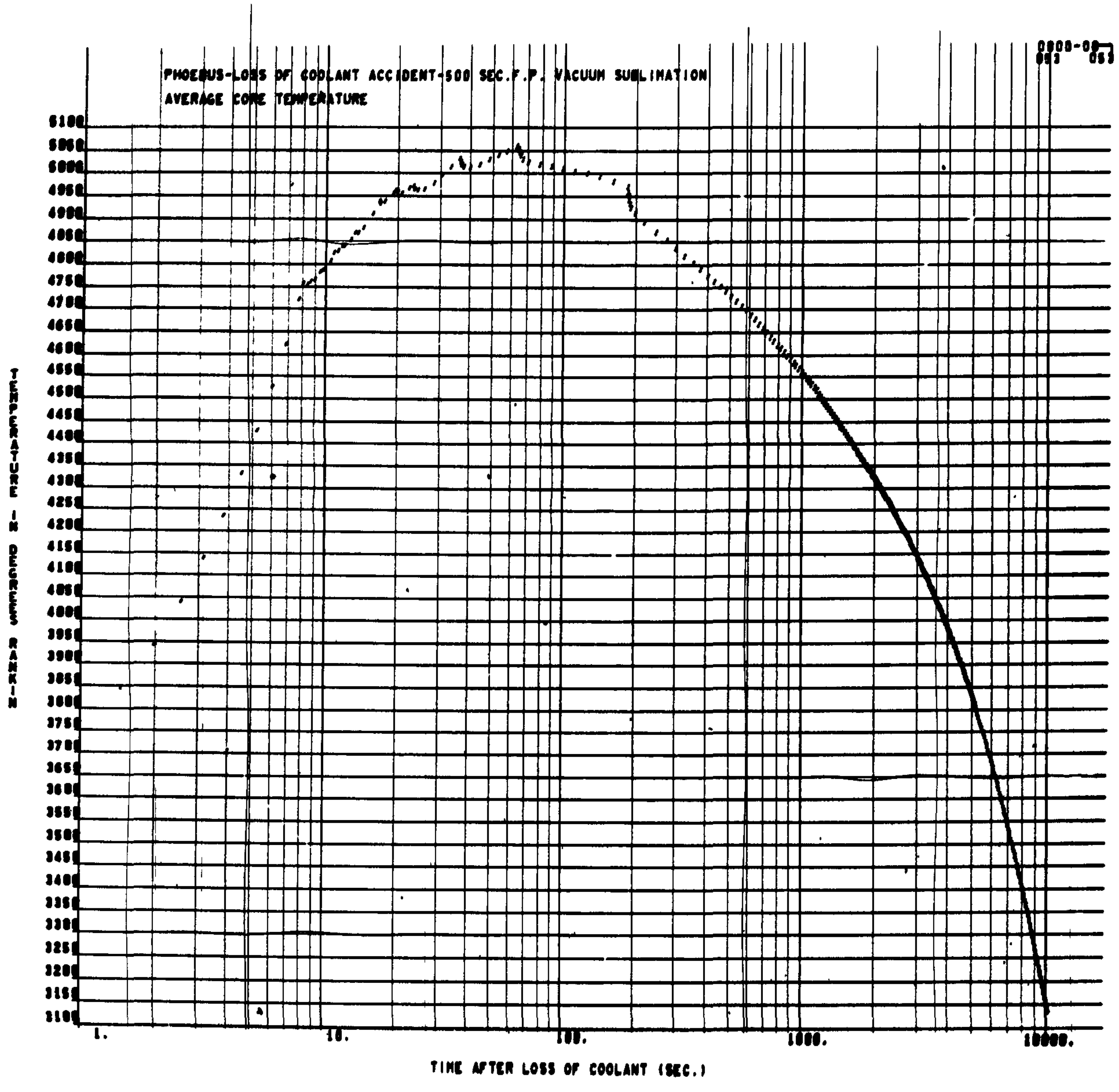

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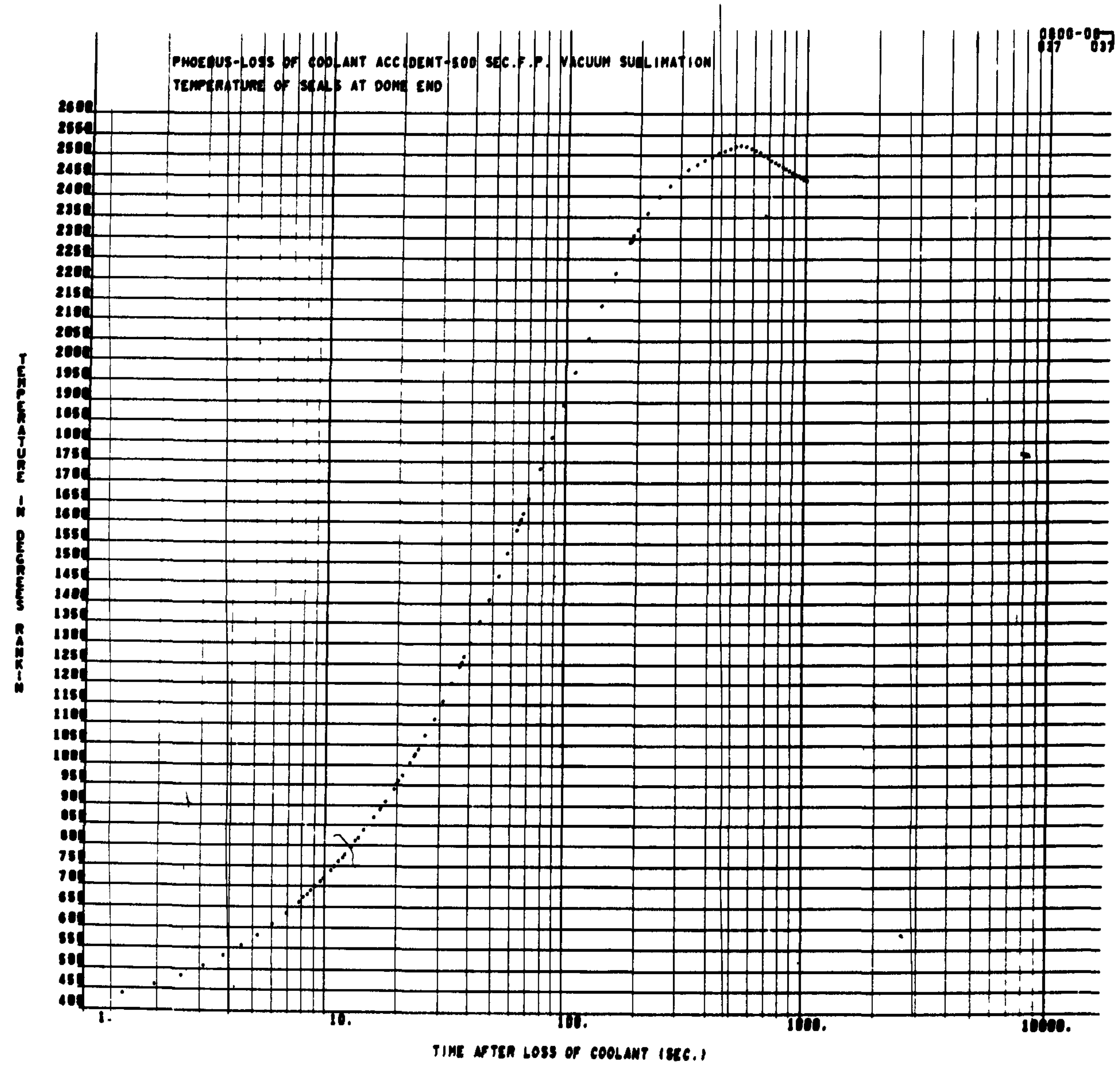

PHOEBUS-LOSS OF COOLANT ACCIDENT-500 SEC.F.P. VACUUM SUBLIMATION
TEMPERATURE OF SEALS AT DOME END

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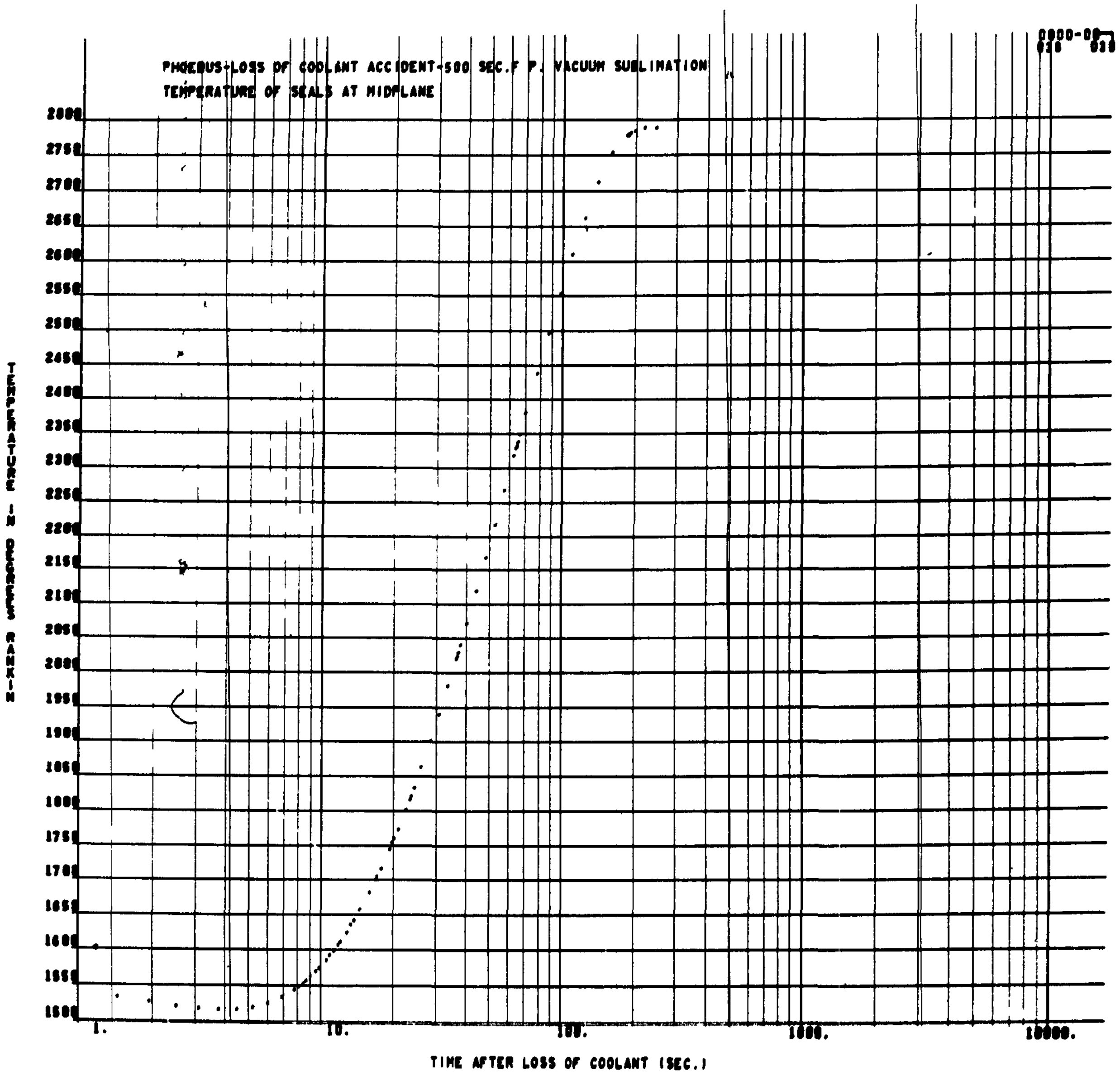

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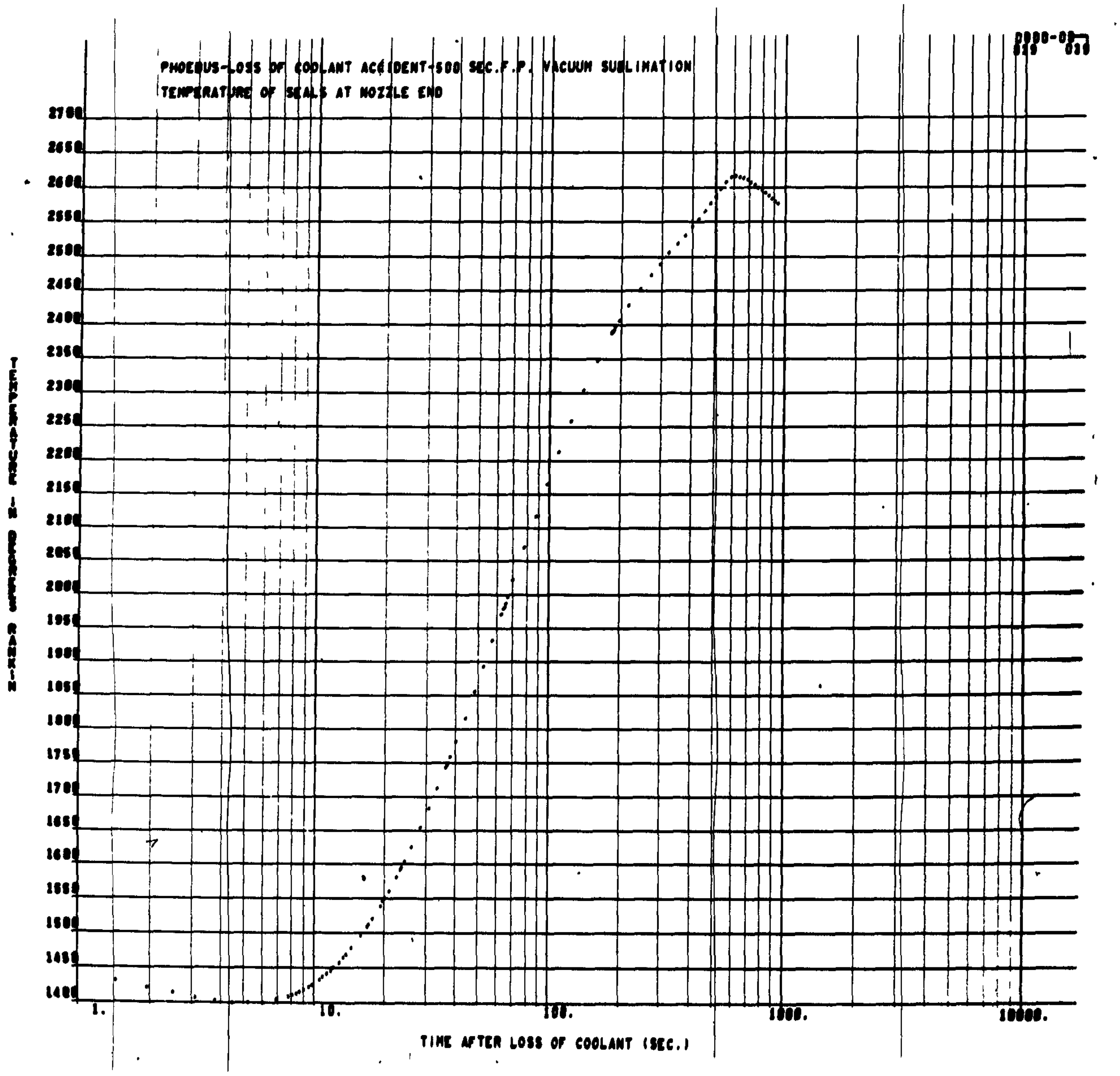

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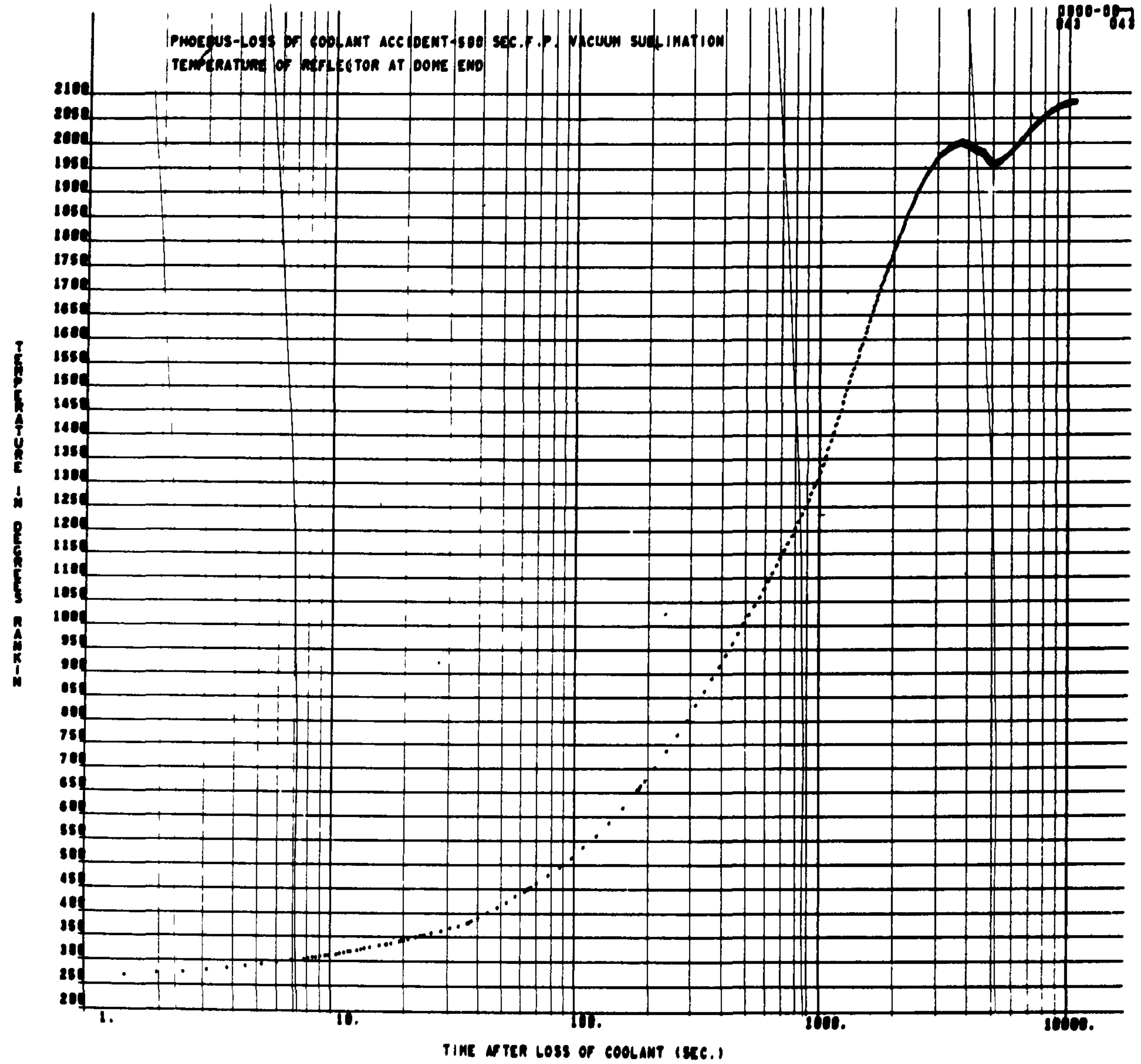

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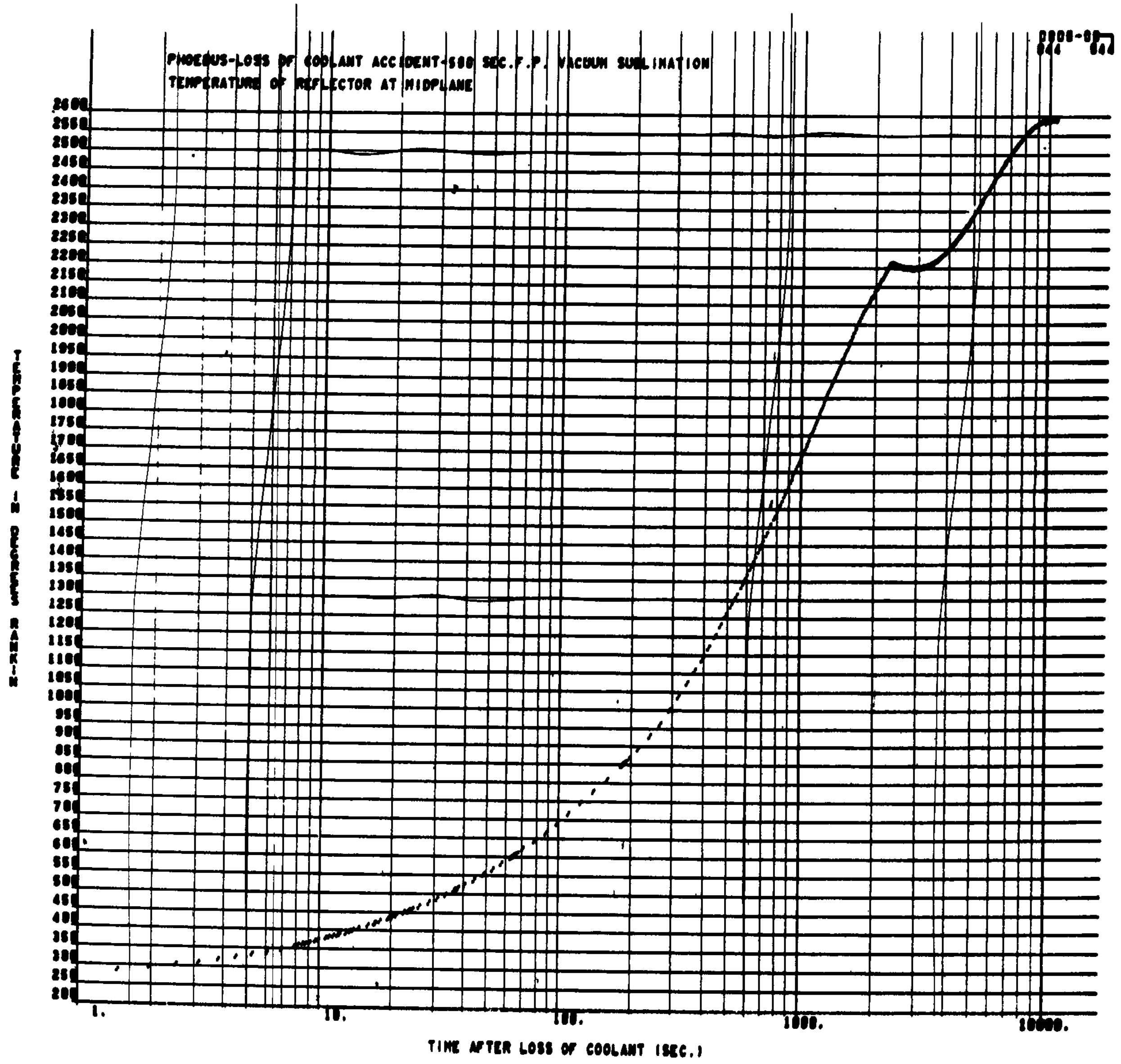

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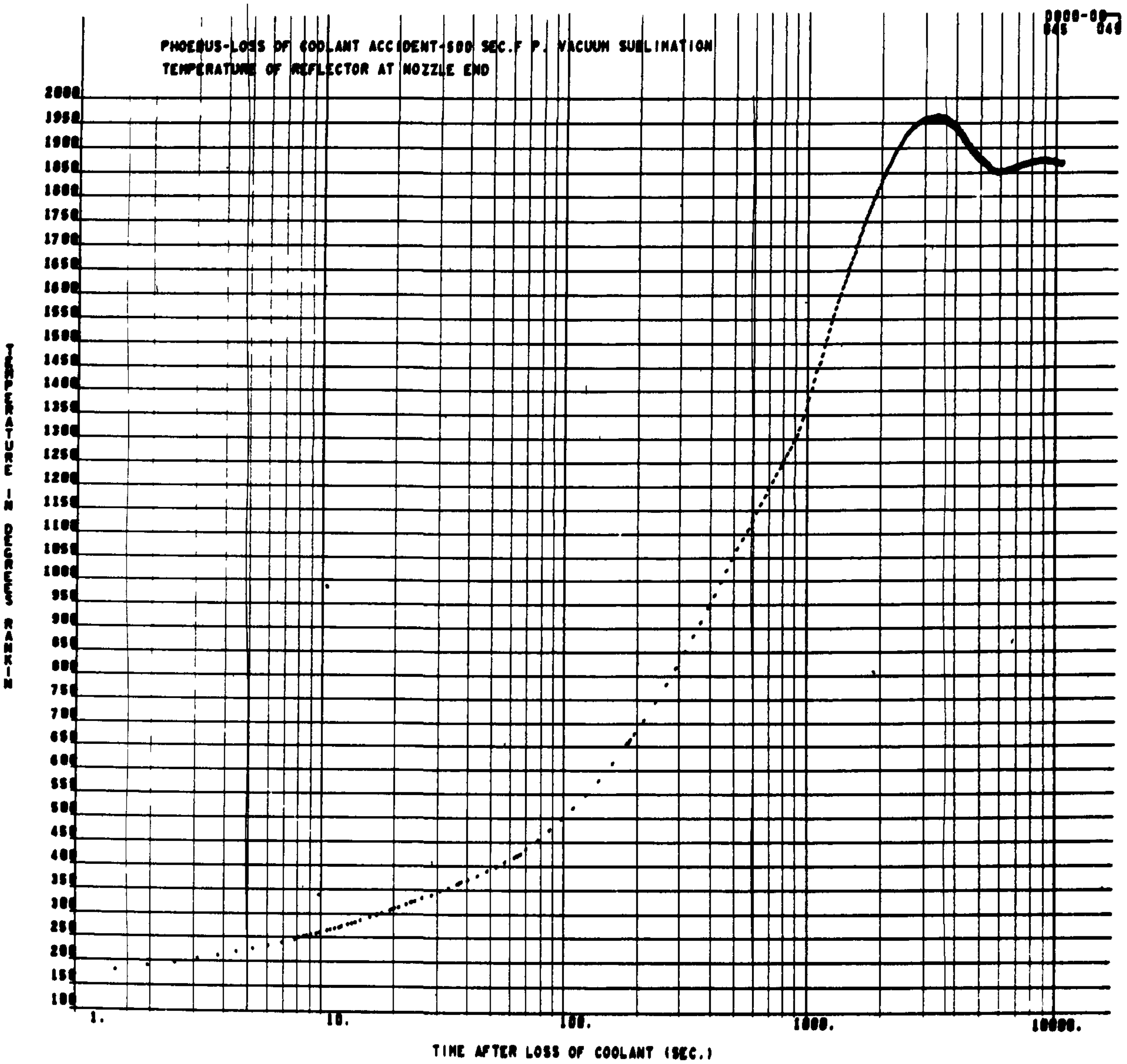

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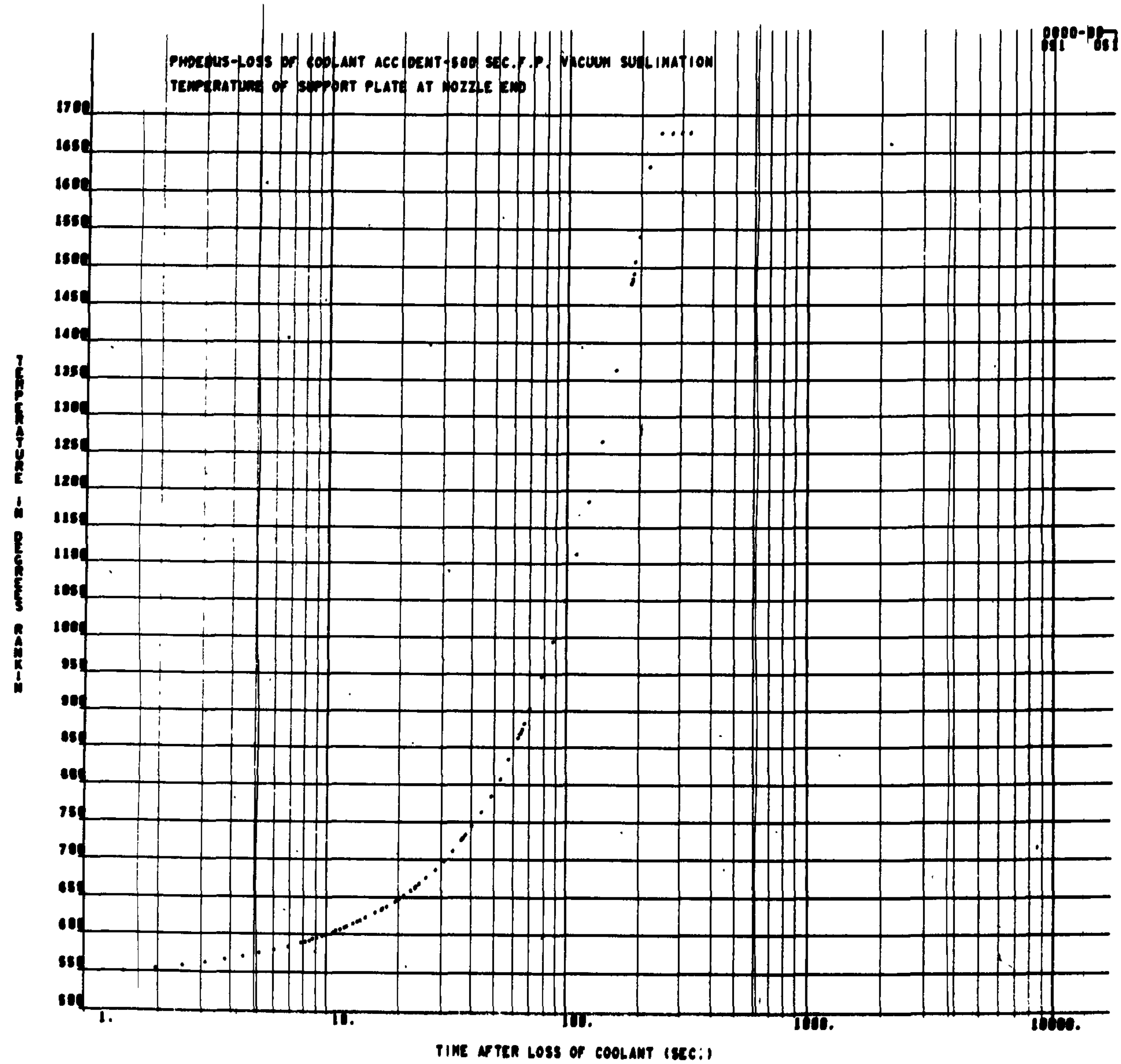
PHOEBUS-LOSS OF COOLANT ACCIDENT-500 SEC.F.P. VACUUM SUBLIMATION
TEMPERATURE OF SUPPORT PLATE AT NOZZLE END

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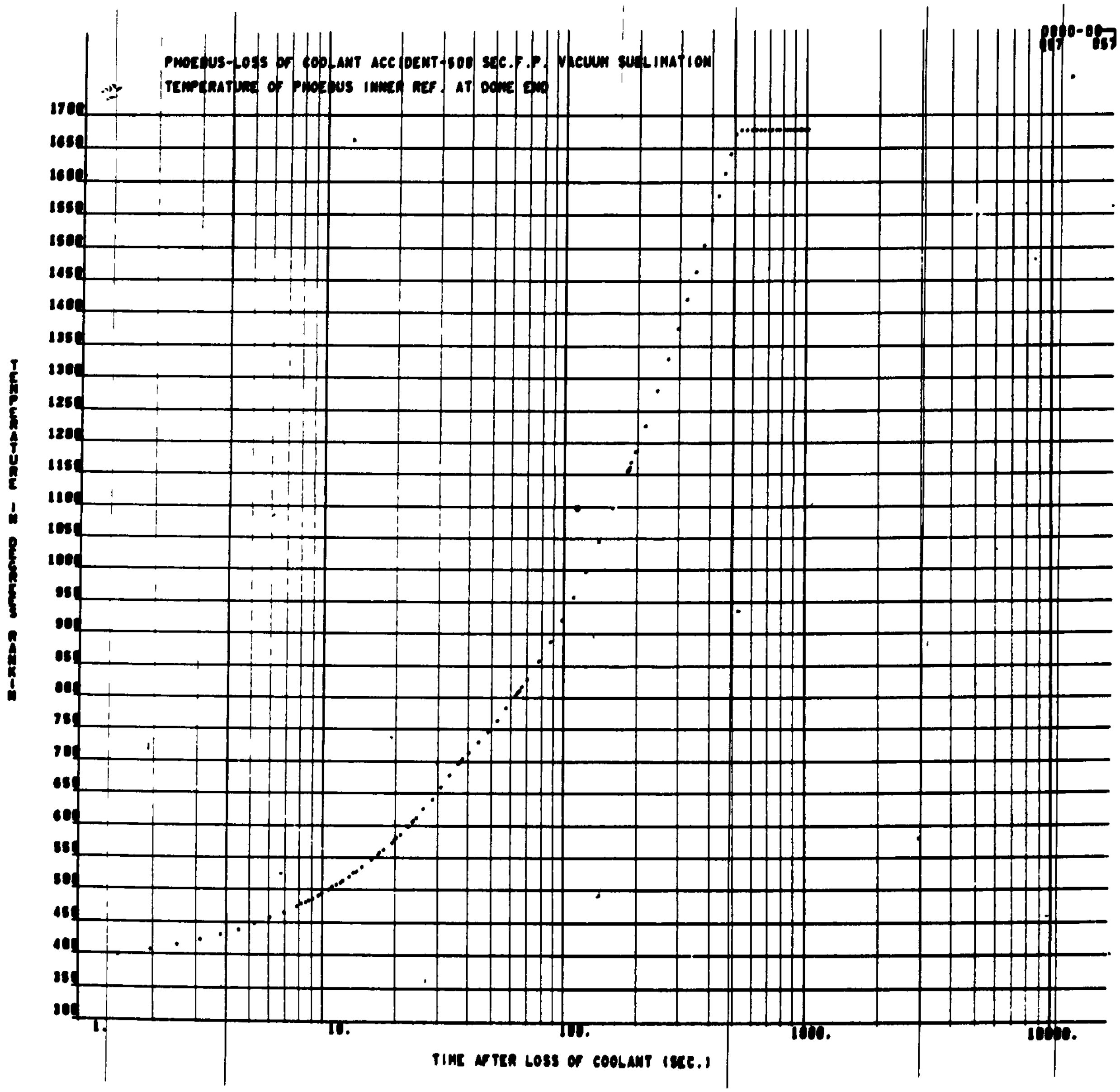
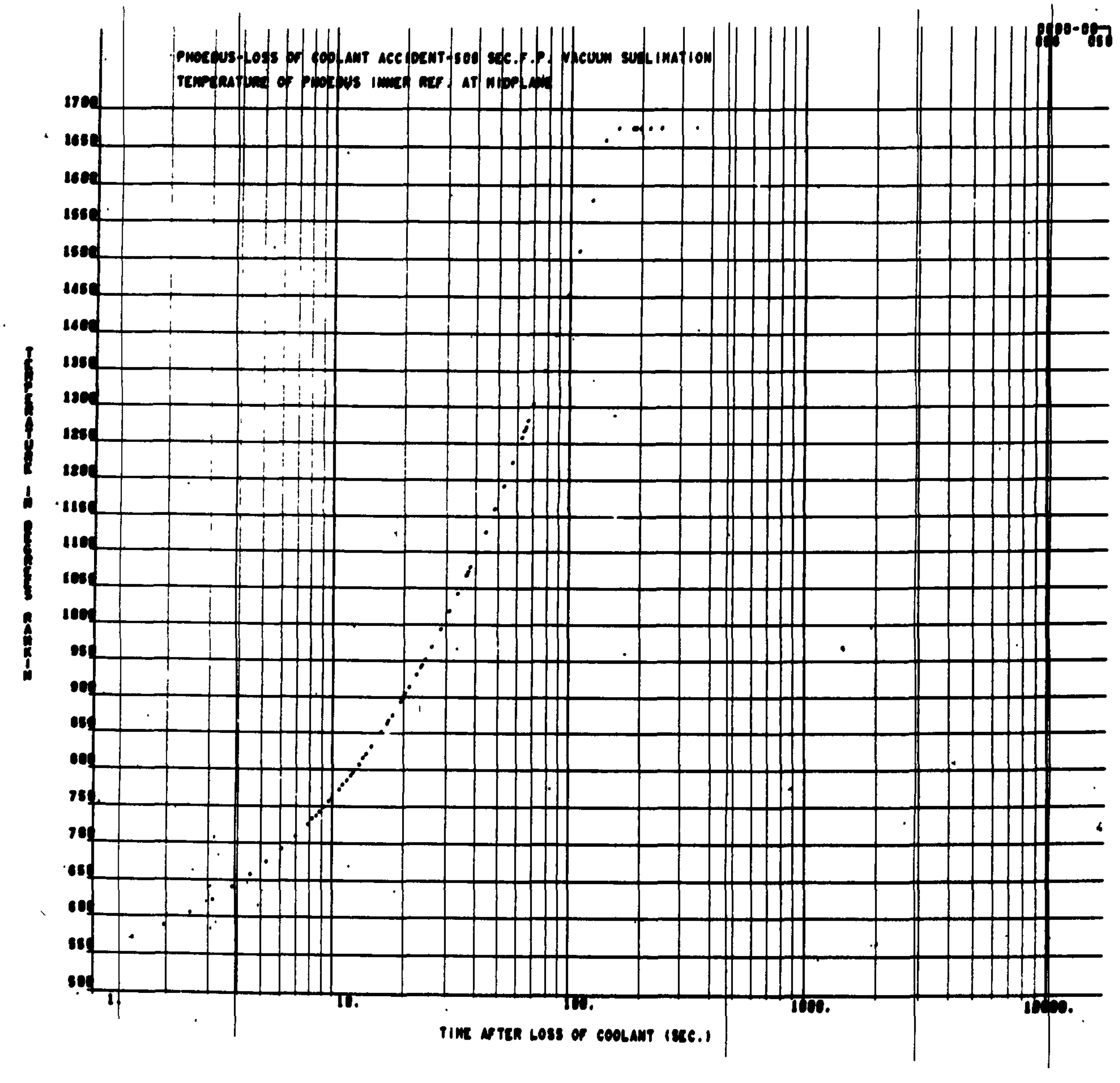

PHOEBUS-LOSS OF COOLANT ACCIDENT-500 SEC.F.P. VACUUM SUBLIMATION
TEMPERATURE OF PHOEBUS INNER REF. AT DOME END
0000-00
057 057
1700
1650
1600
1550
1500
1450
1400
1350
1300
1250
1200
1150
1100
1050
1000
950
900
850
800
750
700
650
600
550
500
450
400
350
300
TEMPERATURE IN DEGREES RANKIN
1.
10.
100.
1000.
10000.
TIME AFTER LOSS OF COOLANT (SEC.)

[redacted]



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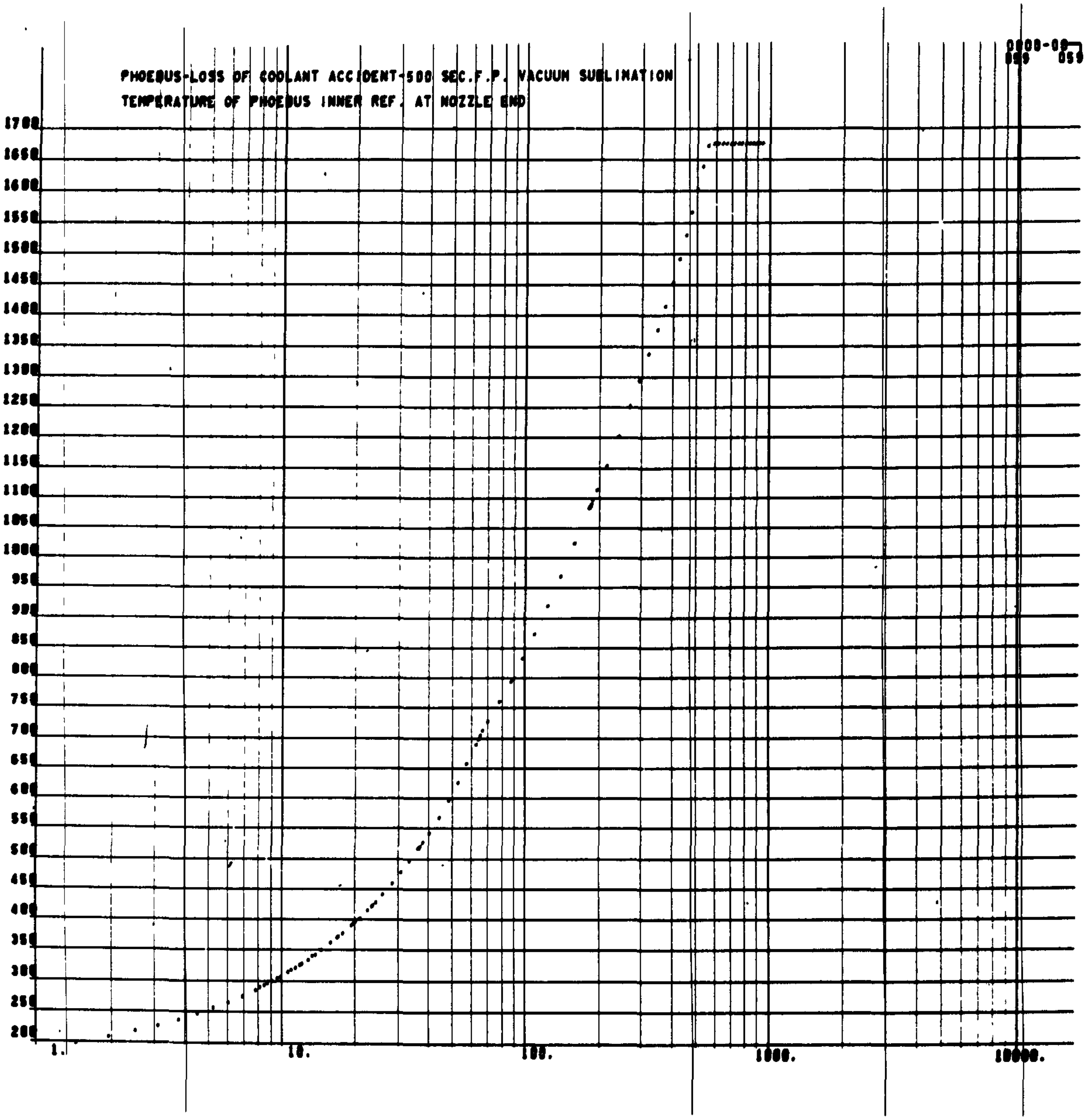

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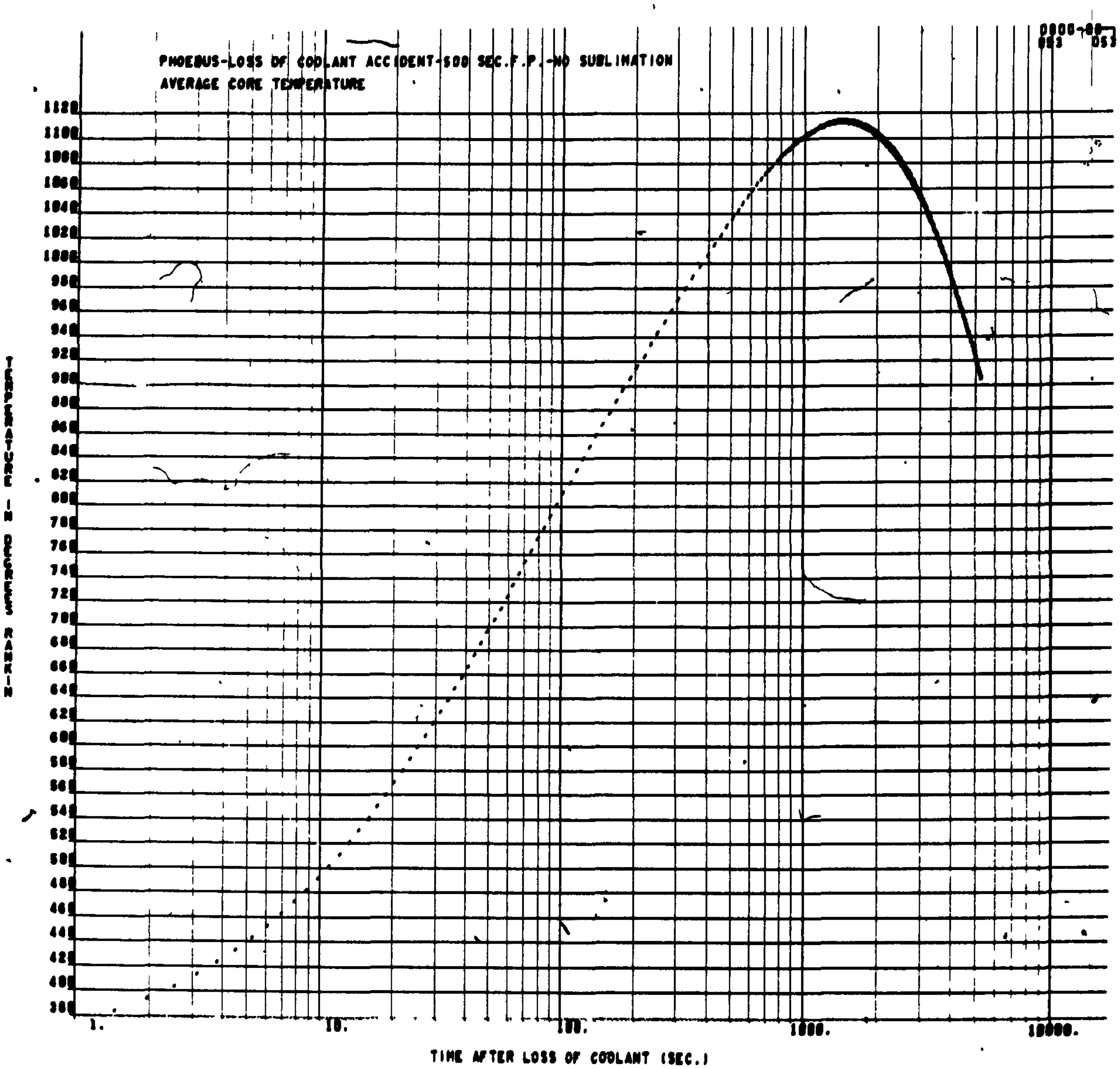

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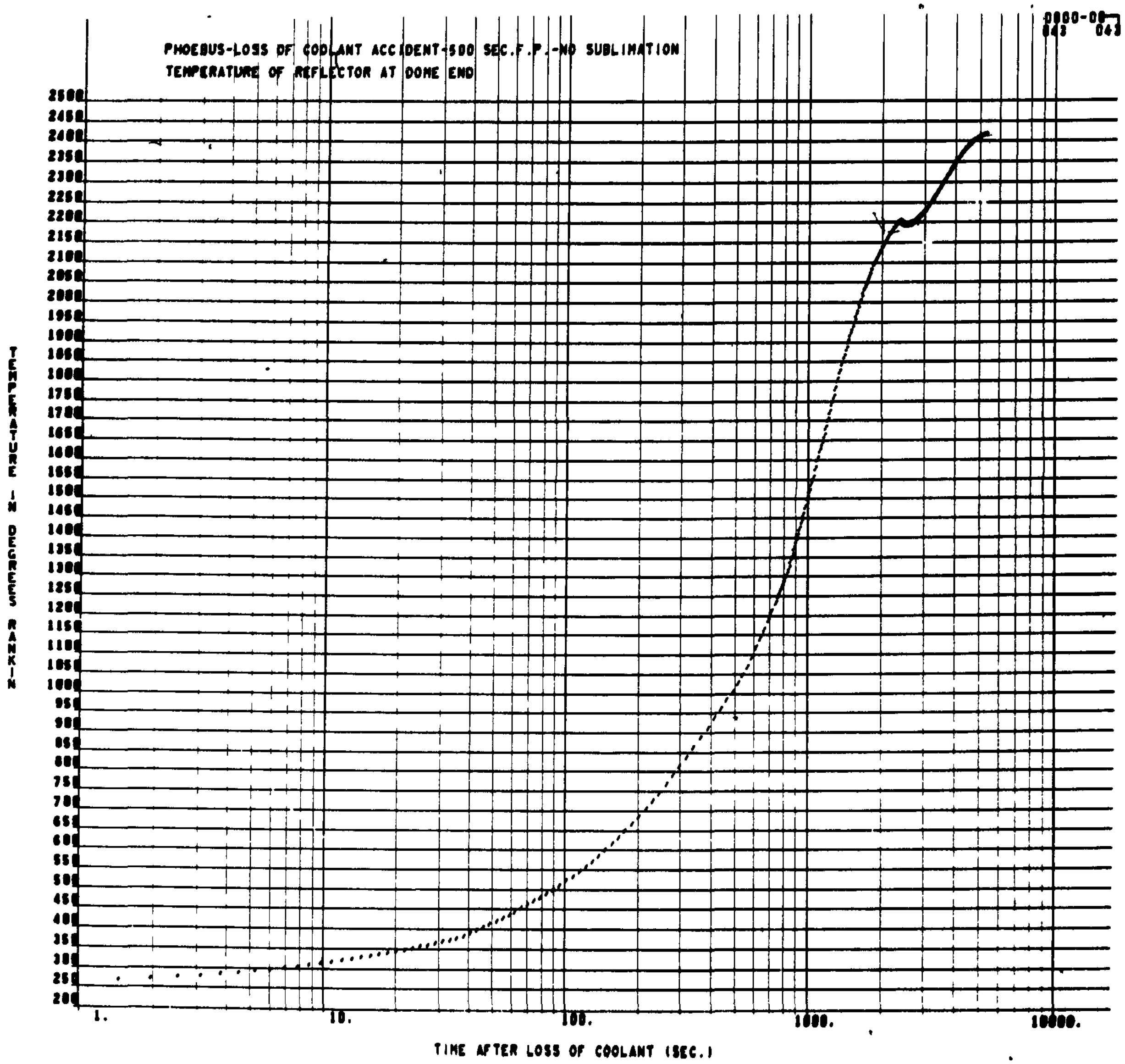

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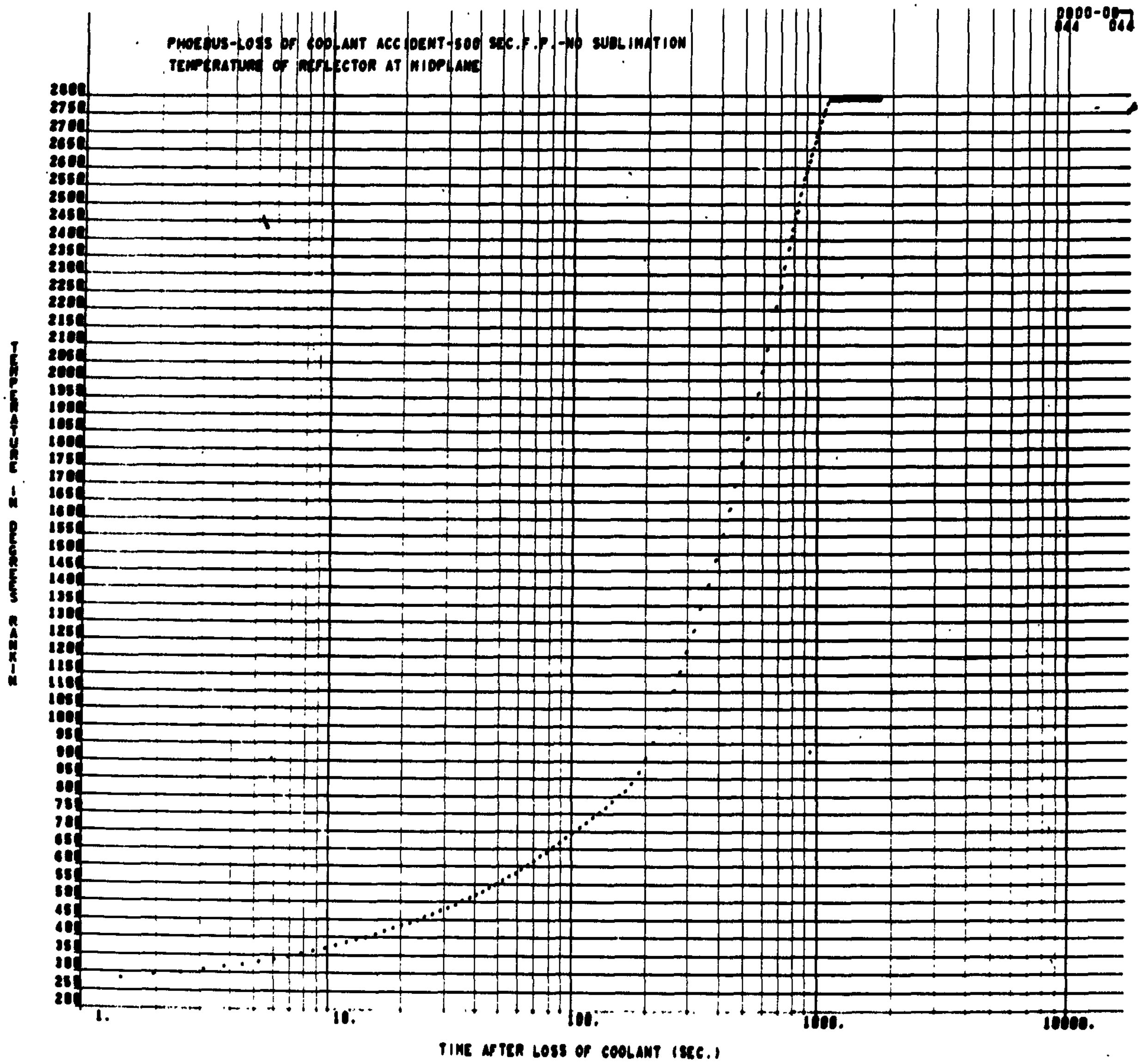

PHOEBUS-LOSS OF COOLANT ACCIDENT-500 SEC.F.P.-NO SUBLIMATION
TEMPERATURE OF REFLECTOR AT MIDPLANE

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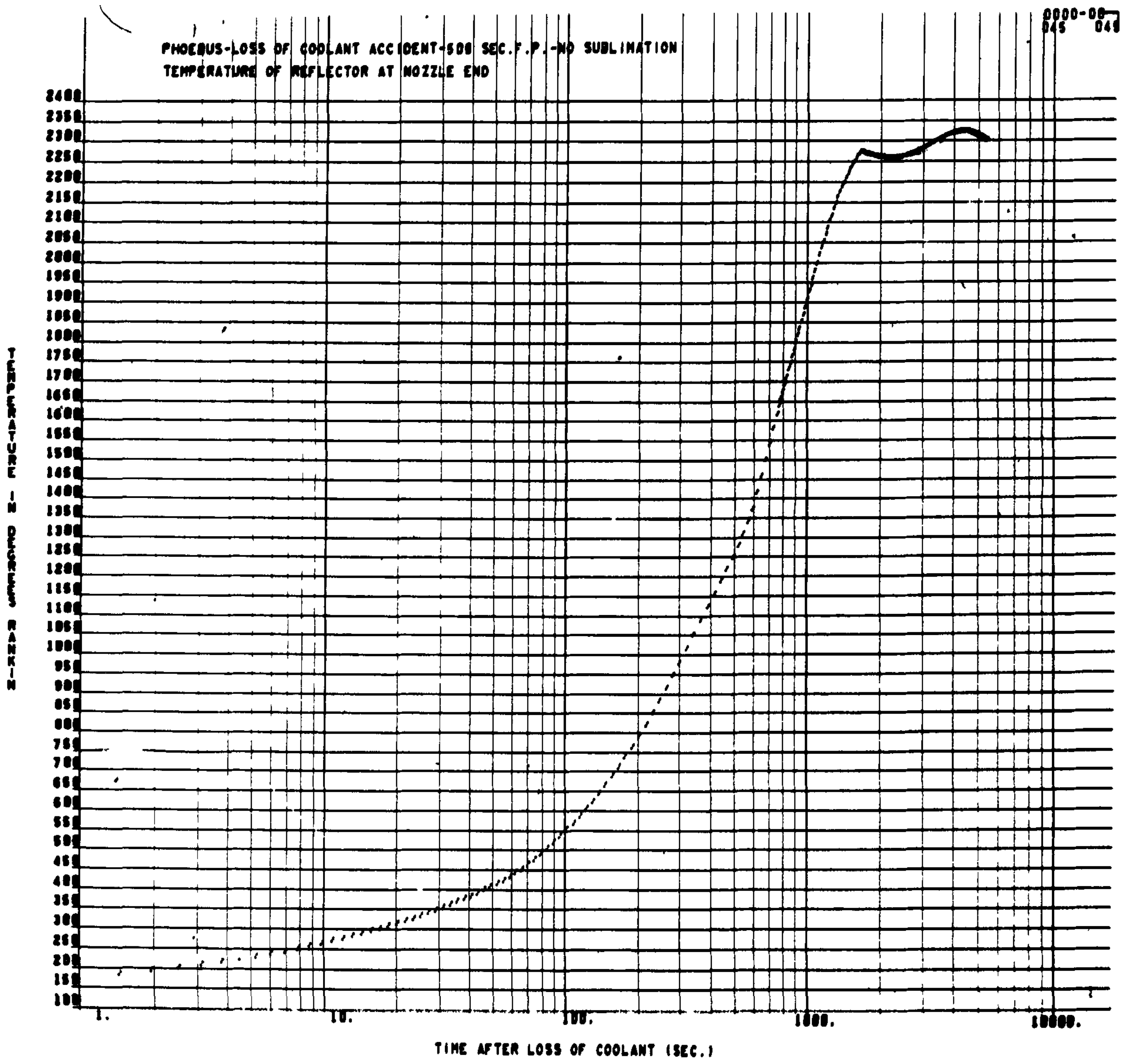

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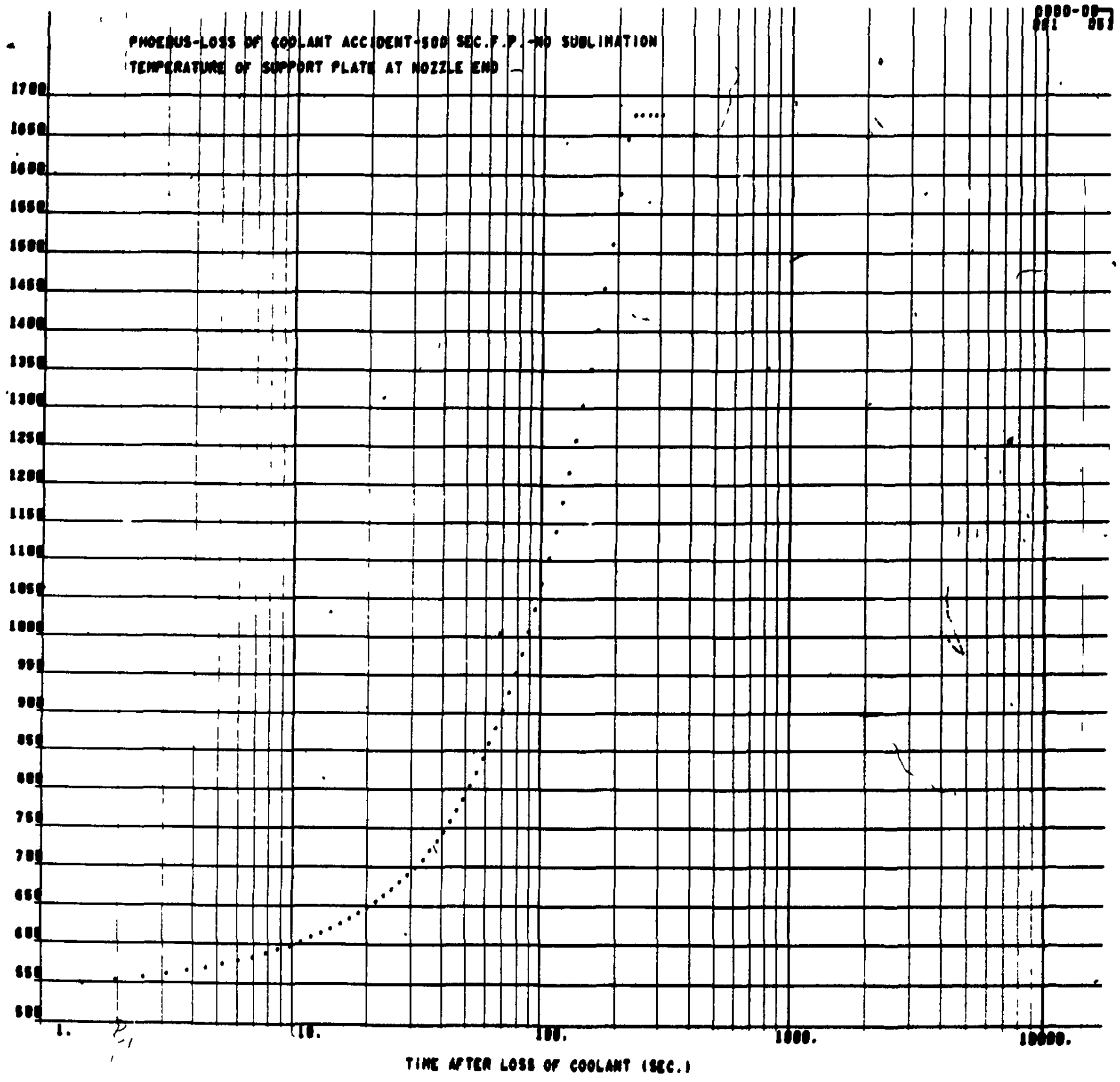

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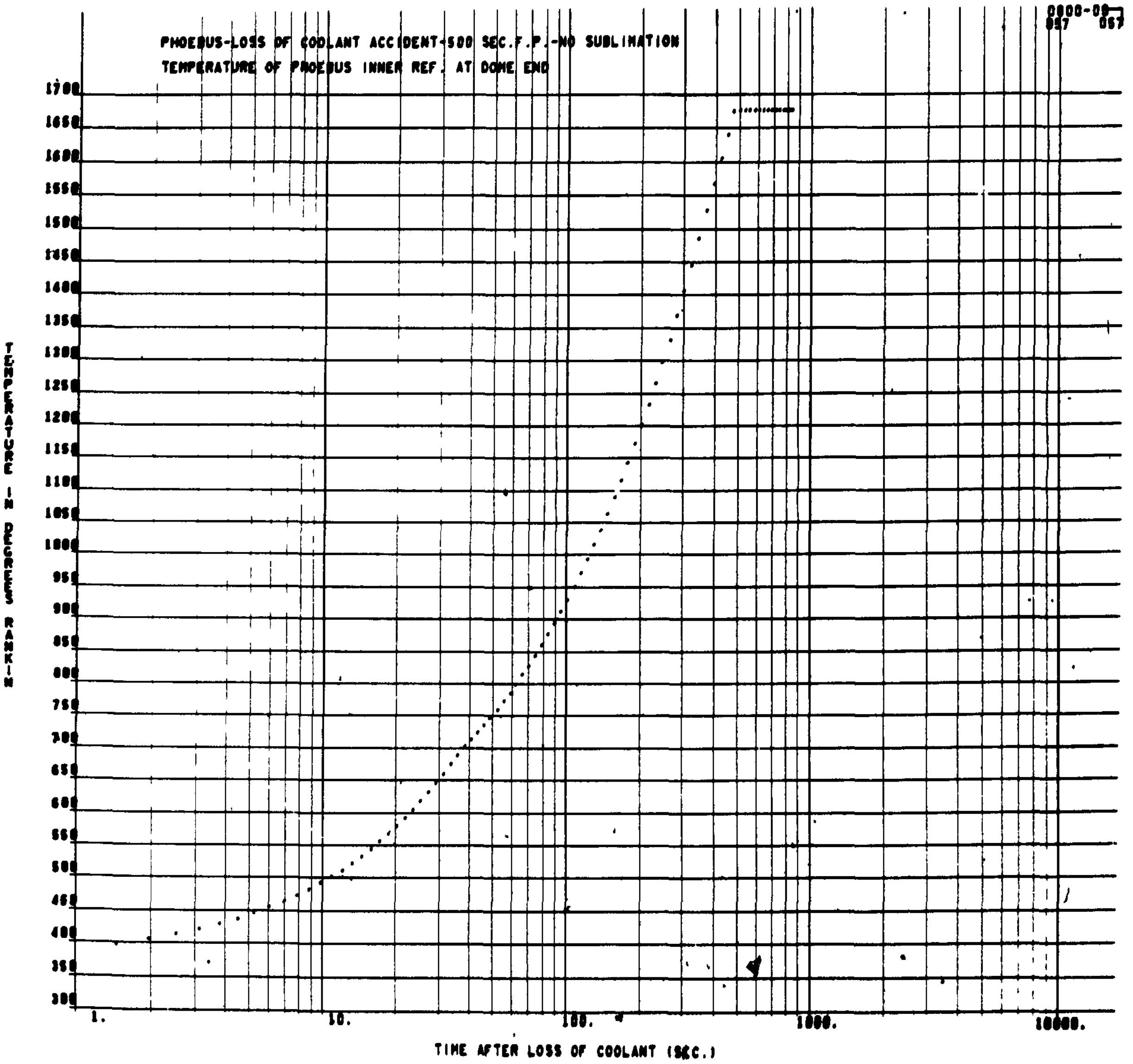

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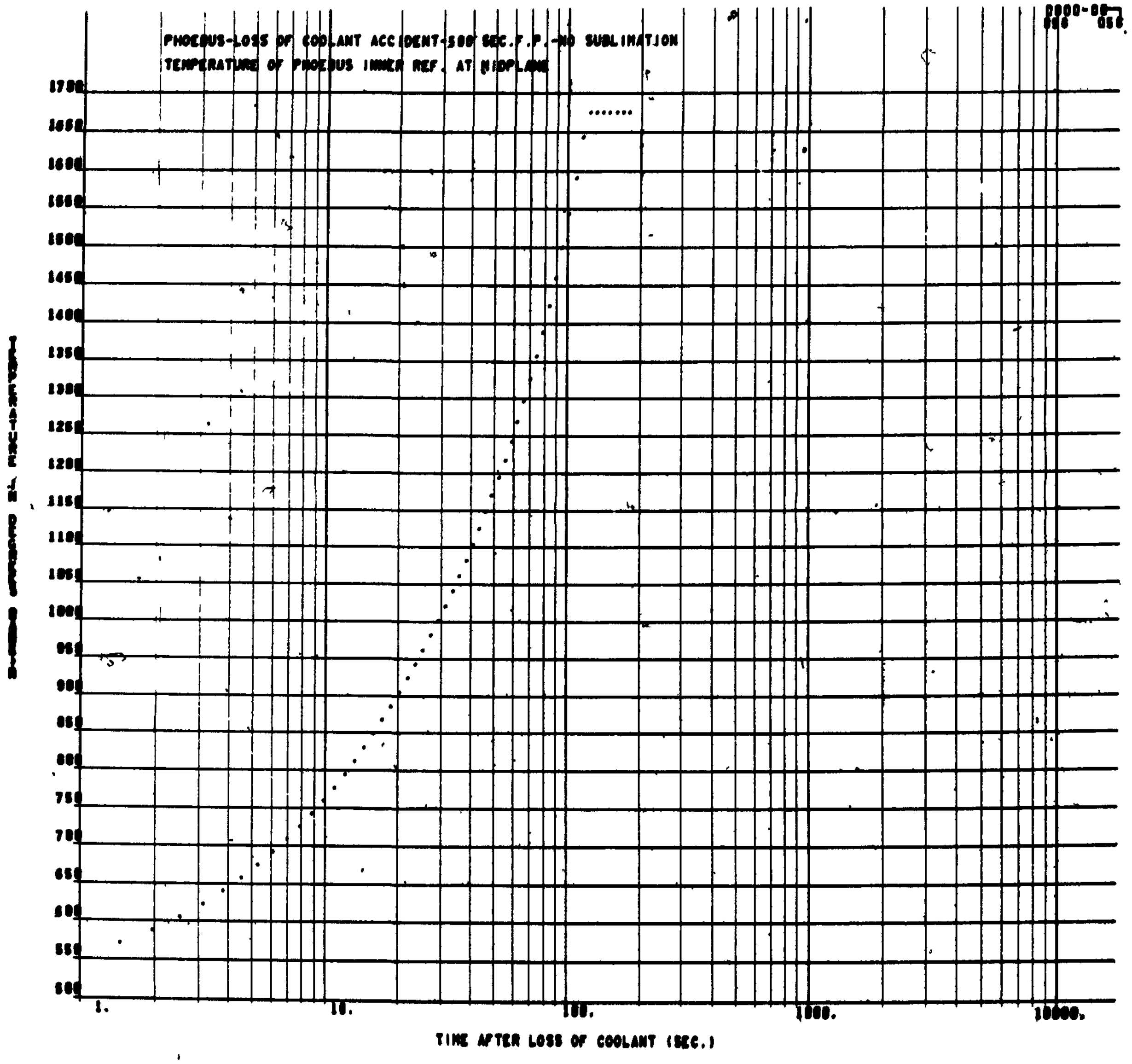

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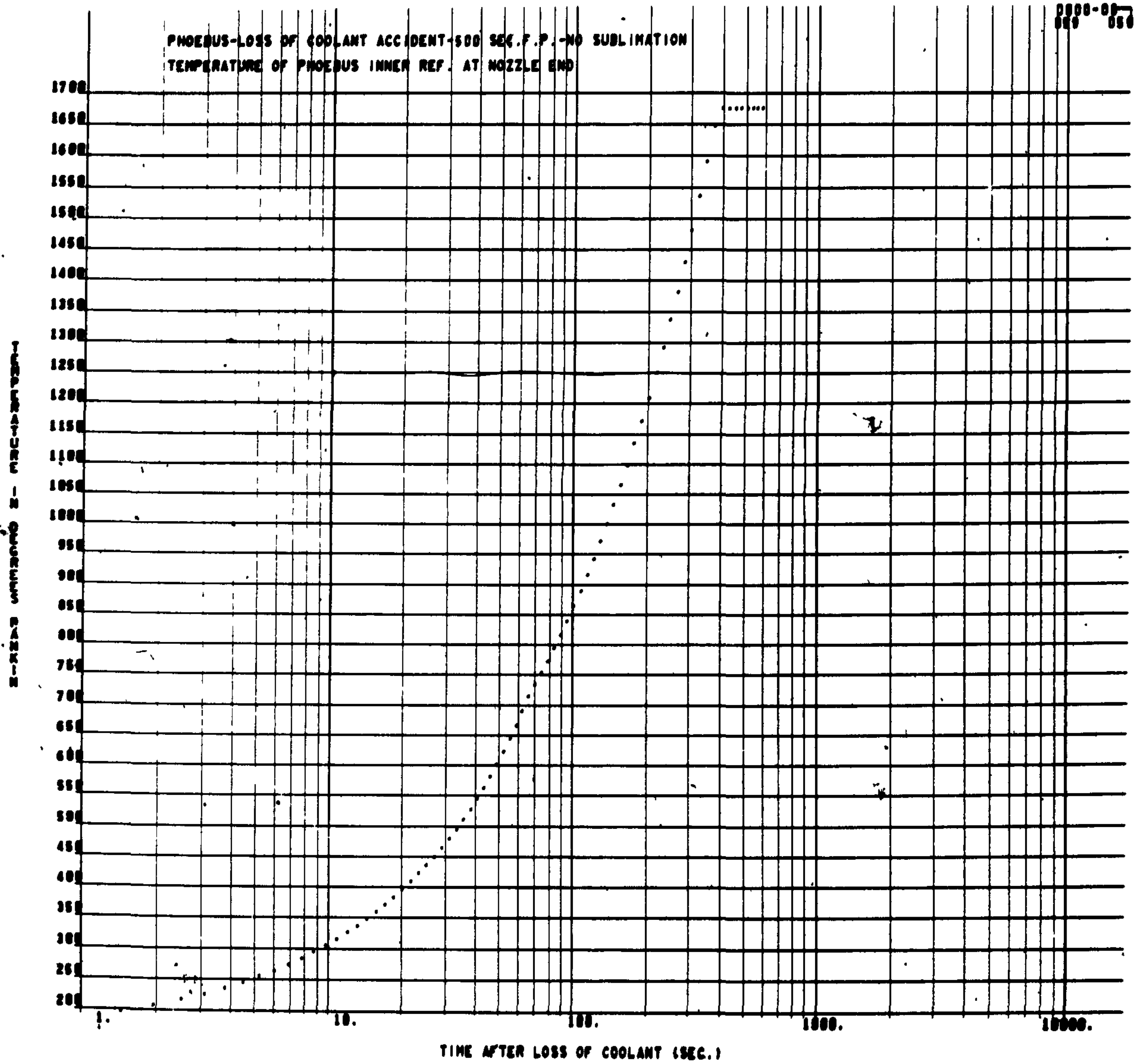

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