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# APOLLO LOGISTICS SUPPORT SYSTEMS MOLAB STUDIES

# TASK ORDER N-45 ON

# RADIOISOTOPE POWER SYSTEMS FOR A LUNAR SURFACE VEHICLE

Prepared under Contract No. NAS8-11096 by

W. L. Breazeale

NORTHROP SPACE LABORATORIES
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Huntsville, Alabama

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NASA - GEORGE C. MARSHALL SPACE FLIGHT CENTER
Huntsville, Alabama

March 1965

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ASTRIONICS LABORATORY

NASA-GEORGE C. MARSHALL SPACE FLIGHT CENTER

# PREFACE

This document by Northrop Space Laboratories, Huntsville Department, is a report to Marshall Space Flight Center on work performed under Task Order N-45, Contract No. NAS8-11096. A 16 man-week effort beginning on October 1, 1964, and ending on March 4, 1965, was expended on this task.

The NASA Technical Liaison Representative for this Task Order was Mr. E. E. Dungan of Advanced Studies (R-ASTR-A).

The information contained in this document represents the tradeoff studies performed on nuclear/fuel cell power systems for the MOLAB and other lunar surface vehicles.

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# SECTION 1.0

## SUMMARY

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The advantages and feasibility of combining a fuel cell with each of five radioisotope electric power systems are investigated. The five nuclear systems considered are a Brayton cycle system, a Mercury-Rankine cycle system, a Dowtherm-A Rankine cycle system, a Stirling engine system, and a thermionic system.

The optimized system weight for each fuel cell/nuclear system is calculated for the MOLAB mission, and weight savings of 500 pounds to 1020 pounds are realized over an all fuel cell system for the mission. In addition to the MOLAB mission, similar calculations are made for other missions. Also the competitive regions for fuel cells and for nuclear systems are established.

Discussion of advantages other than the weight savings afforded by a nuclear/fuel cell system are included, and recommendations for further study are made.

Author

## SECTION 2.0

## INTRODUCTION

The successful completion of a lunar surface exploration mission necessitates the use of a rugged, lightweight, reliable electric power system. The all fuel cell system presented in reference one has several undesirable features which reduces the attractiveness of such a system. One such feature is the large amounts of cryogenic fuels required for the mission and the inherent problems of storing this fuel for extended periods. Also, the large amounts of cryogenics and storage tanks result in a heavy power system, thereby, reducing the allowable weights of other systems and scientific equipment.

One possible way of alleviating the problems mentioned above is to combine a fuel cell system with another electric power system whose specific weight (pounds/kilowatt-hour) for the mission duration is lower than that of the fuel cell system. Batteries are eliminated because of their high specific weights (approximately 15 to 20 pounds/kilowatt hour), and solar cells are ruled out primarily because of the long lunar nights to which the system is subjected. A nuclear radioisotope system which would supply the power for the constant part of the power profile appears to have the necessary requirement, namely low specific weight (0.5 to 1.2 lbs/KWH).

In order to establish the feasibility of combining the fuel cell system with the nuclear system and to obtain the optimum combination of these systems, trade-off studies are necessary. The nuclear systems considered in these trade-off studies are a Brayton gas cycle system, a mercury Rankine cycle system, a Dowtherm-A Rankine cycle system, a Stirling engine system and a thermionic system.

# SECTION 3.0

## GUIDELINES AND ASSUMPTIONS

Since most of the applicable nuclear system designs are based on Apollo requirements, certain changes in the design are necessary to assure compatibility with the lunar surface mission. These changes will be described in subsequent sections of this report. The following assumptions apply to a typical MOLAB mission and insure that the various systems are evaluated on similar requirements.

a. The output range of the nuclear systems is 2 to 4 kW(e).

b. The useful life of the system is one year.

c. State-of-the-art in the power systems is current for the projected application period of 1970-75.

d. Adequate quantities of Pu-238 are available.

e. Shielding sufficient to reduce the dose rate to 100 mrem/hr at one meter is required.

f. Radiator area is limited to less than 100 $ft^2$.

g. The power profile used in the optimization is the one generated in reference 1 and listed in Table 1.

TABLE 1

MOLAB POWER PROFILE

| Time (hrs) | Power Level (kW(e)) |
|---|---|
| 17.0 | 6.750 |
| 0.5 | 6.600 |
| 38.5 | 6.250 |
| 4.0 | 6.000 |
| 0.5 | 5.600 |
| 27.75 | 2.850 |
| 2.5 | 2.600 |
| 114.75 | 2.250 |
| 125.0 | 2.000 |

# SECTION 4.0

# FUEL CELL OPTIMIZATION

## 4.1 POWER PROFILE DEVELOPMENT

The optimization of a fuel cell system requires complete knowledge of the power demands on the system. These power demands are usually described by a power profile, that is, the time duration of each distinct power level. A power profile for the MOLAB mission was developed during a previous study and reported in Reference 1. Since part of the electrical power system's output is furnished by the nuclear system, the power profile to which the fuel cell portion is optimized must be altered. This alteration consists of subtracting the nuclear system output from the "standard" power profile. The remaining power profile is then used to optimize the fuel cell system. These power profiles are given in tabular form in Tables 2 through 5.

## 4.2 OPTIMIZATION TECHNIQUE

Once the desired power profile is obtained, this profile is used as input to an IBM-1620 program, which calculates the weights of the system components for varying numbers of fuel cell modules. This program is described in Reference 1. Figures 1 through 5 illustrate how the system component weights vary with the number of fuel cell modules in the system. The optimized fuel cell system weights are listed below. Figure 6 depicts the same information in graphical form.

| Nuclear Power (kW(e) | Optimized Fuel Cell System Weight (Pounds) |
|---|---|
| 2.0 | 691 |
| 2.5 | 570 |
| 3.0 | 488 |
| 3.5 | 418 |
| 4.0 | 347 |

TABLE 2

POWER PROFILE FOR FUEL CELL OPTIMIZATION
(2 kW(e) Nuclear System)

| Time (hrs) | Power Level (kW(e)) |
|---|---|
| 17.0 | 4.750 |
| 0.5 | 4.600 |
| 38.5 | 4.250 |
| 4.0 | 4.000 |
| 0.5 | 3.600 |
| 27.75 | 0.850 |
| 2.5 | 0.600 |
| 114.75 | 0.250 |

TABLE 3

POWER PROFILE FOR FUEL CELL OPTIMIZATION
(2.5 kW(e) Nuclear System)

| Time (Hrs) | Power Level (kW(e) |
|---|---|
| 17.0 | 4.250 |
| 0.5 | 4.100 |
| 38.5 | 3.750 |
| 4.0 | 3.500 |
| 0.5 | 3.100 |
| 27.75 | 0.350 |
| 2.5 | 0.100 |

TABLE 4

POWER PROFILE FOR FUEL CELL OPTIMIZATION
(3.0 kW(e) Nuclear System)

| Time (hrs) | Power Level kW (e) |
|---|---|
| 17.0 | 3.750 |
| 0.5 | 3.600 |
| 38.5 | 3.250 |
| 4.0 | 3.000 |
| 0.5 | 2.600 |

## TABLE 5

### POWER PROFILE FOR FUEL CELL OPTIMIZATION
### (3.5 kW(e) Nuclear System)

| Time (Hrs) | (Power Level (kW(e) |
|---|---|
| 17.0 | 3.250 |
| 0.5 | 3.100 |
| 38.5 | 2.750 |
| 4.0 | 2.500 |
| 0.5 | 2.100 |

## TABLE 6

### POWER PROFILE FOR FUEL CELL OPTIMIZATION
### (4.0 kW(e) Nuclear System)

| Time (Hrs) | Power Level (kW(e) |
|---|---|
| 17.0 | 2.750 |
| 0.5 | 2.600 |
| 38.5 | 2.250 |
| 4.0 | 2.000 |
| 0.5 | 1.600 |

SECTION 5.0

# NUCLEAR SYSTEMS

## 5.1 GENERAL

As previously mentioned, the nuclear systems, described in References 2 through 6, are designed for use in the Apollo mission. This mission has significantly different requirements from those of the MOLAB, and therefore, some changes are necessary in certain system components.

Two major changes are required in each of the systems considered. One of these is in the radiator size, and the other is in the heat block. The heat block change is required because plutonium-238 is the fuel considered rather than polonium-210. This change results in an increase in the heat block weight due to the lower specific power of plutonium-238 and the additional shielding required. The original heat block concept for each system is adhered to as much as possible, but in some instances the concept is changed to a more favorable geometry for shielding. Shielding weights are established using reference 7.

As mentioned in Section 3.0, the radiator size is limited to less than 100 square feet. In order to reduce the radiator size, the assumption is made that the system can operate at a higher temperature. Such a change in system operating conditions results in a non-optimum system in general, and for some systems, these changes may not be feasible. However, the intent of these studies is to show the benefits of combining nuclear systems with fuel cell systems, but not to select a "best" system or to imply one system is superior to another. For these reasons, caution is required in comparing systems of comparable weights such as the Brayton cycle system and the Mercury Rankine cycle system.

For the purpose of establishing weight data at different power levels, the assumption is made that a certain portion of the system weight, such as controls, radiator, power conditioning, etc., is constant, while the remainder of the system weight depends on power level. Of this variable portion of the system weight, the heat block weight, the isotope weight, and the shielding weight are actually calculated for each power level, while the remainder of the variable weight is assumed linear with power. Such assumptions may penalize one system more than another, but the selection of a "best" nuclear system is not the intention of this report.

Considering all the assumptions made, it is felt that the weight data generated is conservative and fulfills the purpose for which it is intended.

## 5.2 NUCLEAR SYSTEMS DESCRIPTION

### 5.2.1 Brayton Cycle System

The ideal Brayton cycle is composed of two reversible constant pressure processes and two adiabatic, reversible processes. Overall cycle effeciency in the range of 15 to 18 per cent is obtainable. The system is composed of two independent power loops, with each loop consisting of a combined rotating unit (CRU), a radiator and a power conditioning and controls subsystem. The radioisotope heat source is common to both loops as is the power conditioning subsystem. Only one power loop operates at a time with the other loop on standby. The major advantages of the Brayton system are the use of a single-phase, inert working fluid and good efficiency. Disadvantages of the system include low heat rejection temperature and a relatively heavy system weight. A more detailed description of the Brayton cycle system is found in reference 2.

### 5.2.2 Mercury Rankine System

The mercury-Rankine system consists of two CRU's, a boiler-source container, a two-part radiator, and associated auxilliary equipment. The mercury working fluid is vaporized in the boiler and then superheated and subsequently expanded through a two stage turbine to provide shaft work. The exhaust vapor is condensed to saturated liquid in one part of the radiator and then subcooled in the other part of the radiator. The liquid mercury then passes through the pump and back into the boiler. Overall efficiencies in the neighborhood of 12 percent are possible with this system. A complete description of the system is contained in reference 3.

Advantages of this system include the small radiator area (about 90 square feet) and the large amount of developed hardware applicable to the system. However, significant problems are still present in the system. These include corrosion within the boiler and vapor quality at the turbine inlet, which influences corrosion rates within the turbine.

### 5.2.3 Dowtherm-A Rankine System

The Dowtherm-A Rankine system utilizes essentially the same type of components as the mercury-Rankine system. The Dowtherm system, however, operates at lower temperatures than the mercury system, and utilizes a noncorrosive working fluid. The system-overall efficiency is about 15 percent. Major component development is still necessary on this system. A more detailed description of this system is found in reference 4.

### 5.2.4 Stirling Engine

The ideal Stirling cycle is characterized by two isothermal processes and two constant volume processes. Such a cycle with a regenerative arrangement approaches the efficiency of a Carnot cycle. Thus the Stirling engine is a very efficient power generating device (overall efficiency approaching 20 percent). However, the engine is a reciprocating device with the inherent problems of sliding seals, which makes long life operation questionable. Reference 5 discuss the Stirling system in detail.

### 5.2.5 Thermionic System

A complete description of this system is found in reference 6. The thermionic system has three distinct advantages over other systems. These are very low radiator area, low weight, and compactness. Disadvantages include additional development and demonstrated long life capability of the system.

# SECTION 6.0

# RESULTS

## 6.1 GENERAL

In the previous sections of the report, the optimization of the fuel cell system and the development of weight data for the nuclear systems were discussed. This section treats the results of "combining" the fuel cell system with the nuclear systems. However, before the actual results are presented, perhaps some discussion of the expected results is appropriate.

One of the most desired results of combining the nuclear and the fuel cell systems is to obtain a lower power system weight. Since the fuel cell system weight decreases as the amount of power furnished by the nuclear system increases and since the nuclear system weight increases with power level, then the combined system weight should exhibit a minimum. In all the systems investigated, this minimum system weight does exist and is significantly lower than the all fuel cell system weight.

## 6.2 FOURTEEN DAY MISSION

For the fourteen day MOLAB mission, Figures 7 through 11 depict the results of combining the fuel cell system with the various nuclear systems.

Figure 7 applies to the nuclear Brayton cycle/fuel cell system. The minimum system weight is 1500 pounds which is a weight savings of about 500 pounds over the all fuel cell system. The minimum occurs for a system with a 2.5 kW(e) nuclear output which means that the fuel cell portion of the system supplies all power demands over 2.5 kW(e).

Figure 8 shows the weight relationships for a nuclear mercury Rankine cycle/fuel cell system. The minimum weight for this system is 1400 pounds and occurs at a nuclear power level of 2.25 kW(e). The weight savings of this system over the all fuel cell system is 600 pounds.

The minimum weight for the nuclear Dowtherm-A Rankine/ fuel cell system is 1100 pounds as shown in Figure 9. The minimum for this system occurs at a 2.8 kW(e) nuclear power level. The weight savings is 900 pounds over the all fuel cell system.

For the nuclear Stirling engine/fuel cell system, the minimum of 1390 pounds occurs at a nuclear power level of 2.3 kW(e), as shown in Figure 10. This system has a weight advantage of 610 pounds over the all fuel cell system.

The system that appears to exhibit the lightest weight is the thermionic/fuel cell system with a weight of 980 pounds. This minimum weight occurs at a nuclear power level of 2.75 kW(e) and offers a weight savings of 1020 pounds over the all fuel cell system. Figure 11 shows the weight relationships for the thermionic/fuel cell system.

## 6.3 OTHER MISSIONS

Although the use of nuclear/fuel cell systems on a fourteen day MOLAB mission results in considerable weight savings over the all fuel cell system, even larger weight savings are possible on longer missions. For example, Figure 12 shows the weight relationships for a nuclear Brayton cycle/fuel cell system on a twenty-one day MOLAB type mission. The minimum weight is 1650 pounds which is a savings of 950 pounds over an all fuel cell system. For this longer mission, the "hybrid" system results in a 36 percent weight savings over the fuel cell system, whereas the savings for the fourteen day mission is 25 percent. Similarly, for the thermionic system, the savings are 58 percent and 51 percent respectively.

Since the weight advantages of a nuclear system over a fuel cell system vary with mission length, the competitive regions, i.e., power level and mission length, need to be determined for the two systems. In order to establish these competitive areas, the weights of both nuclear and fuel cell systems are calculated for several constant power profiles of varying time duration. Figure 13 shows these weights for the Brayton cycle and the fuel cell systems, while Figure 14 is for the thermionic and the fuel cell systems. From Figure 13 or 14, consider the point where a fuel cell system curve of a given power intersects with the nuclear system curve of equal power. If the mission length at this point is used as the abscissa and the power level as the ordinate, then curves such as shown in Figures 15 and 16 are obtained. Thus these curves are the dividing line between the competitive regions for the fuel cell and the respective nuclear systems. For example, if a mission requiring a constant power level of 2 kW(e) for 15 days is anticipated, then the nuclear Brayton system or the thermionic system would be lighter than a fuel cell system.

The previous results are for unmanned missions. If manned missions are desired, then credit must be taken for the potable water produced by the fuel cells. This credit is accounted for as a weight penalty (26 pounds/day for a two man mission) to the nuclear system. Figures 17 and 18 are the same as Figures 13 and 14 except for the weight penalty on the nuclear system. Using the same method as before, the competitive regions for the manned missions are shown in Figures 19 and 20.

There are two significant features to the results just presented. These are that the nuclear systems do not compete on short missions (less than five days for the Brayton cycle and less than three days for the thermionic) and that the fuel cell do not compete on long unmanned missions (greater than 30 days for the Brayton cycle).

# SECTION 7.0

## DISCUSSION

As previously mentioned, one of the most desired results of the combining of radioisotope nuclear systems with fuel cell systems is to obtain significant weight reductions over the all fuel cell system now proposed for use. The studies indicate that the nuclear/fuel cell system produces weight savings of 500 to 1000 pounds. The advantages of such savings are obvious. However, there are other advantages to be realized from this combined system which are not so obvious.

One of the most important advantages of the nuclear/fuel cell system is the safety aspect afforded by the long life of the nuclear part of the system. Suppose the mission was unexpectedly and unavoidably extended. The nuclear part of the system could provide sufficient power for all the necessary system functions thereby saving the fuel cell reactants for life support purposes. In other words the nuclear system provides substantial power contingenices at no additional weight. In order to further exploit the safety aspect of the nuclear/fuel cell system, part of the expected weight savings can be traded for additional life support expendables.

The primary nature of early lunar surface missions is scientific, and this aspect of the mission could be strengthened by trading some of the power system weight savings for additional scientific equipment. Also, the use of a nuclear system permits an active scientific program during the dormant period without a weight penalty for power system expendables. Similarly, the nuclear system allows an active scientific program after the astronauts' departure. In fact, since the MOLAB can be remotely controlled from earth, the use of a nuclear system makes possible the continued exploration of the lunar surface with an unmanned MOLAB. Such use would significantly increase the scientific yield of the mission.

Certainly the trend in future space exploration and lunar exploration will be to longer missions requiring higher power levels. As shown in subsection 6.3, the nuclear systems have a significant weight advantage over fuel cells in the neighborhood of 30 days or longer. Thus, the use of nuclear systems on early lunar missions guarantees the availability of a suitable power system for extended explorations. In other words, the growth potential of the nuclear systems is excellent.

## SECTION 8.0

## RECOMMENDATIONS

The previous sections of this report are offered as proof of the desirability and the feasibility of combining a nuclear system with a fuel cell system for the MOLAB mission. Since many benefits are derivable from such a combination, the concept should be pursued beyond the trade-off study stage. A logical extension would be to prepare a conceptual and preliminary design of one or more of the nuclear systems for application to a lunar surface vehicle. The many interfaces of the power system with other vehicle systems would have to be accounted for in the design. A follow-on breadboard development and performance testing program appears to be justifiable based upon the current component state-of-the-art in radioisotope generators. A cooperative fuel encapsulating and processing program with the Atomic Energy Commission is highly recommended.

SECTION 9.0

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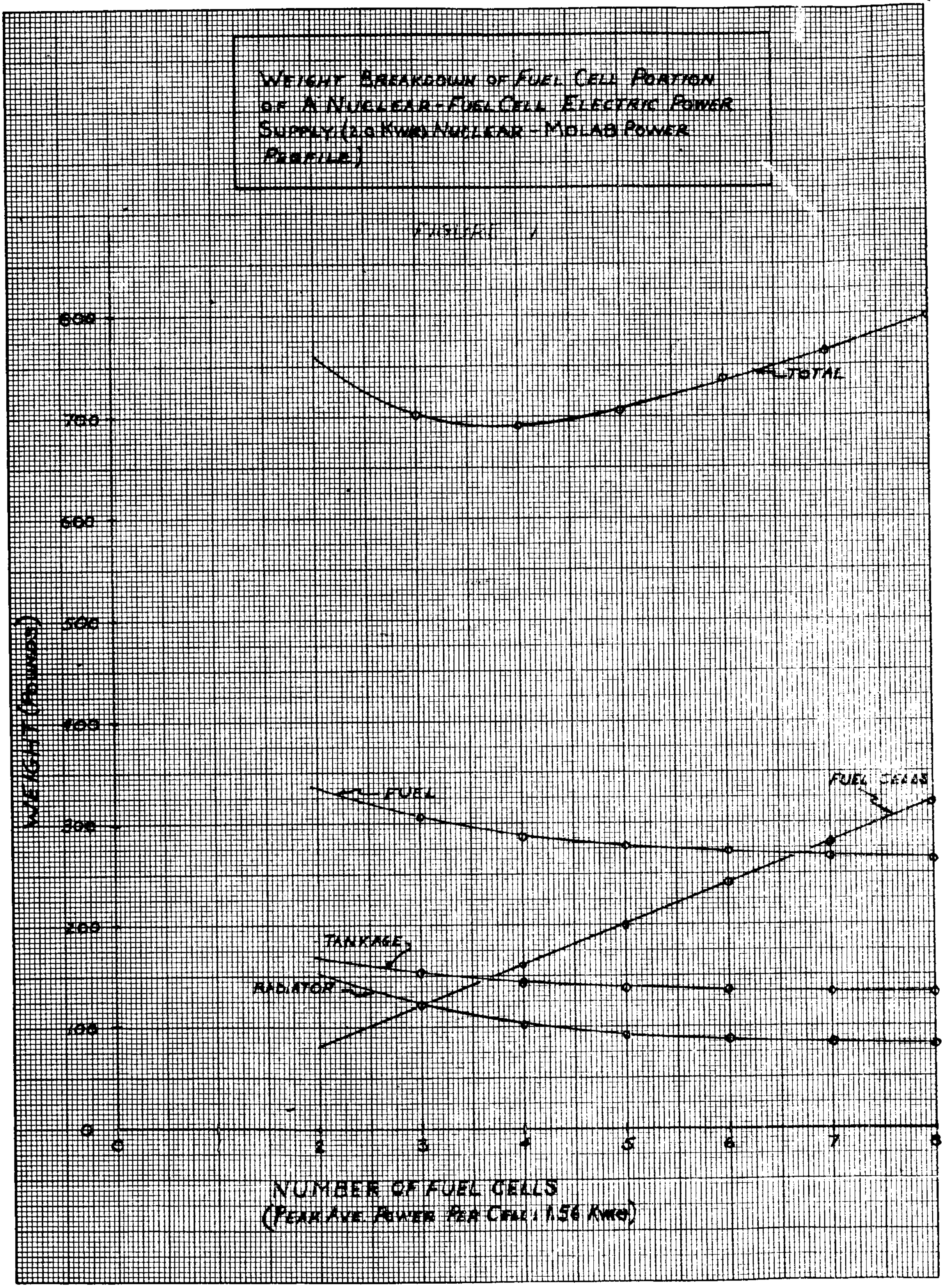


FIGURE 1. WEIGHT BREAKDOWN OF FUEL CELL PORTION OF A NUCLEAR-FUEL CELL ELECTRIC POWER SUPPLY. (2.0 KW(e) Nuclear)

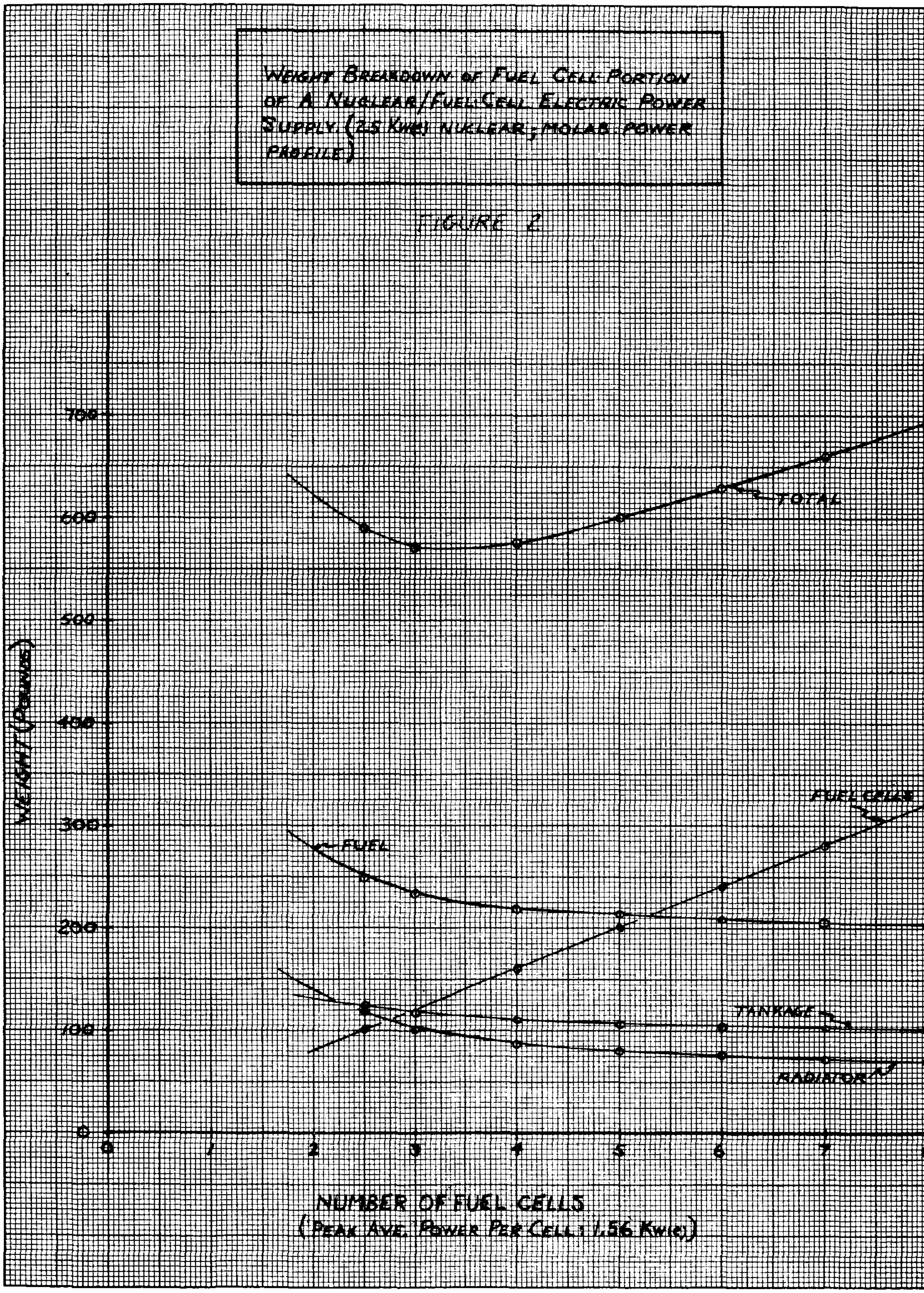


FIGURE 2. WEIGHT BREAKDOWN OF FUEL CELL PORTION OF A NUCLEAR-FUEL CELL ELECTRIC POWER SUPPLY. (2.5 KW(e) Nuclear)

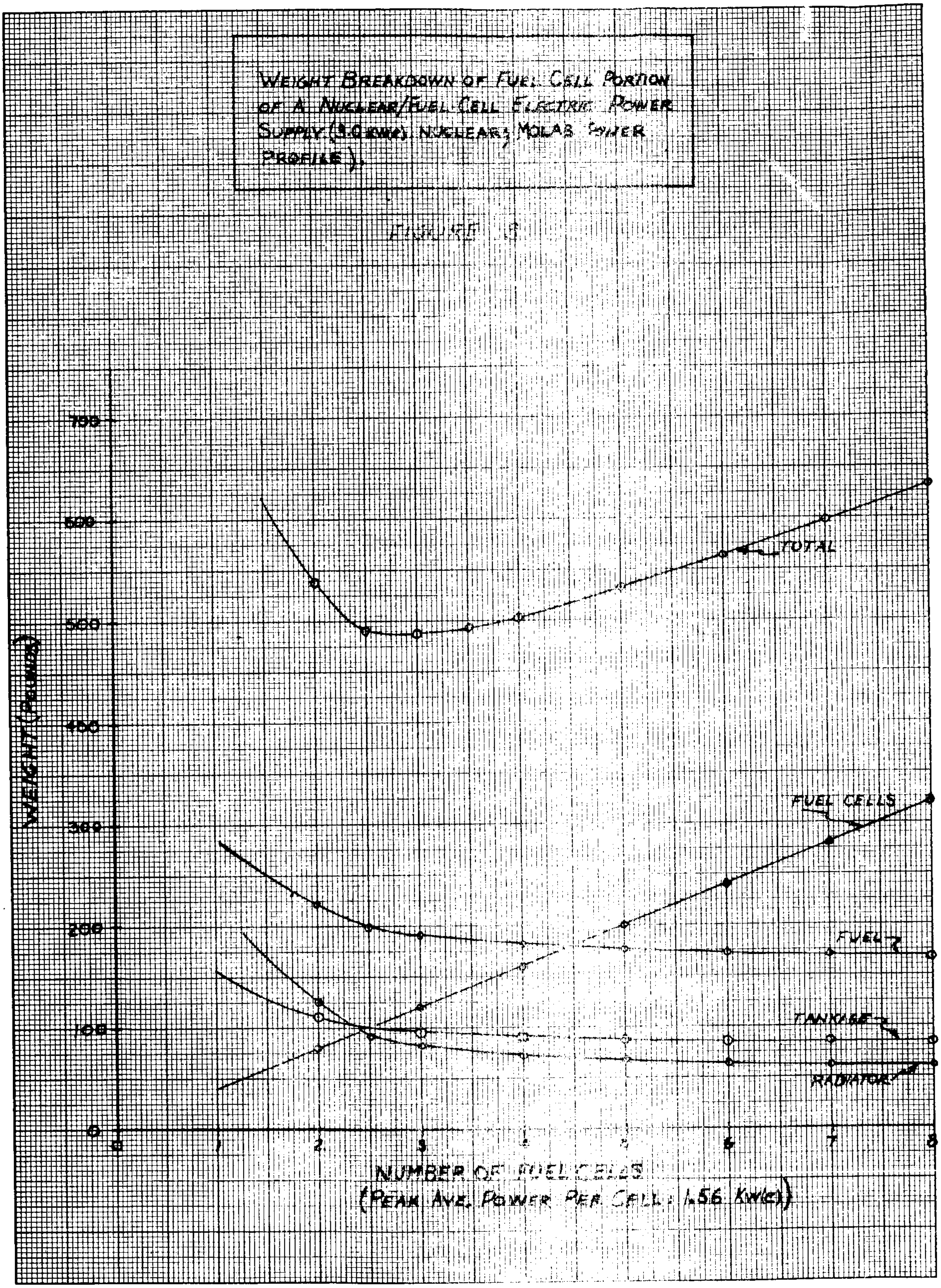


FIGURE 3. WEIGHT BREAKDOWN OF FUEL CELL PORTION OF A NUCLEAR-FUEL CELL ELECTRIC POWER SUPPLY. (3.0 KW(e) Nuclear)

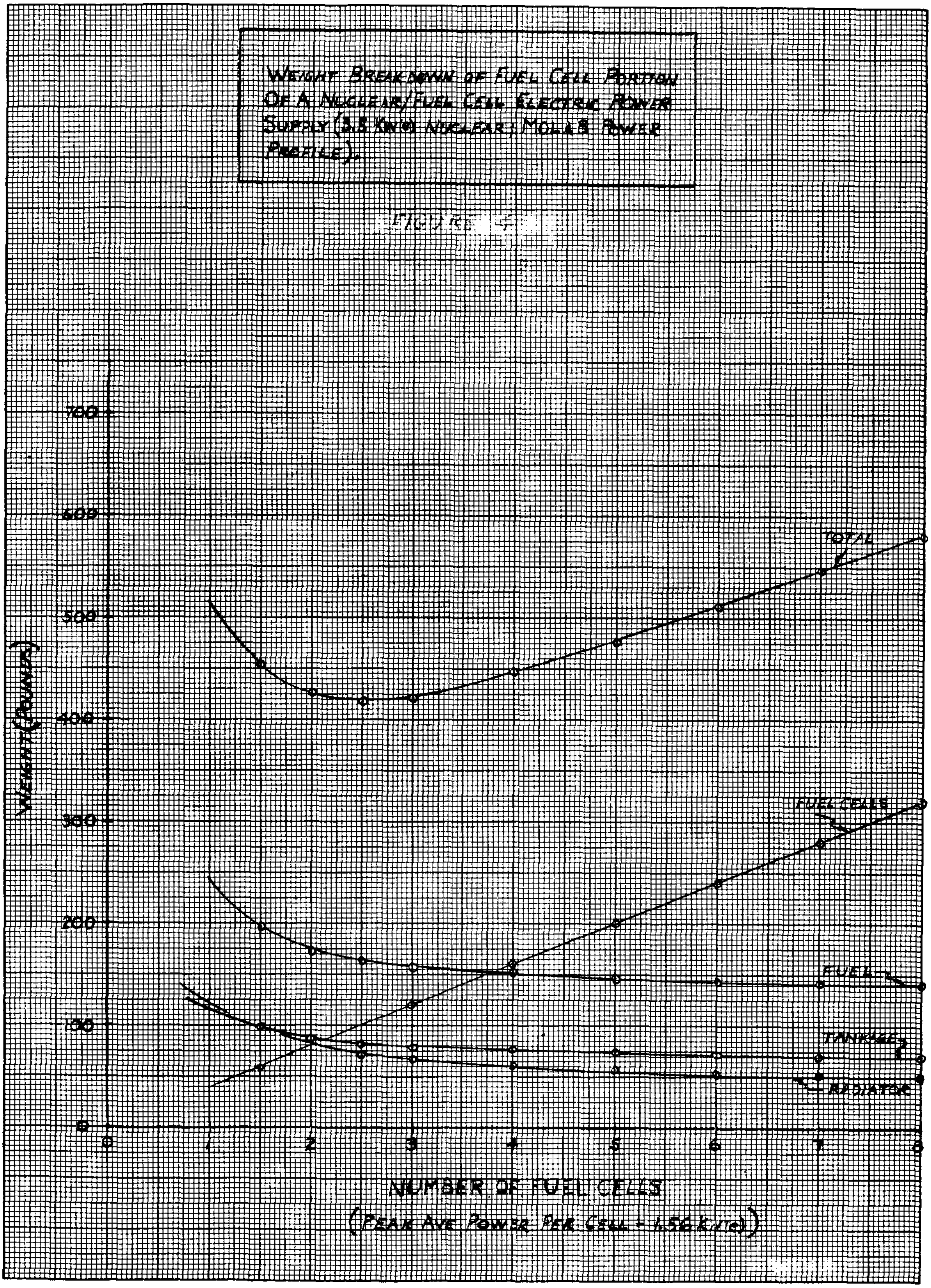


FIGURE 4. WEIGHT BREAKDOWN OF FUEL CELL PORTION OF A NUCLEAR-FUEL CELL ELECTRIC POWER SUPPLY. (3.5 KW(e) Nuclear)

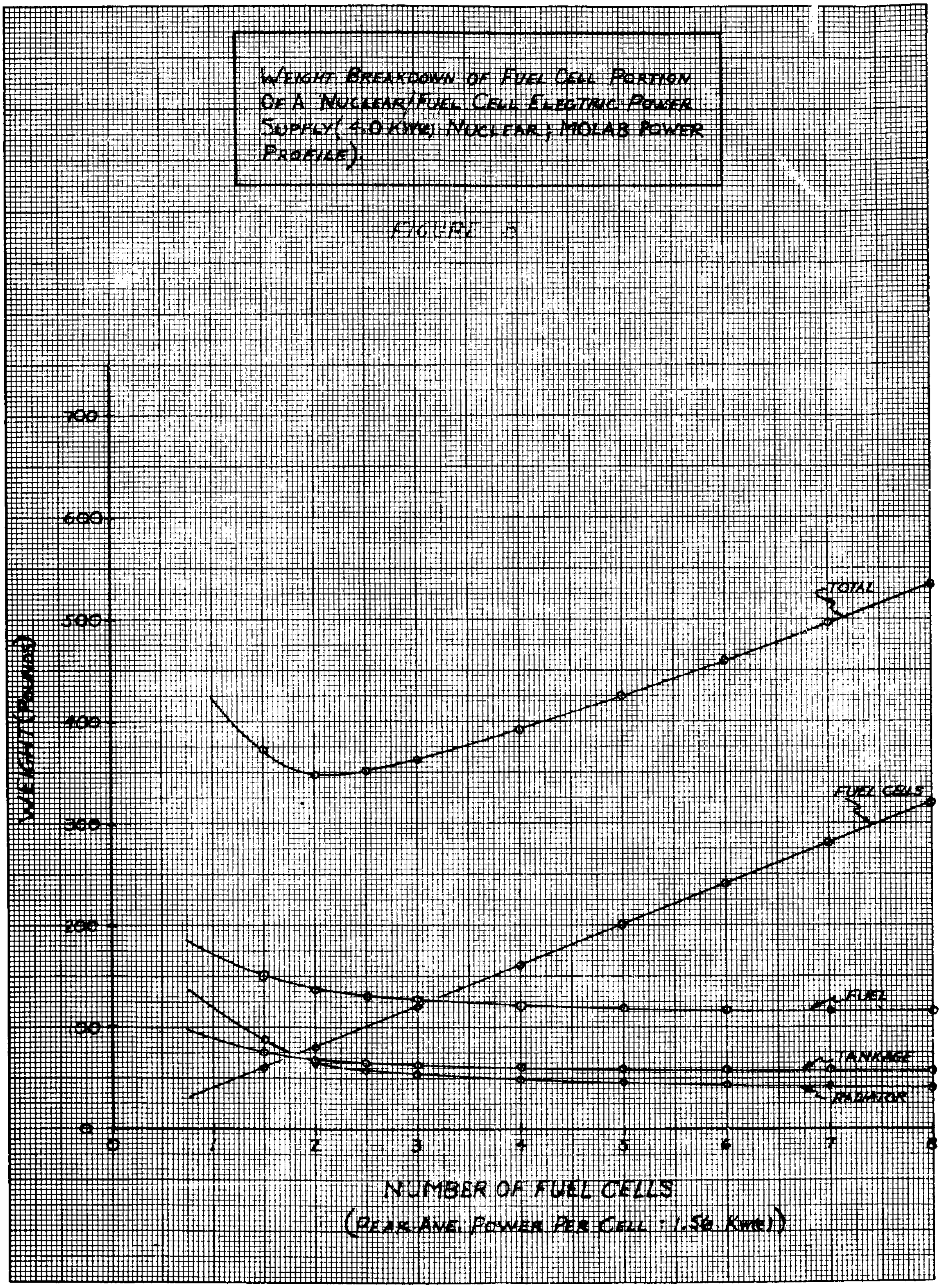


FIGURE 5. WEIGHT BREAKDOWN OF FUEL CELL PORTION OF A NUCLEAR-FUEL CELL ELECTRIC POWER SUPPLY. (4.0 KW(e) Nuclear)

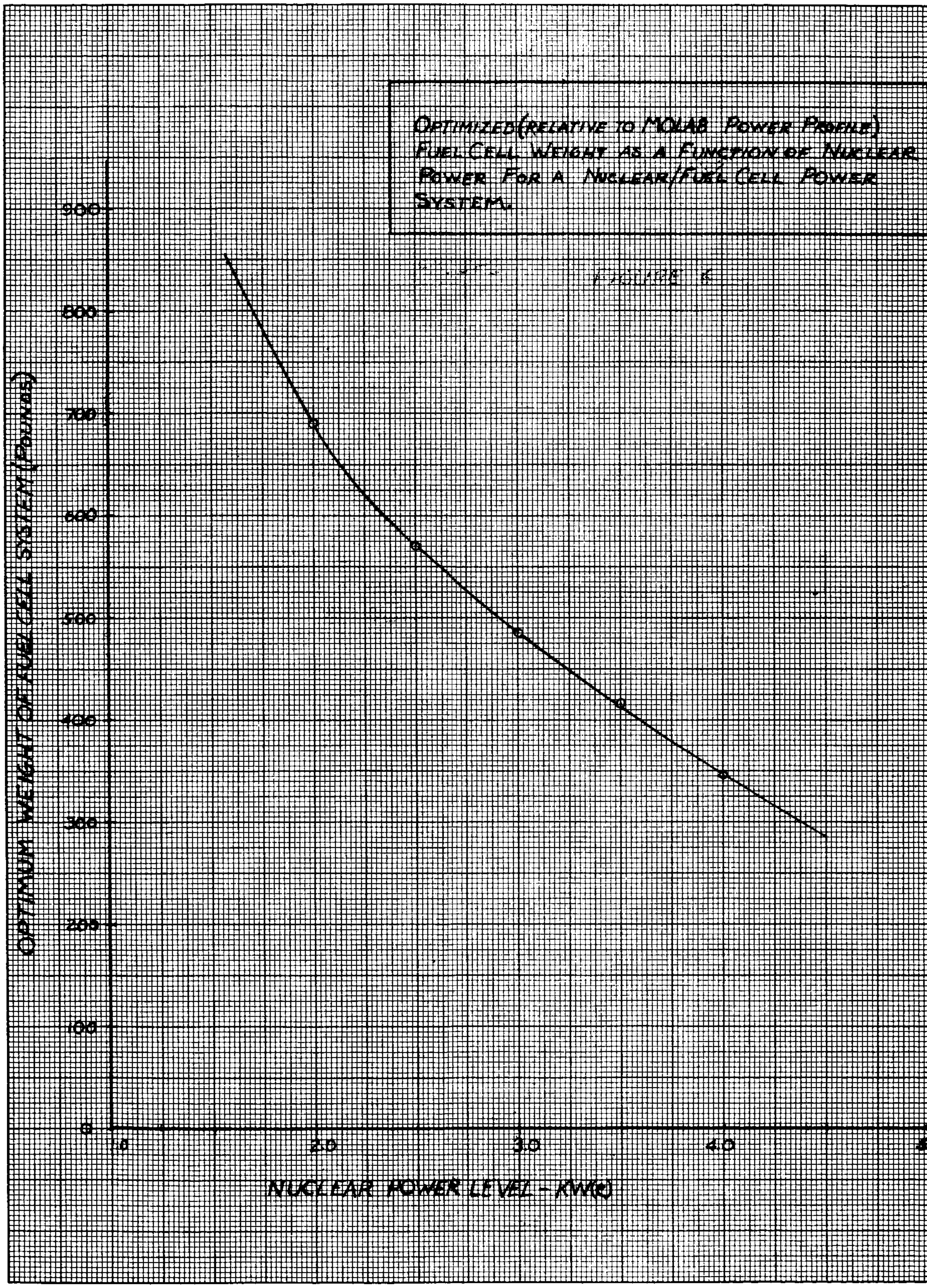


FIGURE 6. OPTIMIZED FUEL CELL WEIGHT AS A FUNCTION OF NUCLEAR POWER FOR A NUCLEAR/FUEL CELL POWER SYSTEM

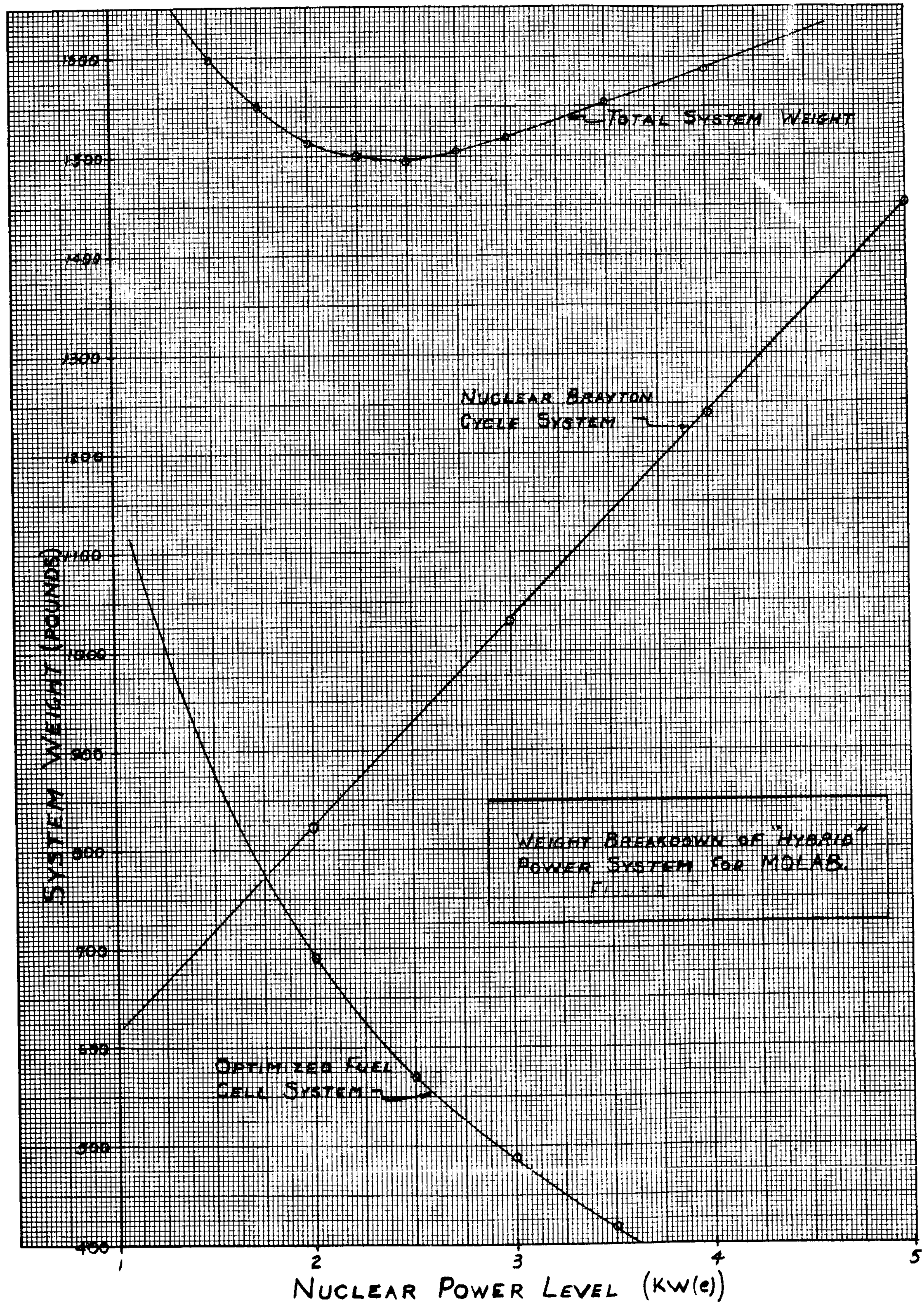


FIGURE 7. WEIGHT BREAKDOWN OF "HYBRID" POWER SYSTEM FOR MOLAB (Brayton Cycle)

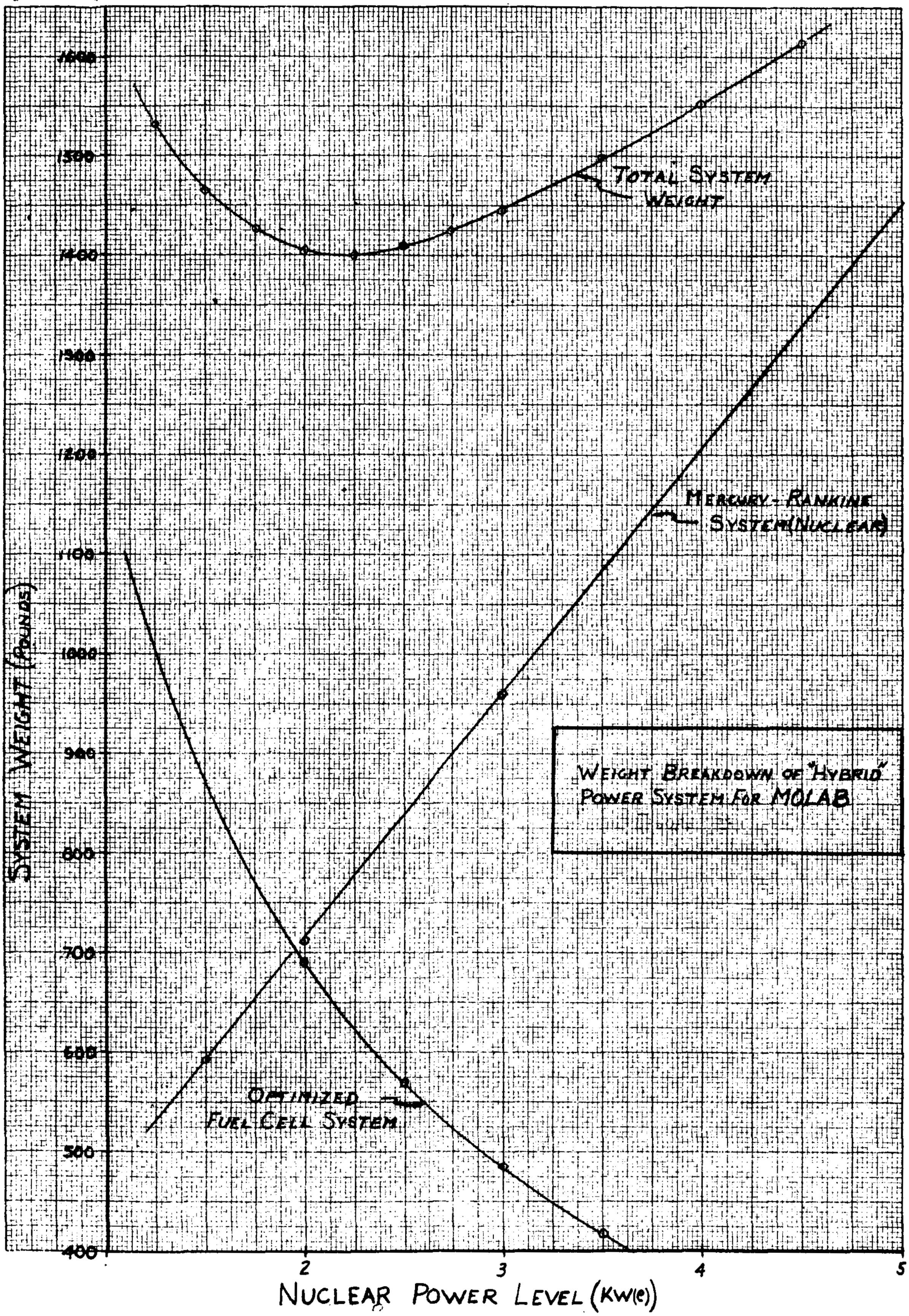


FIGURE 8. WEIGHT BREAKDOWN OF "HYBRID" POWER SYSTEM FOR MOLAB (Mercury-Rankine Cycle)

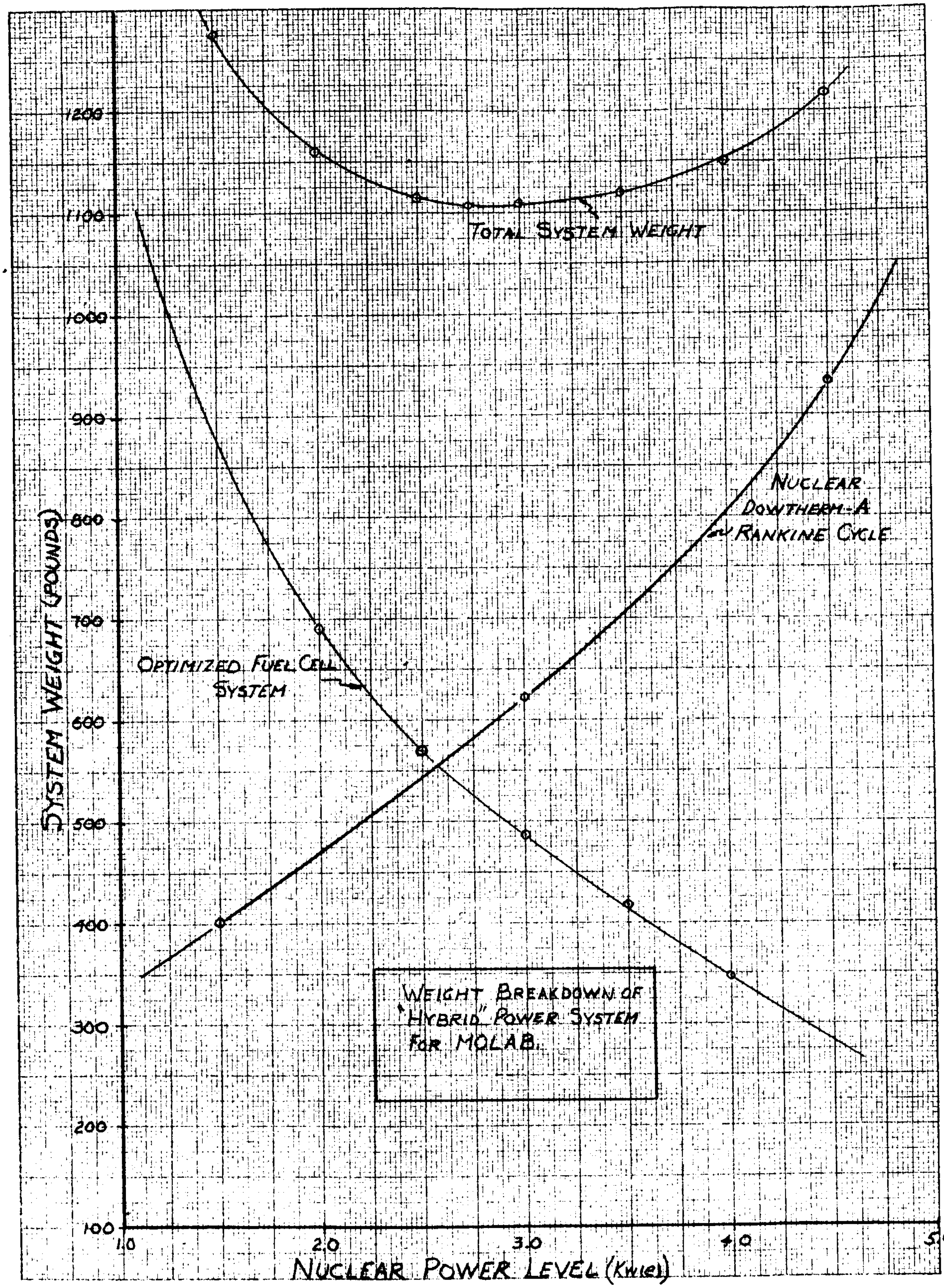


FIGURE 9. WEIGHT BREAKDOWN OF "HYBRID" POWER SYSTEM FOR MOLAB (Dowtherm-A Rankine Cycle)

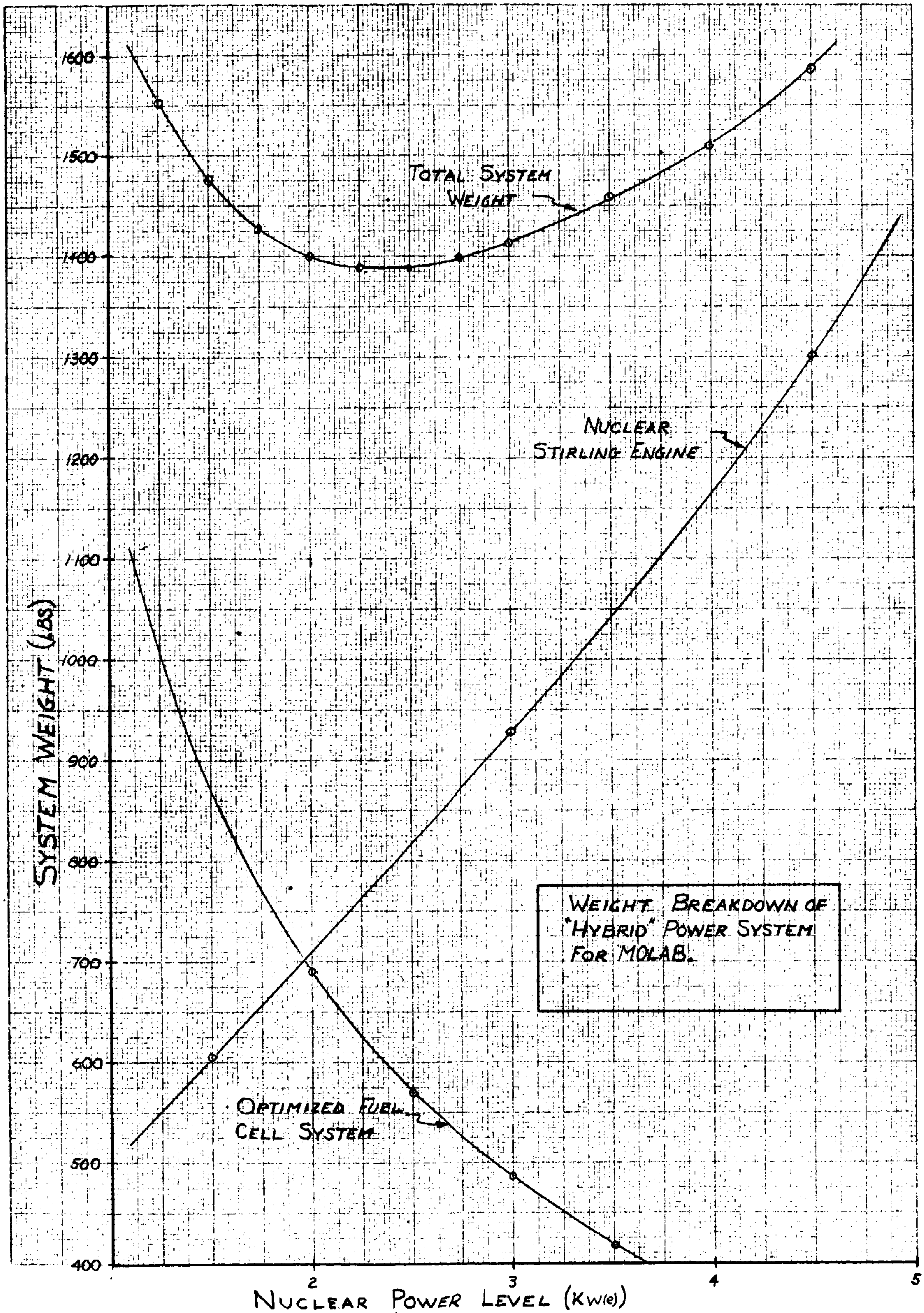


FIGURE 10. WEIGHT BREAKDOWN OF "HYBRID" POWER SYSTEM FOR MOLAB (Stirling Engine)

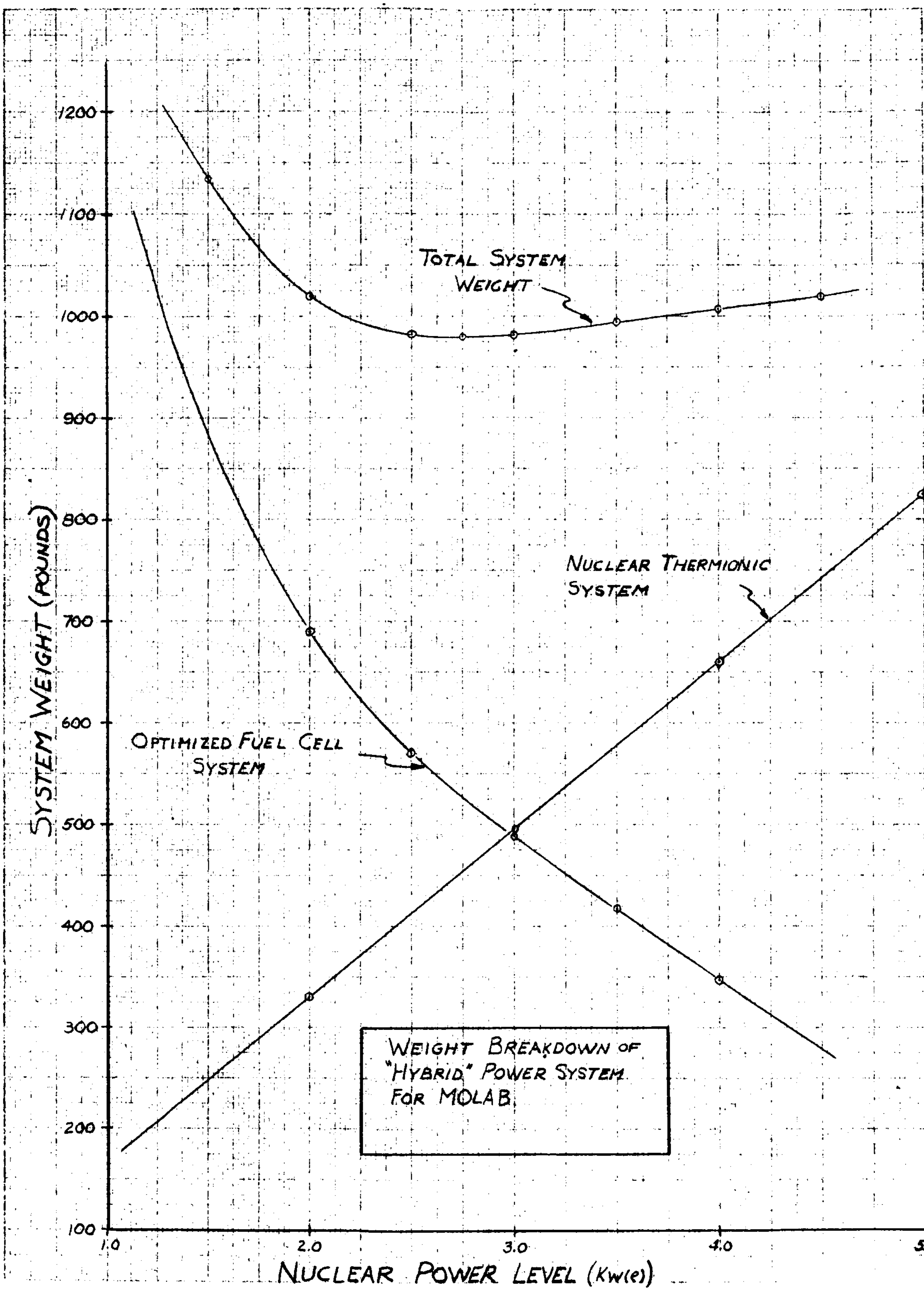


FIGURE 11. WEIGHT BREAKDOWN OF "HYBRID" POWER SYSTEM FOR MOLAB (Thermionic System)

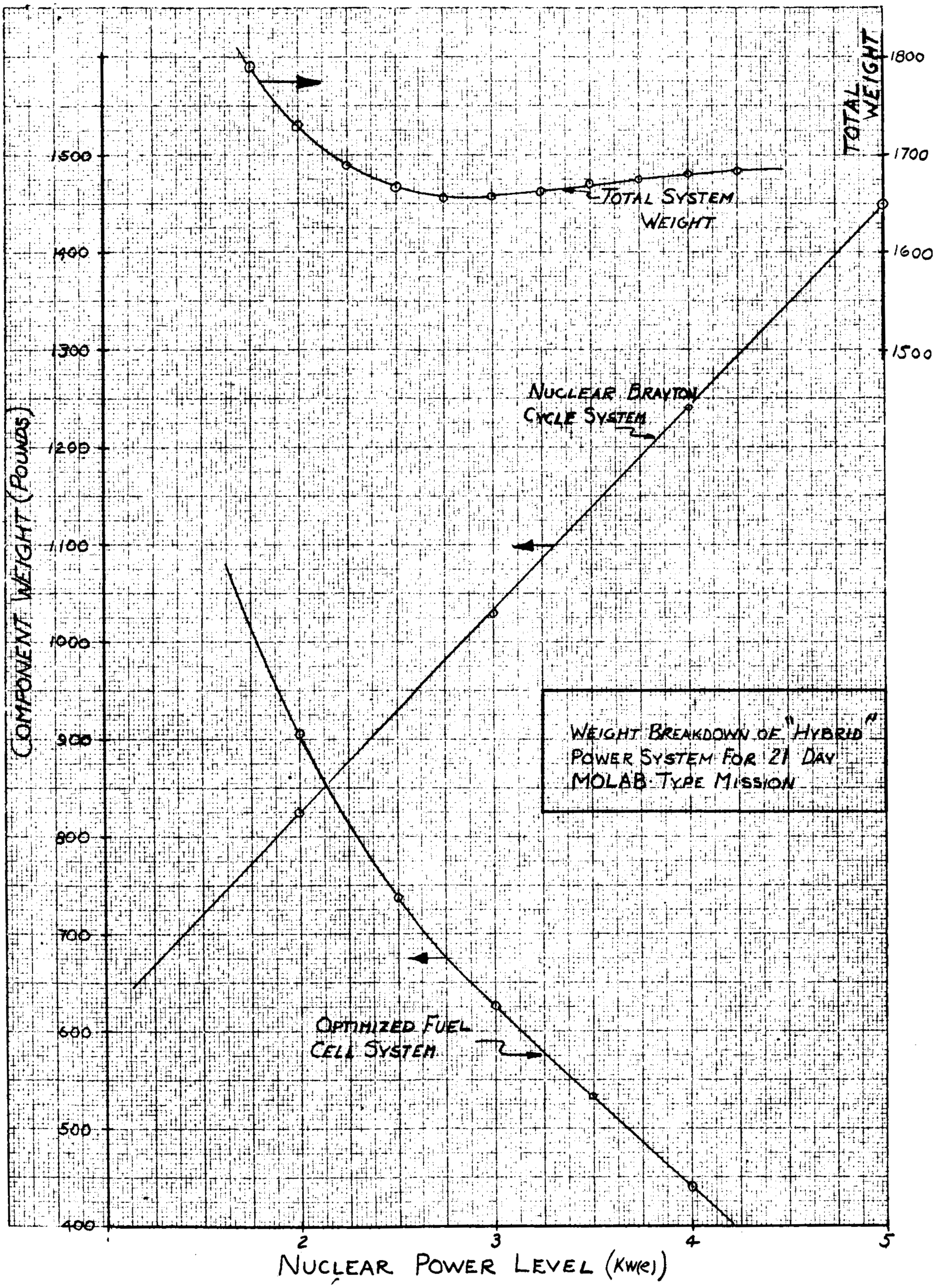


FIGURE 12. WEIGHT BREAKDOWN OF "HYBRID" POWER SYSTEM FOR 21 DAY MOLAB-TYPE MISSION (Brayton Cycle)

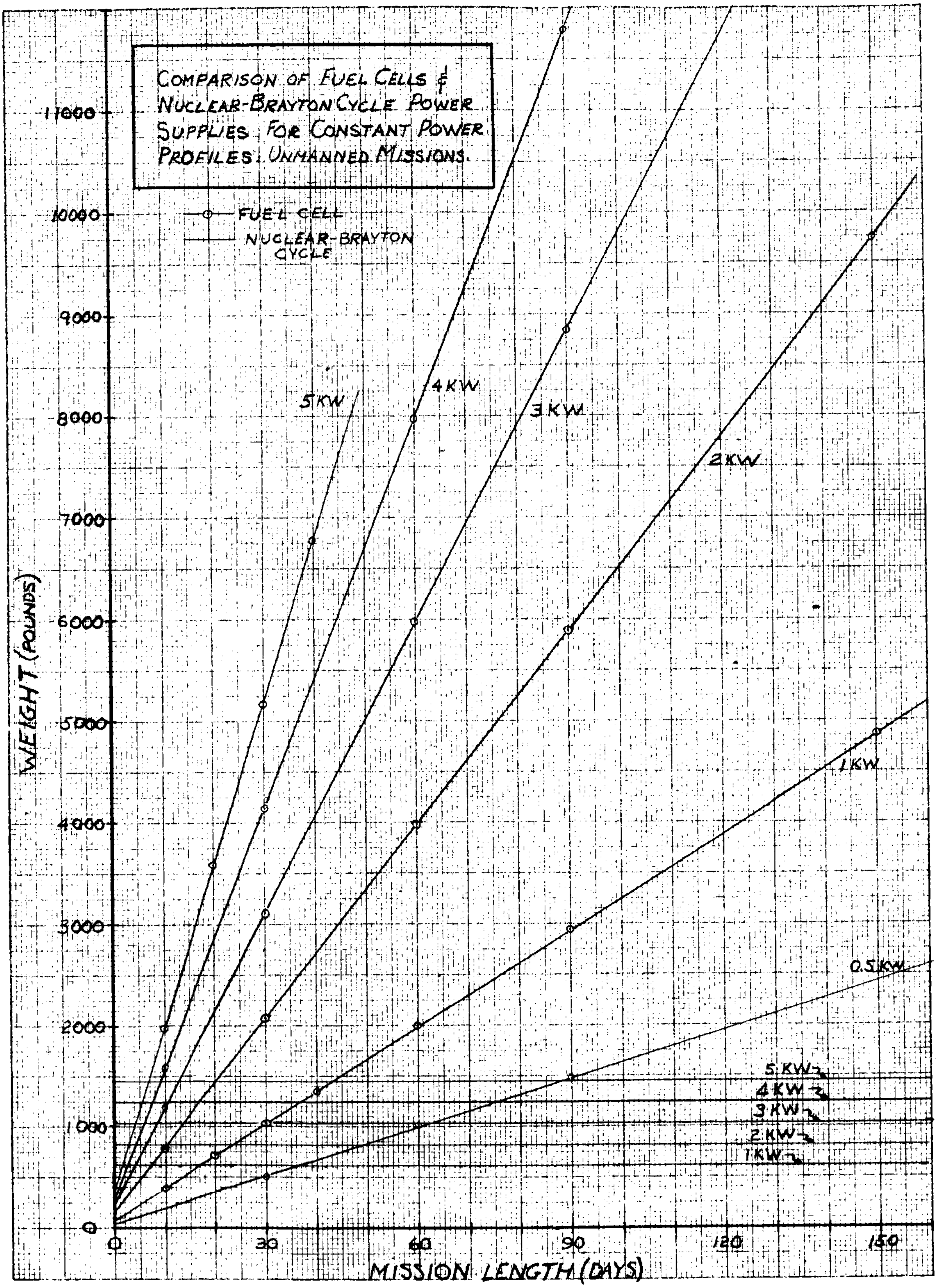


FIGURE 13. COMPARISON OF FUEL CELLS AND NUCLEAR-BRAYTON CYCLE POWER SUPPLIES FOR CONSTANT POWER PROFILES (Unmanned Mission)

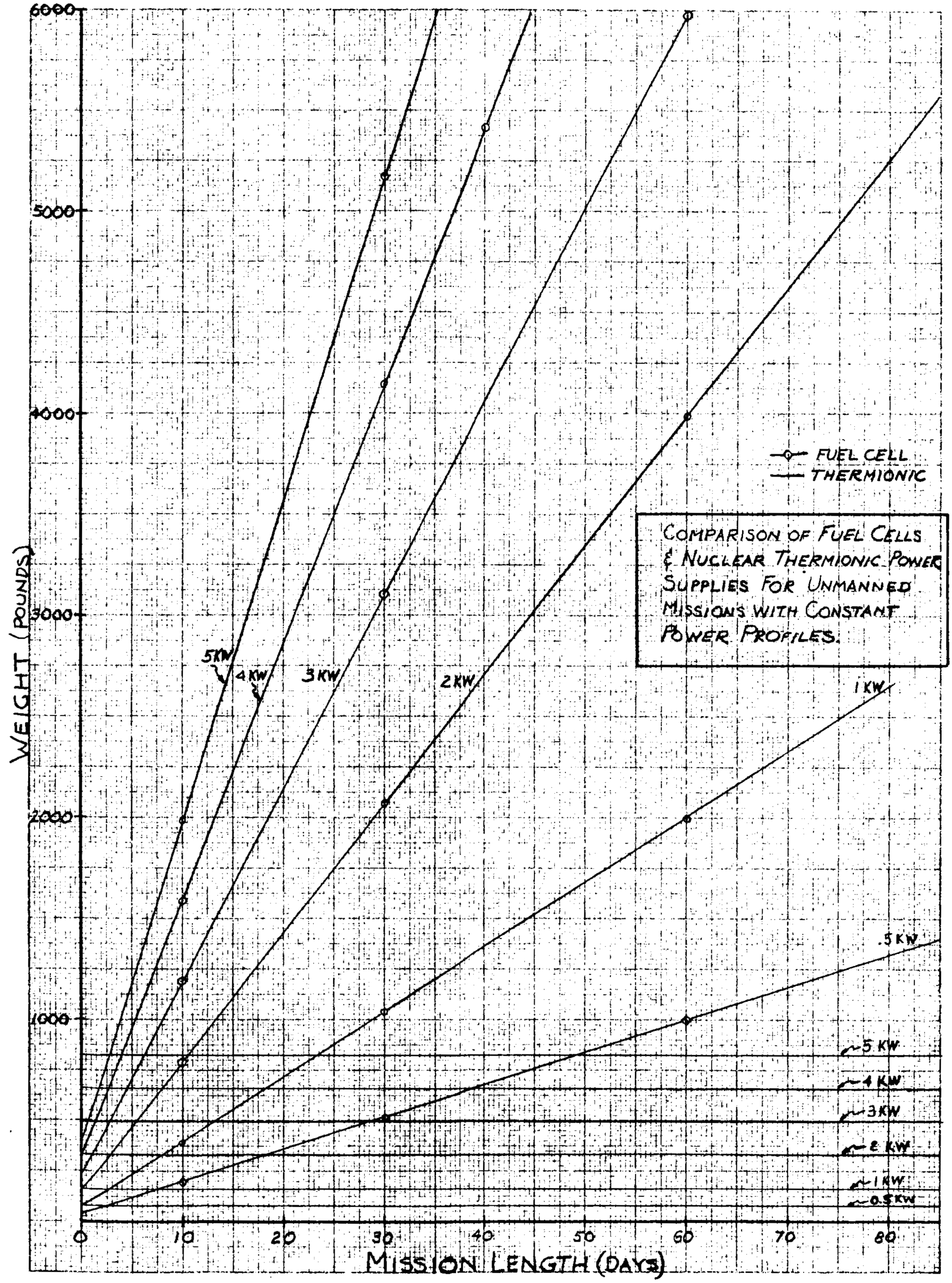


FIGURE 14. COMPARISON OF FUEL CELLS AND NUCLEAR THERMIONIC SUPPLIES FOR UNMANNED MISSIONS WITH CONSTANT POWER PROFILES

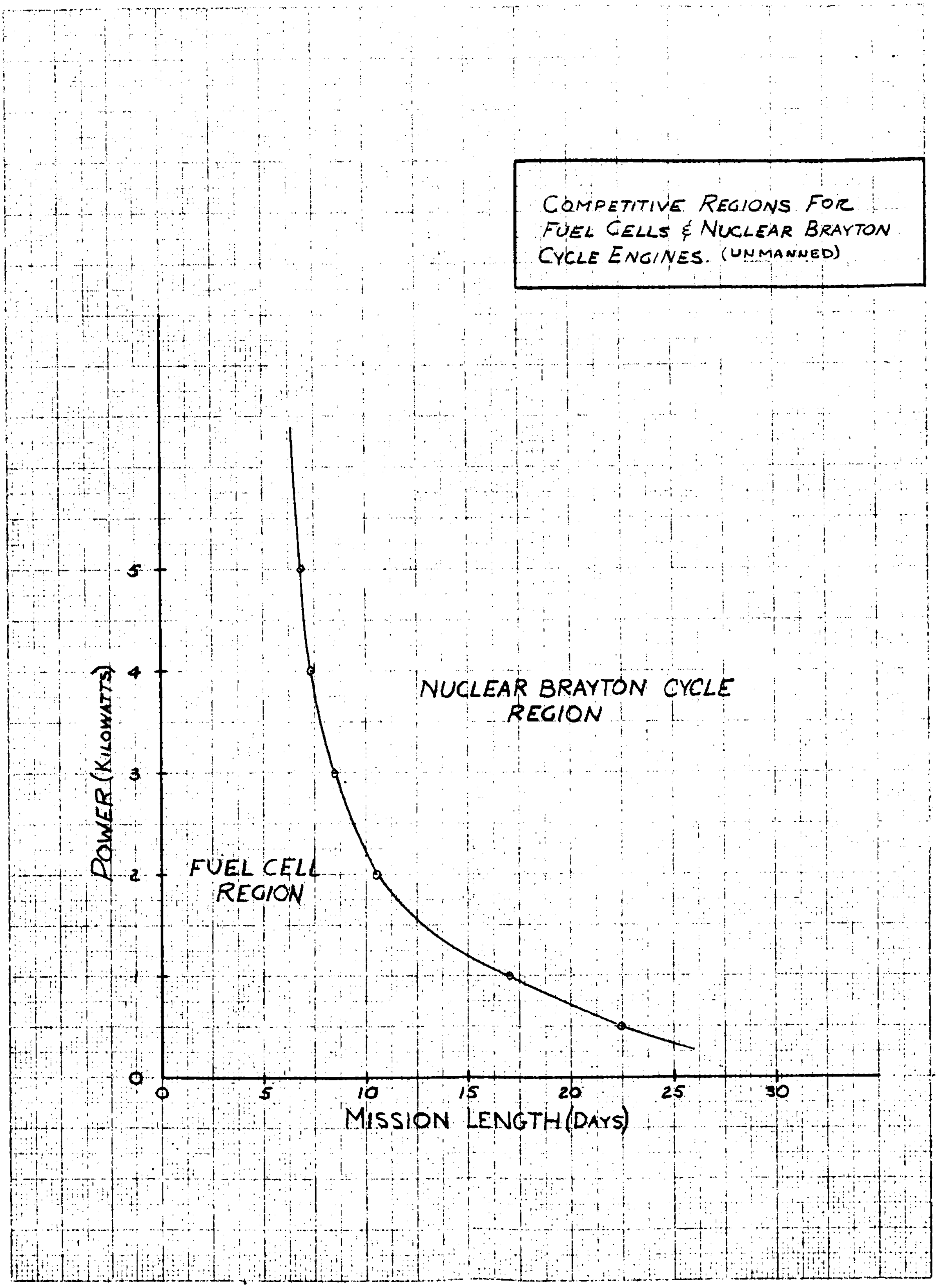


FIGURE 15. COMPETITIVE REGIONS FOR FUEL CELLS AND NUCLEAR BRAYTON CYCLE SYSTEMS (Unmanned)

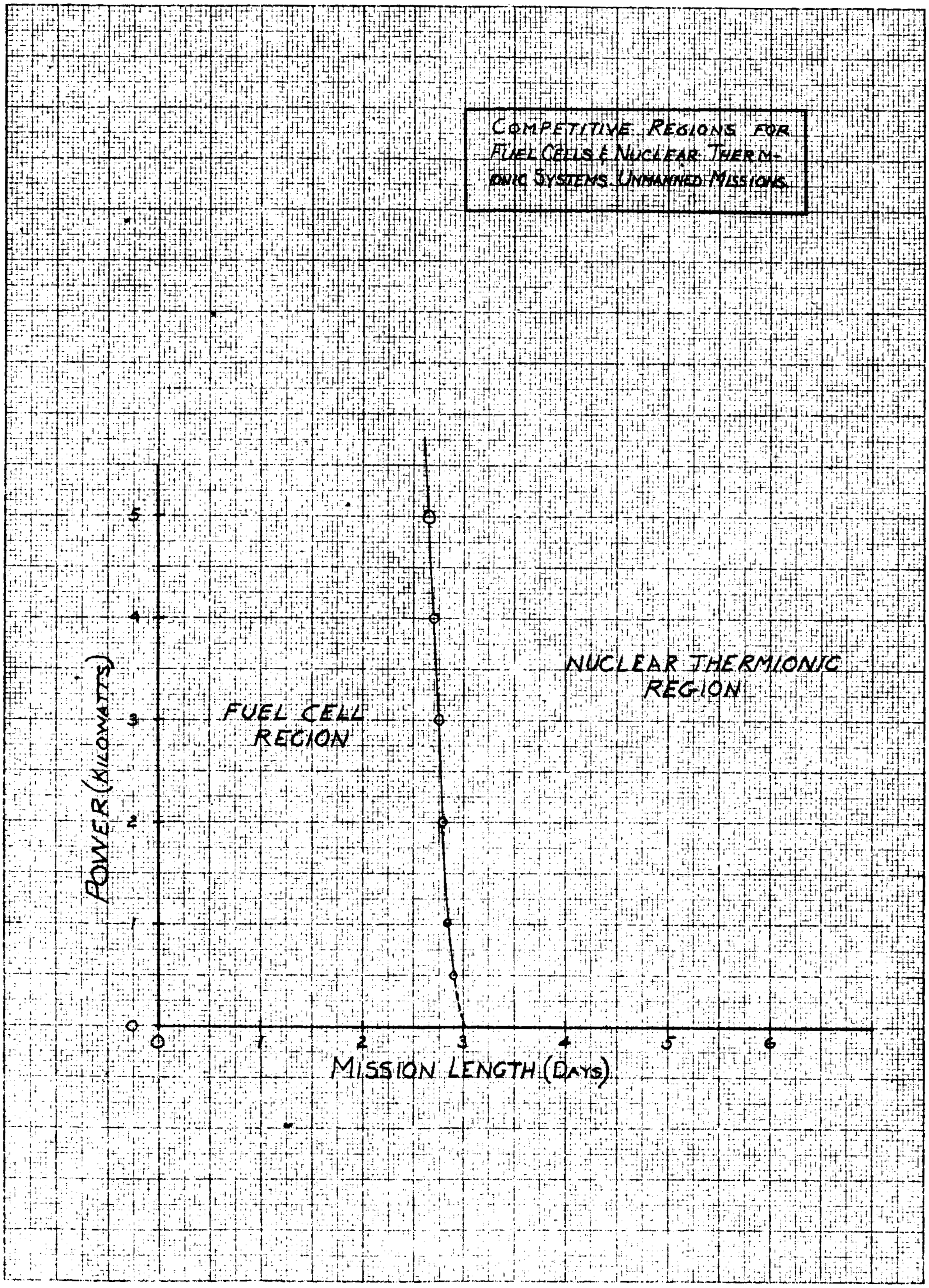


FIGURE 16. COMPETITIVE REGIONS FOR FUEL CELLS AND NUCLEAR THERMIONIC SYSTEMS (Unmanned)

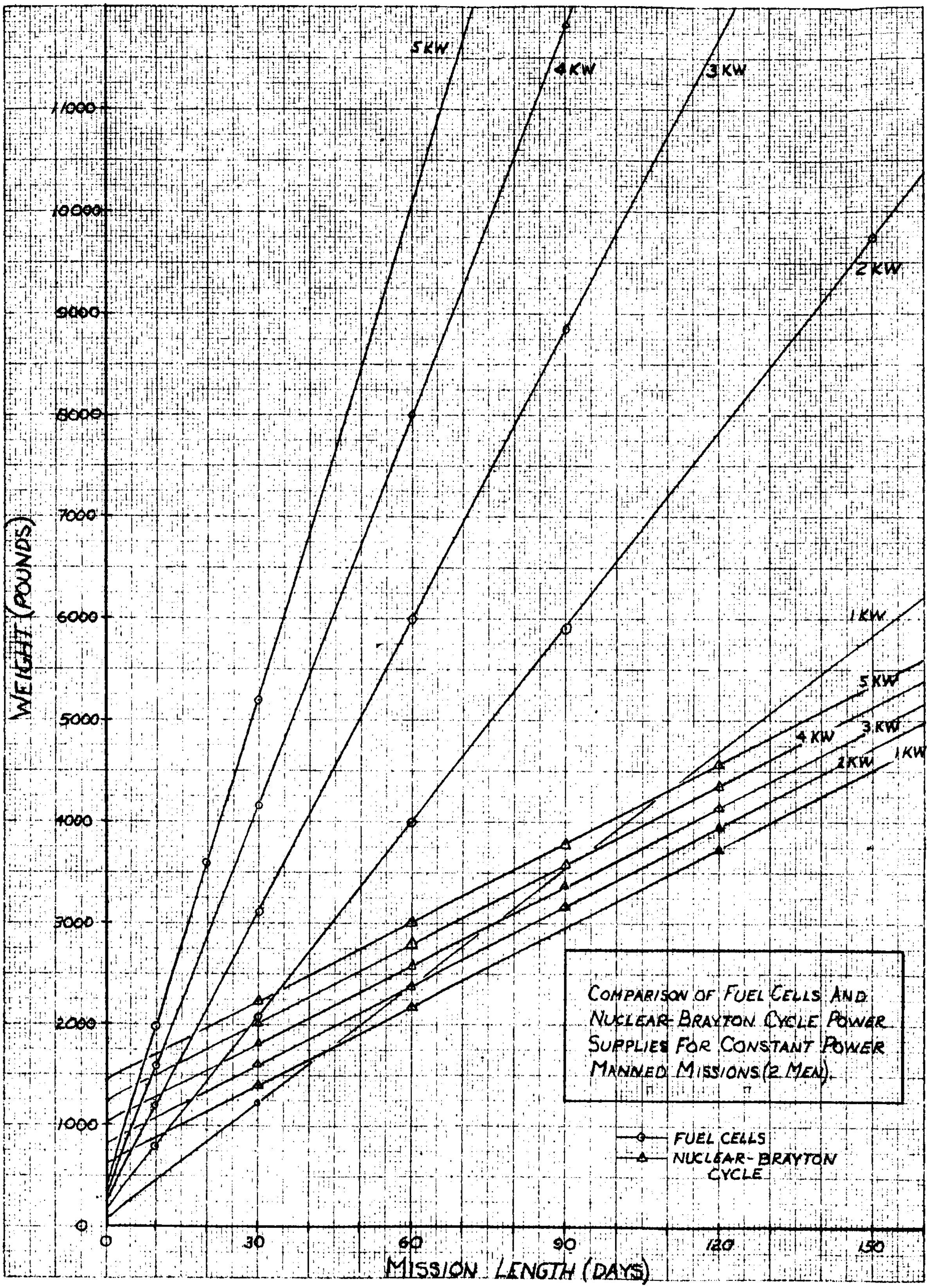


FIGURE 17. COMPARISON OF FUEL CELLS AND NUCLEAR-BRAYTON CYCLE POWER SUPPLIES FOR CONSTANT POWER MANNED MISSIONS (2 Men)

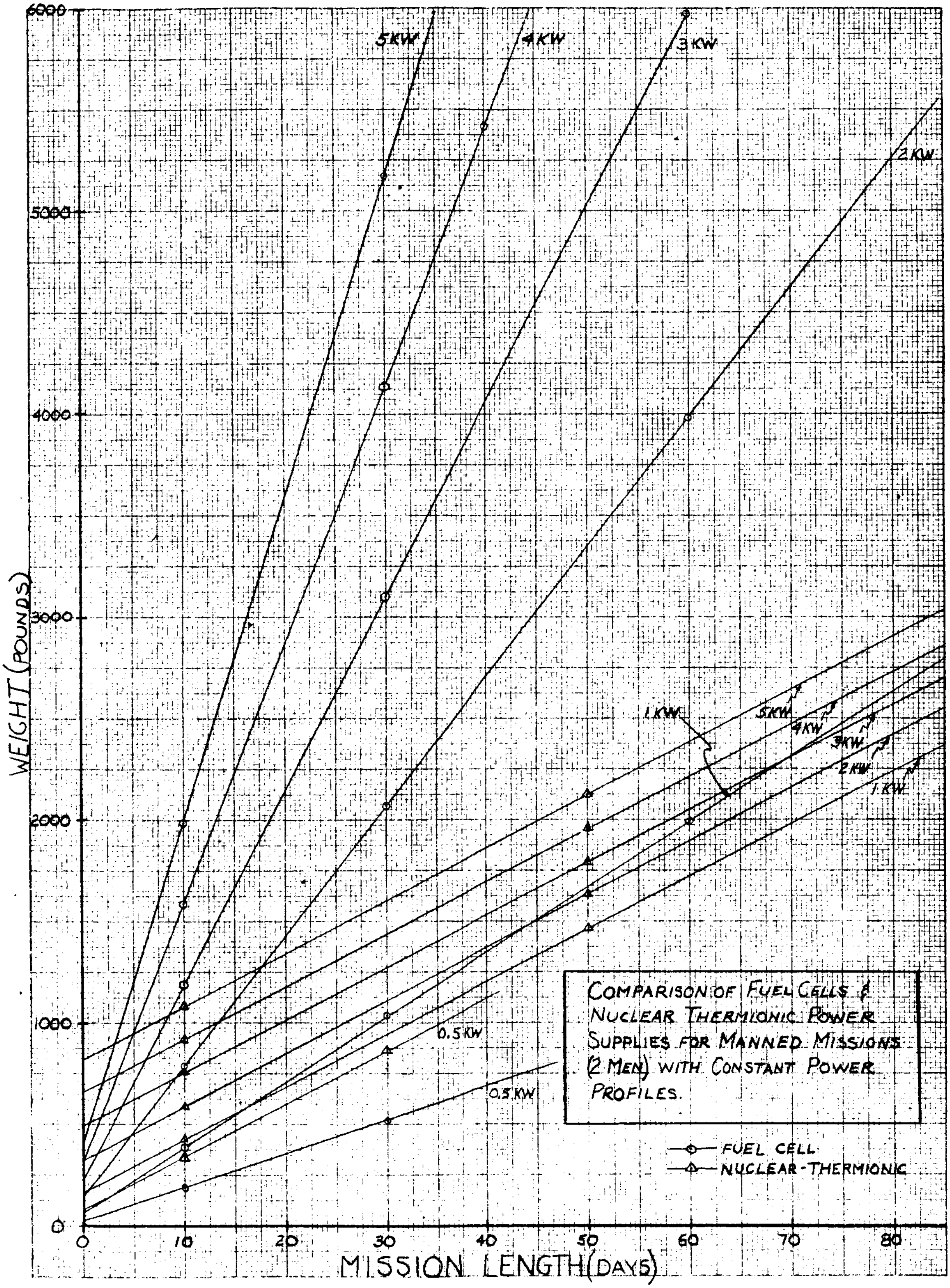


FIGURE 18. COMPARISON OF FUEL CELLS AND NUCLEAR THERMIONIC POWER SUPPLIES FOR MANNED MISSIONS (2 Men) WITH CONSTANT POWER PROFILES

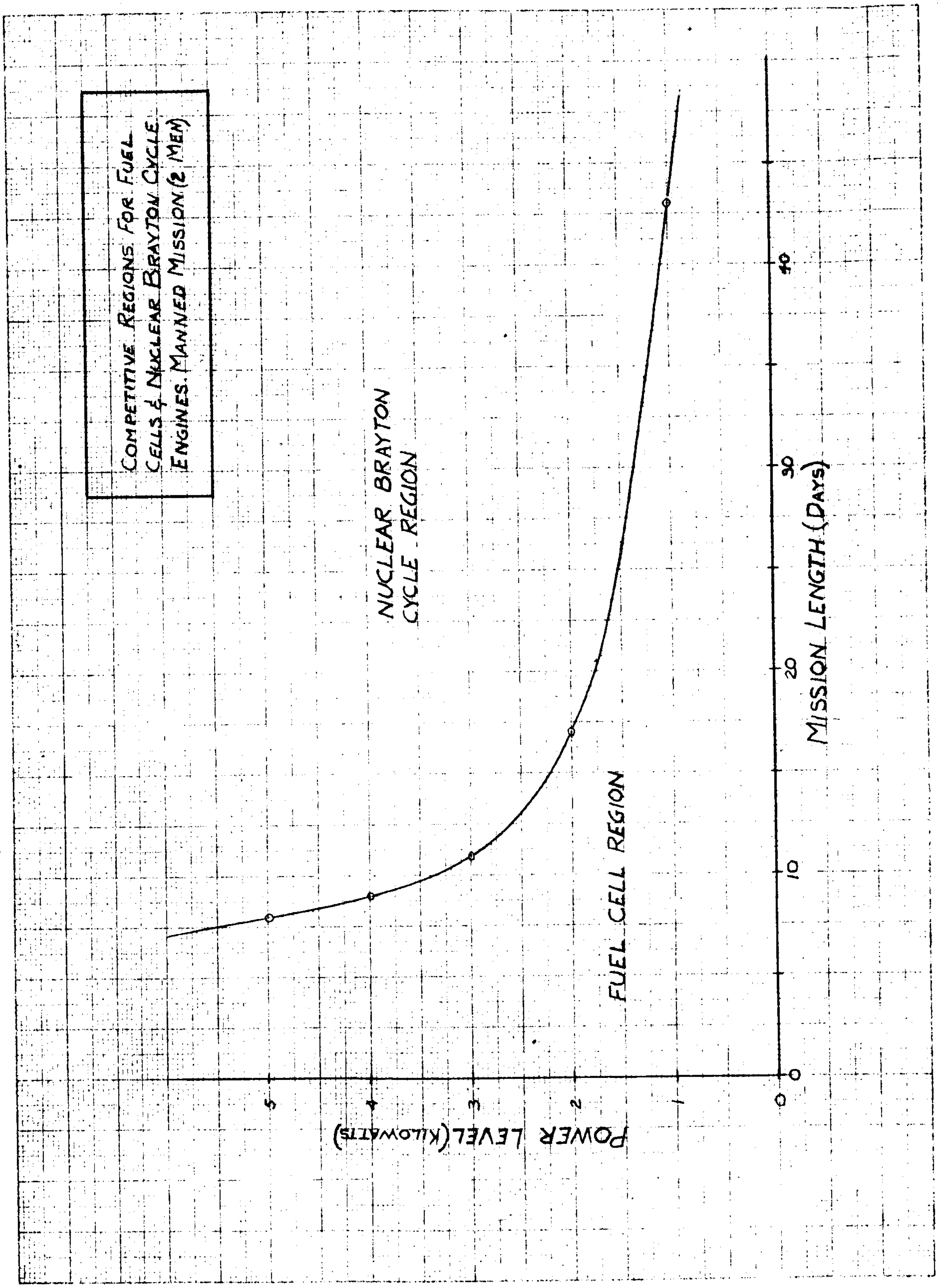


FIGURE 19. COMPETITIVE REGIONS FOR FUEL CELLS AND NUCLEAR BRAYTON CYCLE ENGINES. MANNED MISSIONS (2 Men)

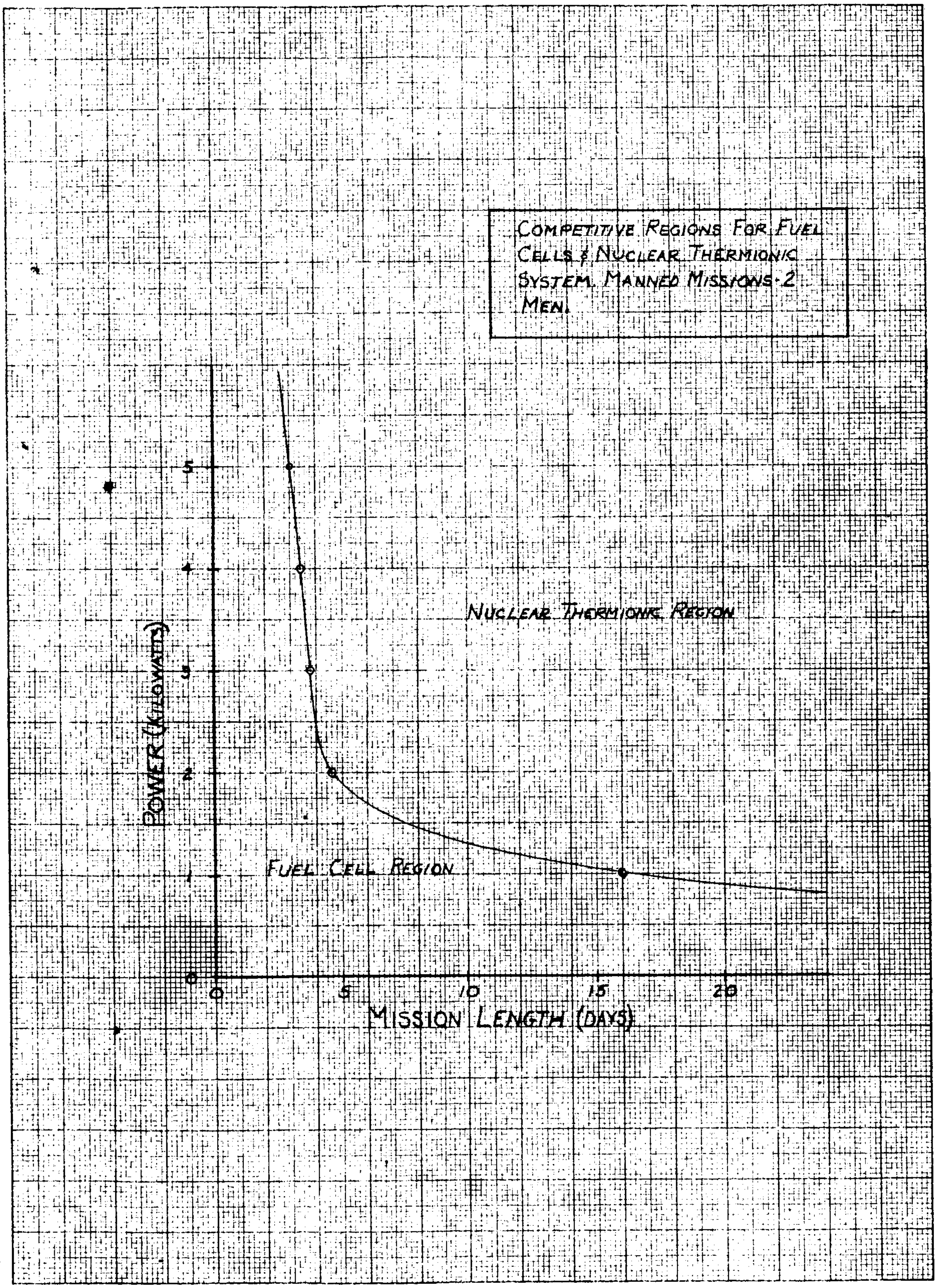


FIGURE 20. COMPETITIVE REGIONS FOR FUEL CELLS AND NUCLEAR THERMIONIC SYSTEM. MANNED MISSION (2 Men)

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