Advancements in Non-Stationary Power Solutions

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Abstract: Mobile systems that require self-contained power sources are becoming increasingly widespread. These markets range from consumer electronics (e.g. cell phones, tablets) to large vehicles (e.g. automobiles, space probes). A number of different power solutions are commercially available including batteries, fuel cells, internal combustion engines, photovoltaics, thermoelectric generators, gas turbines, and hybrid combinations of those technologies. Since the applications are mobile, the mass of the power system is a key design variable. Market research was conducted to determine the relationship between power draw, usage duration, and mass for each of these technologies. This analysis was performed for cutting-edge, commercially-available power solutions to establish a baseline. Each technology were then independently analyzed to identify near-term advancements; these advancements are quantified through mass savings for a fixed power.

Keywords: Mobile Applications, Batteries, Fuel Cells, Internal Combustion Engines, Renewable Energy Sources

I. INTRODUCTION

The usage of powered mobile systems has significantly increased over the previous 50 years with the proliferation of cellphones, automobiles, and tablet computers. Market trends indicate that numerous markets will continue to field increasing numbers of mobile systems that are required to contain their own power supply. For example, the computer market has seen a rapid increase in the proportion of laptop computers and tablets compared to traditional desktop computers [1]. Additionally, Army units are using electronics that are drawing upwards to 1 kW for long duration dismounted missions [2].

Mobile electronic systems require a self-contained power supply. By default, the majority of electronic systems use batteries. While batteries work well for lower powers and usage durations, other solutions are significantly lighter for higher power and usage durations. These power solutions include fuel cells, internal combustion engines, photovoltaics, thermoelectric generators, gas turbines, and hybrid combinations of those technologies. With multiple options available, selection of the appropriate power solution is typically dependent on the mass of the power supply. In particular, manufacturers strive to minimize the mass of the power supply, since mobile applications are often already weight-constrained.

This study uses market research data to identify the relationship between required power, usage duration, and mass. Equations are provided to allow power system designers to approximate the weight of their candidate power solutions.

These equations are then used to identify the optimal power solution, defined as that with the minimum mass for a given power draw and usage duration. The power solutions are based on an analysis of commercially-available technologies, as well as those still in development.

II. DESIGN VARIABLES

The selection of the correct power system technology is based on a number of different variables. For mobile applications, the mass of the power system is a key design parameter, since the devices are typically carried. Additionally, for vehicle systems, additional weight results in an increase in power required, creating an unfavorable feedback loop [3].

The mass of the power system for a given technology is a function of average power draw and the usage duration. The following sections analyze the relationship between mass, average power draw, and usage duration for different power technologies.

Another key parameter in selecting a power solution is the peak power. It is assumed for this study that the peak power is within 20 percent of the average power, allowing for any of the analyzed power solutions to handle that surge power draw.

The variables, symbols, and their corresponding units are given in Table 1. Note that for clarity, units are left off of the constants in the equations presented in this paper. Therefore, the variables in the subsequent equations must be input with the units in Table 1 to ensure proper calculation.

TABLE I
VARIABLES, SYMBOLS, AND UNITS FOR ANALYSIS

Measure	Symbol	Units
Mass	M	Kg
Average Power	$\bar{p}$	kW
Time	T	Hr
Energy	E	kWHr
Efficiency	ε	n/a

III. COMMERCIALLY AVAILABLE TECHNOLOGIES

A. *Batteries*

Batteries are typically categorized as primary and secondary batteries. Primary batteries are non-rechargeable, while secondary batteries are rechargeable. Though primary batteries typically have a much higher energy density, they are associated with lower power output, in addition to higher costs and disposal issues. Therefore, secondary batteries are preferred for the majority of applications.

A number of secondary battery chemistries are available, the most common being lead acid, nickel metal hydride, and lithium ion. Lithium ion batteries dominate the commercial sector and are widely used in applications ranging from electric cars to cell phones [4]. A subset of lithium ion batteries are lithium ion polymer batteries which are common in many applications due to their higher power outputs.

The energy density of state-of-the-art lithium-ion polymer cells is approximately 220 WHr/kg. The corresponding power density can reach up to 10 kW/kg. In addition to the mass of the actual battery cell, a number of accessories are required, including a battery management system and packaging. These components impose approximately a 10% increase to the mass of the battery. The mass of a battery system is given in (1).

$$m = 1.1 \times \max\left(\frac{\bar{p}}{10}, \frac{\bar{p} \times t}{0.220}\right) \quad (1)$$

For short usage durations, the battery mass is set by the maximum power output required from the cells. For longer missions it is set by the energy contained in the cells.

B. Fuel Cells

Fuel cells provide power by converting the chemical energy stored in a fuel into electricity through a catalyzed chemical reaction. Since the power conversion is a chemical-electric process, fuel cells do not have the same Carnot limitations as an internal combustion engine. Three different fuel cell options are viable options as power solutions [5].

The first fuel cell option is the Proton Exchange Membrane Fuel Cell (PEMFC). A PEMFC uses pure hydrogen as a fuel. These fuel cells have been used in many applications including the Gemini spacecraft, hydrogen-powered vehicles, and portable power generators. PEMFCs can achieve conversion efficiencies up to 40%, which coupled with the high energy density of hydrogen (33,333 WHr/kg) provides a very attractive option. The downside of the PEMFC is that they require pure hydrogen for operation. The storage system for the hydrogen is typically 10 times the mass of the hydrogen being stored. Another downside is the low power density of the dry fuel cell which is typically 0.2 kW/kg. Additionally, there is a minimum set of accessories that are required for a PEMFC which are approximately 1 kg. Equation (2) gives the mass of the PEMFC and associated fuel.

$$m = 1 + \left(\frac{\overline{p}}{0.2}\right) + \left(11 \times \frac{\overline{p} \times t}{0.4 \times 33.3}\right) \tag{2}$$

The second fuel cell option is the Direct Methanol Fuel Cell (DMFC), which is a subset of the PEMFC. As the name suggests, the DMFC uses methanol has its fuel. Methanol is easier to handle than hydrogen and can be readily held in a container that is 10% of the fuel mass. However, methanol has a fairly low energy density (5.5 kWHr/kg), and the DMFC has a low conversion efficiency (25%). The power density is comparable to a PEM fuel cell. The mass for a DMFC and associated fuel is given in (3).

$$m = 1 + \left(\frac{\overline{p}}{0.2}\right) + \left(1.1 \times \frac{\overline{p} \times t}{0.25 \times 5.5}\right) \tag{3}$$

The third fuel cell option is the Solid Oxide Fuel Cell (SOFC). The SOFC operates at much higher temperatures than a PEMFC, allowing for carbon monoxide to be used as a fuel in addition to hydrogen. As such, the SOFC can be used with a reformer to operate off gasoline or diesel [6]. SOFCs have high conversion efficiencies (32%) and can take advantage of the high energy density of gasoline (12.2 kWHr/kg). Additionally, gasoline can be stored in containers that are approximately 10% of the mass of the fuel. Current SOFCs have power densities of approximately 0.055 kW/kg. However, SOFCs require numerous accessories including a gasoline reformer, totaling 10 kg. The low power density and the mass of the accessories significantly limit their usage. Equation (4) gives the mass for a SOFC and associated fuel.

$$m = 10 + \left(\frac{\overline{p}}{0.055}\right) + \left(1.1 \times \frac{\overline{p} \times t}{0.32 \times 12.2}\right). \tag{4}$$

C. Internal Combustion Engines

Internal combustion engines are ubiquitous, powering devices ranging from battleships to automobiles to lawnmowers. Internal combustion engines can be broken up into two main categories, 2-stroke and 4-stroke. While 2-stroke engines are less complex and require less moving parts, 4-stroke engines tend to have a higher energy conversion efficiency [7, 8].

Two-stroke engines are currently used to power larger military aerial drones due to their high power density (1.78 kW/kg). Though the engines themselves are lightweight, they require an alternator to convert rotary motion of the engine into electricity. The alternator is typically comparable in mass to the engine itself. Additionally, a number of other accessories are necessary for operation, such as a fuel pump, ignition system, and intake/exhaust plumbing. These accessories are typically 30% of the engine mass. Though 2-stroke engines take advantage of the high energy density of gasoline (12.2 kWHr/kg), they have a fairly low conversion efficiency, which is approximately 28% for a 10 kW engine. As the engine gets smaller, the efficiency decreases as shown in Equation 5. The mass of the 2-stroke engine and associated fuel is given by (6).

$$\varepsilon_{2st} = \min\left(0.13 \times \overline{p}^{1/3},\ 0.36\right) \qquad (5)$$

$$m = \left((1 + 1 + 0.3)\frac{\overline{p}}{1.78}\right) + \left(1.1 \times \frac{\overline{p} \times t}{\varepsilon_{2st} \times 12.2}\right) \qquad (6)$$

Four-stroke engines are currently used to power most vehicles and power generators, due to their high energy conversion efficiency (32% for a 10 kW engine). Similar to the 2-stroke, the efficiency decreases with the size of the engine. These engines require significantly more hardware than a 2-stroke engine, and hence have a lower power density (1.11 kW/kg). The 4-stroke engine requires similar accessories as a 2-stroke, including an alternator (62% of engine mass) and other accessories (19% of engine mass). The efficiency and mass of a 4-stroke engine with fuel are given in (7) and (8).

$$\varepsilon_{4st} = \min\left(0.158 \times \overline{p}^{1/3},\ 0.40\right) \qquad (7)$$

$$m = \left((1 + 0.62 + 0.19)\frac{\overline{p}}{1.11}\right) + \left(1.1 \times \frac{\overline{p} \times t}{\varepsilon_{4st} \times 12.2}\right) \qquad (8)$$

The market research found that there are very limited engines, both 2-stroke and 4-stroke, that are designed for producing power outputs below 500W. The low efficiencies, coupled with the need for very high precision machining have made these engines technically unfeasible [8].

D. Hybrid Internal Combustion Engine Solutions

Internal combustion engines suffer from several major limitations. First, as mentioned above, the conversion efficiencies drop to very low values as the power decreases below 500 W. Additionally, these engines have noise and emissions issues, such that an internal combustion engine would not be appropriate for many applications, especially those indoors.

Several of these drawbacks can be addressed through using a hybrid power architecture. For power requirements under 1 kW, a 1kW engine can be outfitted that runs part-time to recharge batteries. The sizing of the batteries must be determined based on the mission profile. An approximation based on the market research is that the batteries are sized to run without recharge for at least 10% of the mission time up to two hours.

Hybrid technology also requires a power management system. Power management systems can vary in mass in regards to system complexity and range of values. The power manager typically weighs 0.5 kg per kW of power managed.

Therefore, the mass for a hybrid 2-stroke option can be calculated from combining (1), (5), and (6), and adding in the mass of the power manager. Similarly, the mass for a hybrid 4-stroke option can be determined from combining Equations 1, 7, and 8 with the mass of the power manager.

E. Gas Turbines

Gas turbines provide a fairly efficient and compact power solution for large scale applications such as airplanes and power plants. However, at power outputs below 20 kW, they have traditionally been fairly heavy and have low conversion efficiencies. Recent advancements in recuperation technology have allowed for gas turbines to be a viable solution at lower power requirements as well [9]. State-of-the-art, small, recuperated, gas turbines are achieving conversion efficiencies similar to 2-stroke engines with a power density of 0.9 kW/kg. At higher power outputs, it is possible to get conversion efficiencies up to 50 percent, as shown in Equation 9. Similar to the other engines, they require accessories that are similar in mass to the actual engine. The mass of the engine and associated fuel is given in (10).

$$\varepsilon_{gt} = \min\left(0.13 \times \overline{p}^{1/3},\ 0.50\right) \tag{9}$$

$$m = \left((1+1)\frac{\overline{p}}{0.9}\right) + \left(1.1 \times \frac{\overline{p} \times t}{\varepsilon_{gt} \times 12.2}\right) \tag{10}$$

F. Photovoltaics

In environments with available sunlight, photovoltaic cells are an option for providing power. These cells convert sunlight into electricity. Current photovoltaic cells are made of silicon which produce 175 W/m2 and weigh approximately 10 kg per square meter. This equates to a power density of 17.5 W/kg.

Photovoltaics work best as part of a hybrid system with batteries that are recharged [10]. Though the size of the battery bank is dependent on the mission, the market research found that the batteries are sized to operate for half of the usage duration up to 12 hours. For missions longer than 12 hours, the batteries are sized to account for 12 hours of operations during night time. Therefore, the mass of the hybrid photovoltaic system is shown in (11).

$$m = \left(\frac{\overline{p}}{0.0175}\right) + \left(\frac{\overline{p} \times \min\left(0.5 \times t, 12\right)}{0.22}\right) \tag{11}$$

G. Thermoelectric Generators

Thermoelectric generators use a temperature differential to drive an electrical current. These devices typically have similar power densities to photovoltaics and are very inefficient (5%). To offset the low efficiencies, radioisotopes are commonly used due to their very high energy density [11]. The most common type of radioisotope used is Plutonium-238, which has a half-life of 87.7 years and an energy density of 0.54 kW/kg. Additionally, Plutonium-238 has low shielding requirements. The mass of a radioisotope thermoelectric generator is given in (12).

$$m = \left(\frac{\overline{p}}{0.00083}\right)^{0.4} + \left(\frac{\overline{p}}{0.05 \times 0.54}\right) \tag{12}$$

These applications tend to be for missions that have very long durations, such as those in space.

IV. OPTIMAL SOLUTION WITH COTS COMPONENTS

Fig. 1 shows the optimal power-solution across a range of different power draws and usage durations. The power draws span from 10W to 50kW. The usage durations considered span from 6 minutes to 42 days.

The analysis found that for short missions or those with lower power draws, a battery solution has the minimal mass. As power increases past approximately 1kW and usage durations are multiple hours, fuel based solutions become more optimal. Initially, 2-stroke engines have the lowest mass due to their high power density and few accessories. However, as usage durations increase past a few hours, the low efficiency of the 2-stroke engine creates substantial fuel weight additions. Eventually, the mass savings from more efficient energy conversion offsets the low power densities of a 4-stroke engine, PEMFC, and gas turbine.

As usage durations increase to being multiple-days, the increasing fuel weight necessitates the need for solutions that do not require fuel or battery resupply. The two available options are photovoltaics and the RTG. These options provide for long-term power production without depleting a fuel.

The low power density of the SOFC and the low energy density of the methanol in a DMFC limited the use of these two technologies. Lighter weight alternatives are available at any given power draw or usage duration.

Fig. 2 shows the mass associated with the power systems for a given power draw and usage duration. The energy requirement ranges from 1 WHr to 50 MWHr. The associated mass of the optimal power system scales with this energy requirement, increasing from 4.4g to 1400kg. As expected, the mass scales somewhat linearly with the energy required.

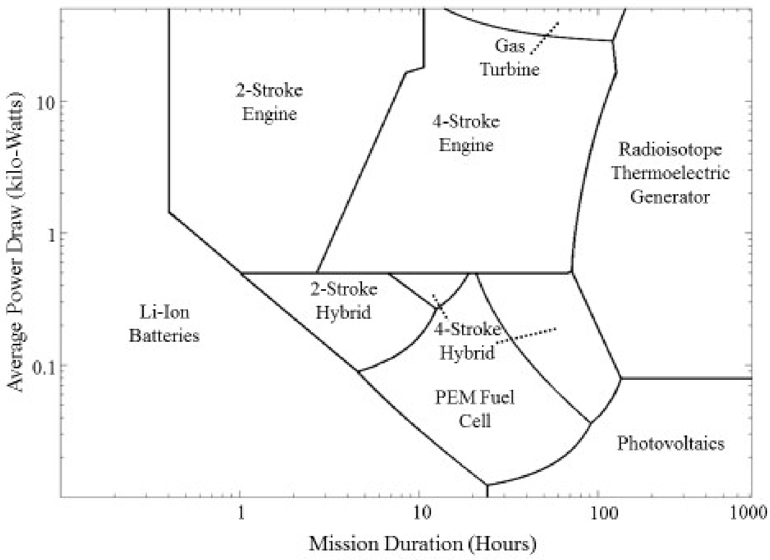

Fig. 1. Optimal power-solution over a range of power draws and mission durations. The solutions are based on market research on commercially available technology

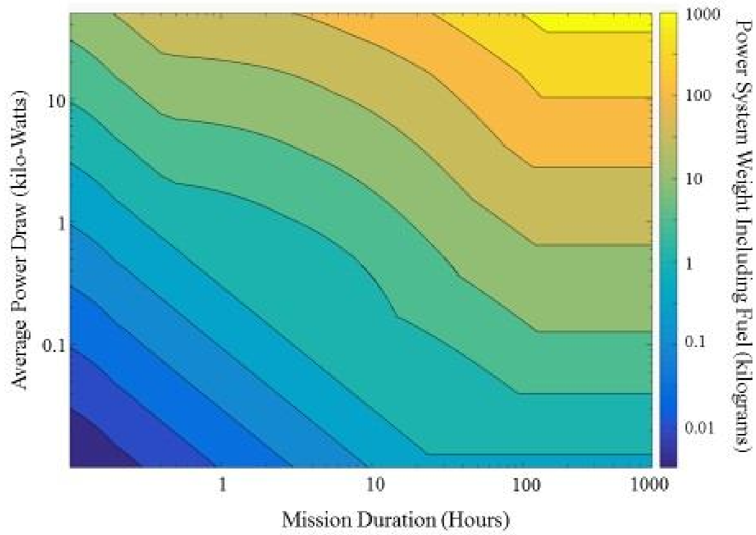

Fig. 2. Power system weight using the optimal power solution over a range of power draws and mission durations

V. Advancements in Technology

A substantial amount of global research and development is allocated towards developing more efficient, compact, and lighter power solutions. Over the next four years, numerous new technologies will reach technology maturity and can be used as power systems.

A. Batteries

The energy and power density of Li-Ion batteries have historically been increasing by approximately 4 percent annually [12]. These advancements are due to increased demands on battery life for electric vehicles, cell phones, and lap tops. Therefore, with a modest development effort, a 20 percent increase in power and energy density can be readily achieved.

B. Fuel Cells

The heaviest component of the PEMFC is the hydrogen storage mechanism. Several large Department of Energy and Department of Defense initiatives are looking at methods to decrease these values. Potential candidates include novel metal hydride solutions. The multiplication factor for the hydrogen storage mechanism can potentially decrease from 10 to 6 [13].

Little effort is underway to improve the mass of the DMFC. The issues with the DMFC, including the complexity of the system, have limited their usage and popularity.

The low power density of the SOFC makes it a non-starter for most current application. However, the market research found several companies working towards lightweight SOFC, achieving power densities up to 0.44 kW/kg. Similar developments will result in smaller packaging and less heat losses, increasing the overall conversion efficiency to 35 percent.

C. Internal Combustion Engines

The ubiquitous nature of internal combustion engines has led to significant research to improve their efficiencies. However, having been used for a century, these advancements are only incremental improvements.

Several developments are underway to try to increase the efficiency of 2-stroke engines through different techniques including charging the engine, better thermal management, and novel geometries

[14]. With these developments the efficiency can be increased by a factor of 1.1.

Similarly, several novel geometries are being investigated in regards to 4-stroke engines. A variation of a standard engine design is the rotary engine which uses the Wankel cycle. Several low-TRL rotary engines under development have efficiencies that are a factor of 1.2 greater than that of the standard 4-stroke engine.

D. Gas Turbines

As discussed in the earlier section, recuperation technology allows for lightweight and efficient gas turbines at low power requirements. Further advancements in recuperation technology will allow for a 10 percent increase in power density [9].

E. Photovoltaics and Thermoelectric Generators

Newer photovoltaic chemistries, such as gallium-arsenide have a 33 percent higher power density than traditional silicon [16]. These technologies have traditionally been cost-prohibitive. However, major investment into wearable photovoltaics will increase the use of gallium-arsenide.

Similar to photovoltaics, novel thermoelectric material chemistries are under development that can have significantly higher conversion efficiencies. The conversion efficiency is expected to increase from 5 percent to 7 percent [11].

VI. Optimal Solution With Low-TRL Components

An optimization analysis for the different low-TRL power solutions is presented in Fig. 3. There are two major changes from the solution for current technologies. First, the improved efficiencies of the 4-stroke engine now make that technology more optimal for a larger range of power draws and usage duration. Second, the large increase in power density for the SOFC makes it the optimal solution for a range of values around 1-5 kW for 40-100 hr missions. Further investments in SOFC technology could make it an ideal candidate power solution for a larger range of operational parameters.

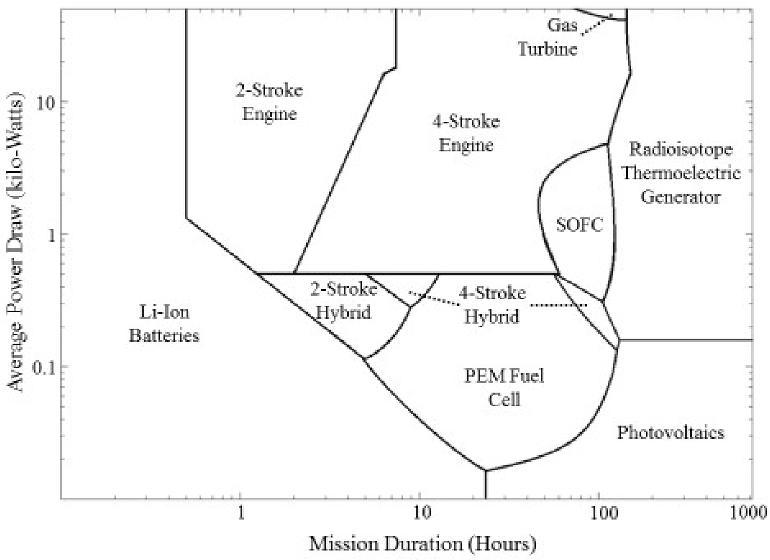

Fig. 3. Optimal power-solution over a range of power draws and mission durations. The solutions are based on market research on technology currently under development.

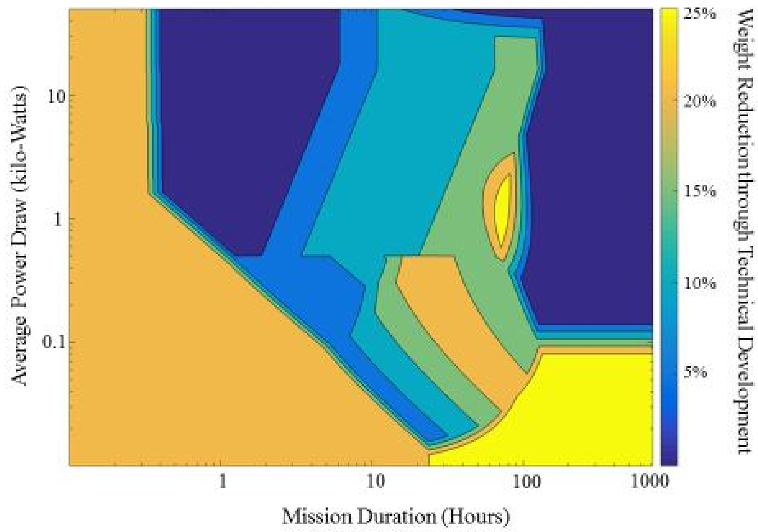

Fig. 4. Weight reductions associated with the development of new power technologies.

Fig. 4 shows the decrease in power system mass associated with the development of these power systems. Advancements in battery technology, photovoltaics, and the SOFC provide up to 25 percent reduction in power system mass. Additionally, more efficient engines allow for a 5 to 15 percent reduction in the power system mass.

VII. CONCLUSIONS

As more markets are moving towards mobile platforms, it is increasingly necessary for these systems to be self-powered. A number of different power solutions were identified that can serve as power sources. These solutions include batteries, fuel cells, internal combustion engines, photovoltaics, thermoelectric generators, gas turbines, and hybrid combinations of those technologies. Market research was conducted to identify the relationship between mass, power requirement, and usage duration for these power technologies. These trends are given as equations that can allow systems engineers to approximate the mass of different power alternatives. A tradeoff analysis was performed to determine the optimal system in regards to mass over a range of power draws and usage durations. This analysis found that different power solutions are optimal over certain power and duration ranges. For example, for low-power, low-duration missions, a battery solution has the lowest weight. As durations and/or power draw increases, fuel based options are required. And for very long durations, photovoltaics and radioisotope thermoelectric generators have the lowest weight; despite their low power density. With investment and development, certain technologies become feasible over a range of operational parameters, such as solid oxide fuel cells.

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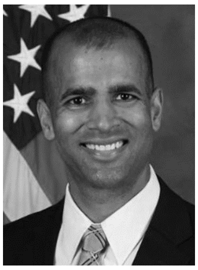

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