Additive Manufacturing in the Oil Gas Industry: Strategies for Managing Powder Waste in Multi Jet Fusion Printing (MJF)

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In the context of the Product Development Process (PDP), particularly during the development phase, there is growing recognition of the importance of waste management in producing components used in the industry. This increased awareness has led to a progressive interest in formulating approaches to understand and mitigate the possible resulting environmental impacts. Within this context, considering the substantial increase in the application of Additive Manufacturing techniques in the oil and gas industry, especially the deposition of polymeric layers, notably through the use of PA 12 and PP powder, it becomes imperative to thoroughly examine the production process in order to assess the feasibility of reincorporating discarded materials into the production chain of polymeric materials. In this context, this article proposes a detailed analysis of the manufacturing flow of a Multi Jet Fusion (MJF) Additive Manufacturing machine to assess the percentage of waste generated in small-scale prints by quantifying the mass of waste generated in the process, as well as pointing out alternatives for disposing of this waste. When the parts are produced, PA12 and PP powder waste is generated; in this deposition process, the powder is reused, returning to its production process. However, after the part has been made, it needs to be blasted with glass microspheres to remove all the powder residue that is trapped in the part. The waste generated during blasting is a mixture of PA12, PP, and glass microspheres, which, if not disposed of in an environmentally appropriate way, can have an environmental impact. Over 9 days, the results revealed an average of 12.15% waste from the component blasting process. It is suggested that this waste be used to manufacture filaments by extrusion and in additive manufacturing machines to deposit molten material. This material can produce other components for the oil and gas industry using FDM printers. It should be noted that bibliographical references identify viable techniques for reintegrating discarded materials into other manufacturing processes. Reducing PA12 and PP waste in additive manufacturing contributes to economic efficiency. It aligns with environmental and social goals, promoting sustainable practices and supporting the achievement of the Sustainable Development Goals in the oil and gas sector.

Keywords: Waste Reduction. Additive Manufacturing. Polymers. Oil and gas.

Additive manufacturing, commonly called 3D printing, is a revolutionary process of fabricating objects by depositing materials in successive layers. Unlike traditional subtractive manufacturing methods, which involve removing material from a solid block, additive manufacturing constructs parts incrementally, layer by layer, until the final object is completed [1].

Among the diverse range of additive manufacturing techniques, powder bed fusion methods are particularly notable. These methods create parts by fusing powdered materials. One prominent example is HP Multi Jet Fusion (MJF) technology, an advanced polymer-based additive manufacturing technique. MJF operates by selectively melting powdered material to form the desired part.

The process begins with the uniform spreading of a thin layer of polymeric powder across the printing bed. A fusing agent is then selectively jetted onto areas of the powder where fusion is intended. This agent defines the regions that will subsequently be exposed to infrared light. The infrared light causes the powder in the targeted areas to fuse, layer by layer, following the digital design until the part is fully formed [2].

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Figure 1 illustrates this process, demonstrating the precision and efficiency of HP Multi Jet Fusion technology.

The efficiency and precision of HP Multi Jet Fusion (MJF) technology underscore its pivotal role in driving technological innovation and enhancing production processes.

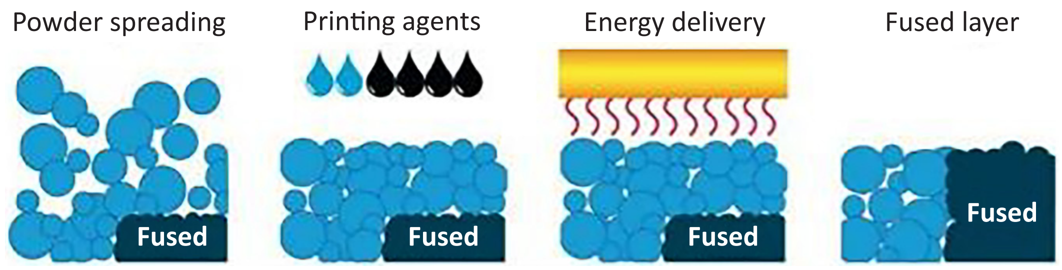
This method offers several significant advantages, including high production efficiency, minimal material waste, and the ability to produce intricate geometries without additional support structures.

These attributes make MJF particularly suitable for producing final-use parts, expanding its applicability across various industries.By enabling the creation of complex designs with ease, additive manufacturing fosters innovation and provides unparalleled flexibility in the design and production of components. Industries ranging from aerospace and automotive to healthcare and consumer goods increasingly leverage this technology to meet evolving demands and reduce manufacturing constraints [3].

Figure 2 illustrates a systematic representation of the MJF part manufacturing process, providing a detailed visualization of the steps involved in transforming a digital model into a tangible printed component.

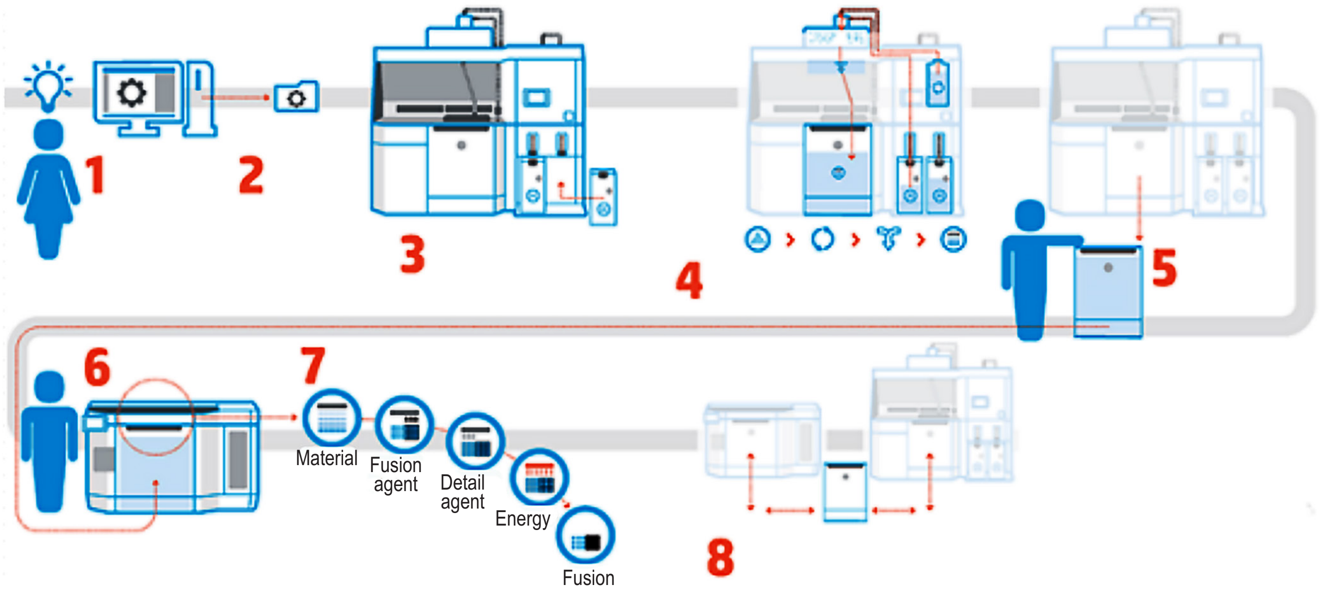
The workflow of HP Multi Jet Fusion (MJF) technology involves a systematic series of steps designed to ensure the efficient and precise production of parts. The process proceeds as follows:

Figure 1. Material fusion process.



Adapted from HP Multi Jet Fusion (2018) [4].

Figure 2. HP usability workflow.



Adapted from HP (2017) [5].

1. **Prepare the project for printing:** Finalize and configure the digital model for the printing parameters.
2. **Place the model into the printer:** Load the prepared digital model into the printer's system.
3. **Insert the material cartridge:** Add the material cartridge containing a virgin and recycled polymer blend.
4. **Fill the printing tank with material:** Load the required amount of polymer powder into the printing tank.
5. **Remove the tank filled with material:** Transfer the tank to the printer, ensuring it contains the quantity specified by the project.
6. **Power the development printer:** Turn on the printer and prepare it for printing.
7. **Start the material deposition process:** Initiate the layer-by-layer and fusing process, following the digital model specifications.
8. **Remove the vat with printed material:** After printing, remove the vat and allow the printed part to cool. Once cooled, return it to the processing printer for unpacking.

During the unpacking stage, unmelted powder is vacuumed back into the recycled material container for future use, highlighting the sustainable aspects of this technology. However, the printed part often retains significant amounts of polymer powder residue. This necessitates a post-processing stage, during which the part undergoes blasting to clean its surface and achieve the desired finish (Figure 3).

This workflow emphasizes efficiency and sustainability and showcases the attention to detail required to produce high-quality parts using MJF technology.

The CMV® machine plays a crucial role in the post-processing stage of Multi Jet Fusion (MJF) additive manufacturing by blasting the parts to remove surface residue. In this process, glass microspheres are used as the blasting material, effectively cleaning the surface of the printed parts. However, this procedure generates waste from a mixture of polymers and glass microspheres. This waste is directed to the disposal sector without being reused, presenting a missed opportunity for sustainability and resource optimization.

Disposing of such waste poses a significant environmental challenge due to the inherent environmental impacts of polymer and glass waste. Additionally, this practice results in losing valuable raw materials that could otherwise be recovered and repurposed [6].

The primary objective of the present study is to conduct a comprehensive analysis of the MJF manufacturing workflow, with a particular focus on the post-processing stage. This involves:

1. Mapping the post-processing process to identify areas where waste is generated.
2. Quantifying the percentage of waste produced during the blasting process.
3. Proposing a route for reusing the generated waste, specifically by extruding the polymer-glass composite to create polymeric filaments for additive manufacturing.

The study seeks to enhance the sustainability of MJF technology by integrating waste recovery into the manufacturing cycle. The extrusion of polymeric filaments addresses environmental concerns and reintroduces waste materials into the production chain, fostering a circular economy model within additive manufacturing.

Figure 3. Unpacking the part.

Materials and Methods

Four distinct phases were implemented to thoroughly evaluate the disposal and potential reuse of waste generated in the Multi Jet Fusion (MJF) additive manufacturing process. This approach ensured a comprehensive understanding of waste management and its implications within the production process.

Analysis of Production Flow

In the initial phase, the printer's production flow was systematically analyzed to identify the specific stages at which waste was generated. This step aimed to pinpoint the primary sources of waste within the manufacturing process and establish a baseline for subsequent evaluations.

Defining Waste Collection Frequency

The second phase involved determining the frequency of waste collection. This was done by analyzing the current waste collection schedule to establish consistent intervals for waste data collection, ensuring an accurate representation of waste generation trends over time.

Waste Collection and Weighing

During this phase, the collected waste was systematically weighed to calculate the average weight of waste produced across multiple production cycles. This data provided a quantitative foundation for assessing waste volumes and their potential for reuse.

Waste Quantification

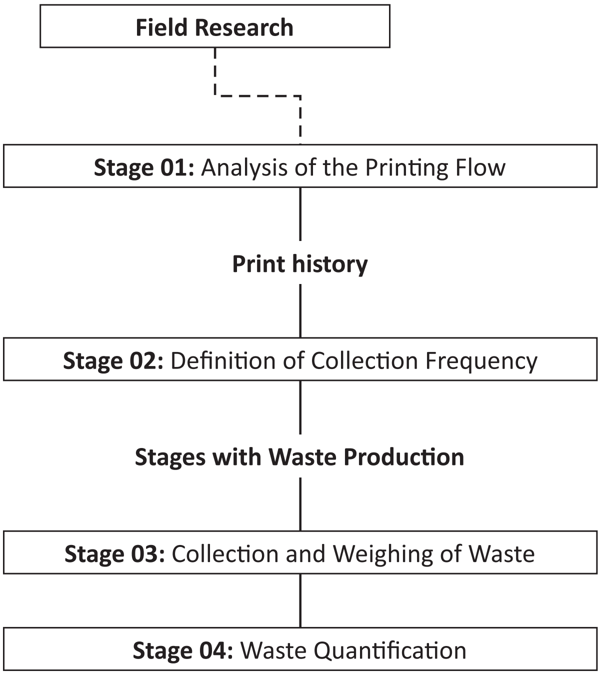
In the final phase, the percentage of waste generated about the total material used was calculated. A specific formula was defined to consistently quantify waste, allowing for comparative analysis and exploring reuse strategies. This methodological design offers a structured and comprehensive waste evaluation approach, emphasizing quantitative and qualitative insights. The results contribute to identifying opportunities for improved waste management practices, particularly in exploring the reuse of materials in the production process.

Figure 4 illustrates the schematic representation of the methodological flow, providing a visual overview of the sequential steps undertaken in this study.

Production Flow Analysis

A thorough examination of the Multi Jet Fusion (MJF) production flow and post-processing was conducted to map all activities from raw material input to the completion of finished products. This mapping process was instrumental in pinpointing critical stages where material waste occurs, enabling the identification of opportunities for implementing waste reduction or reuse measures. The volume of waste generated during production is directly tied to the filling capacity of the vats, which are the compartments where the parts are printed. This volume fluctuates depending on the printing material required for each production cycle. After

Figure 4. Methodological collection flow.



the printing stage, all parts undergo a mandatory post-processing procedure that involves blasting to remove residual material adhered to their surfaces.

In the blasting process, materials are handled collectively without segregating different polymer types. Production schedules dictate that some collections may include a mix of polypropylene (PP) and polyamide 12 (PA12), while others primarily consist of PA12, the predominant polymer in MJF production. This variability in waste composition underscores the importance of tailored waste management strategies, as the distinct properties of each polymer can significantly affect disposal and recycling processes.

It is vital to systematically measure and analyze all waste generated during the production flow to address these challenges. Accurate waste quantification is crucial for a deeper understanding of its composition and volume, which supports the development of more effective control, management, and potential reuse practices. This process enhances sustainability and aligns with the principles of resource optimization and environmental stewardship.

Definition of Collection Periodicity

The production cycle of the Multi Jet Fusion (MJF) system is dictated by the demand of ongoing projects, leading to fluctuations in production volume, with alternating periods of high and low activity. To establish the optimal periodicity for waste collection and analysis, we evaluated historical production data to determine the average duration required to achieve representative production volumes.

Based on this evaluation, a 15-day interval was identified as the ideal measurement period. This interval corresponds to the blasting machine's typical cleaning cycle, during which an average of 11 vats are produced. The data collection process effectively captured a representative sample of production activities by aligning the collection schedule with the cleaning cycle.

We planned five collection periods over consecutive cycles to ensure a robust and comprehensive analysis. This approach allowed for the integration of production history with variations in machine cleaning and project demand, offering a clear picture of waste generation across different scenarios.

Given the variability in project timelines, the number of vats produced during each collection period differed, reflecting the dynamic nature of production. Despite these variations, the 15-day interval ensured consistent and comparable data points for each collection.

With the periodicity defined, collections and measurements were conducted as planned (Table 1). This data forms the foundation for analyzing waste generation trends and identifying opportunities for improved waste management practices.

Collection, Weighing, and Quantification of Waste

The waste generated from the production and post-processing stages was collected and measured during the defined collection periods to assess its quantity and characteristics. The cleaning process, while straightforward, required manual handling to

Table 1. Collection period.

Collection Number	Collection Date	Quantity of Vats
1	12/26/2023	8
2	01/09/2024	7
3	01/23/2024	12
4	05/06/2024	11
5	05/20/2024	17

extract the accumulated dust from the equipment's reservoir.

The collection began by opening the reservoir valve located at the back of the equipment. Using an internal shovel, the accumulated dust was manually removed and transferred into plastic bags for storage and transportation. The waste was then prepared for weighing using a 300Kg IDR 7500 ABS Scale—RAMUZA-2012, ensuring accuracy in mass measurement.

Upon weighing, the collected waste was packed and transported to its destination—currently a specialized recycling company. This step highlights the importance of aligning waste management practices with environmental sustainability principles.

Quantification Process

The waste quantification was based on calculating the percentage of waste generated relative to the material initially processed in the vats. The total mass of waste was recorded for each collection, and the material usage per vat was determined. This calculation considered:

- The dimensions of the printing vat and
- The density of the powdered material, as specified by HP and BASF, the respective manufacturers of the materials.

The resulting values were used to derive the percentage of waste generated per vat during the process. Detailed data for material properties and densities are summarized in Table 2, providing a foundation for analyzing waste trends and identifying potential areas for optimization.

This methodology ensured a systematic approach to waste quantification, enabling a detailed understanding of material usage and disposal practices across the production cycle.

Figures 5 and 6 show the printing vat and a graphic representation of its internal dimensions, respectively.

The calculation of the mass of the polymer used for printing was performed using Equation (1), which assumes that the printing vat was filled with raw material during the printing process:

$$M=V.\rho \tag{1}$$

Where:
M: Mass of the polymer (in kilograms).
V: Volume of the printing vat (in cubic meters).
ρ: Density of the polymer powder (in kilograms per cubic meter).

This Equation accurately estimated the material's initial mass, which was crucial for quantifying waste generated during the production cycle. By knowing the exact mass of polymer used for printing, the proportion of material that transitioned into waste versus that which was effectively utilized in the final printed parts could be determined.

Results and Discussion

Variations in waste results were evident across the different collections, primarily influenced by the sizing and geometric complexity of the printed parts. For instance, parts with features such as holes or lower density tended to retain more powdered material in specific regions, which led to a noticeable increase in the recorded waste amounts.The waste was separated into two bags during each collection cycle and weighed individually to ensure accurate data gathering. Using Equation (1), the mass of the material used in printing

Table 2. Printing vat dimensions.

Material	Vat Dimensions	Material Density
Polypropylene (PP)	L = 380 mm, D = 284 mm, H = 370 mm	0.87 g/cm³
Polyamide 12 (PA12)	L = 380 mm, D = 284 mm, H = 380 mm	1.01 g/cm³

Figure 5. Print vat.

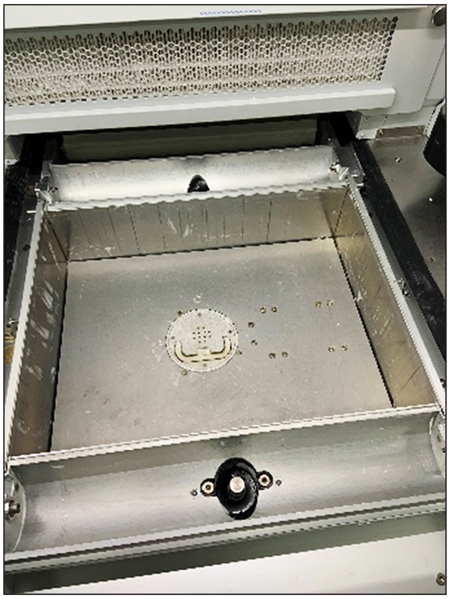
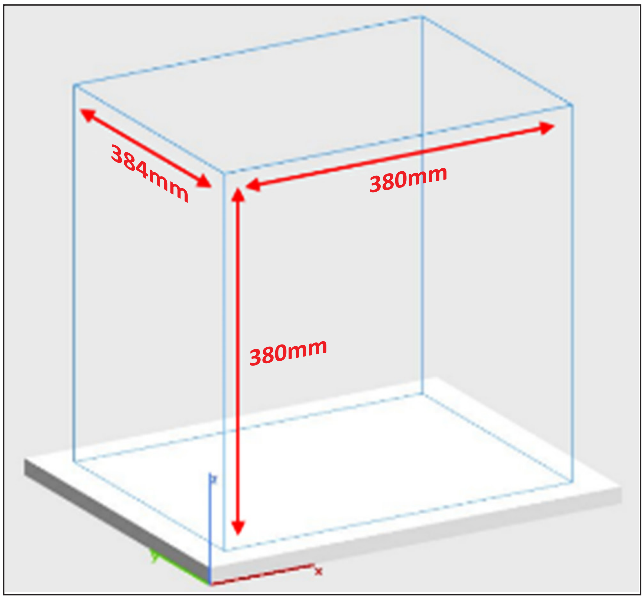


Figure 6. Graphical representation.



was calculated, and the percentage of waste generated was subsequently determined. This allowed for a precise quantification of the waste-to-material ratio. Table 3 presents the detailed results of these collections, along with the calculated waste percentages. This data offers valuable insights into the relationship between part geometry and waste generation, highlighting areas where process efficiency and waste reduction improvements may be achieved. By thoroughly analyzing these results, strategies for optimizing raw materials and minimizing waste can be developed, contributing to more sustainable manufacturing practices.

As previously highlighted, the amount of waste generated was notably significant, with an average mass measured in collections of 18.8 ± 8.9 kg.

This substantial waste presents an opportunity for reprocessing through the extrusion process, which has been identified as a viable method for reusing such material [7]. The recycled material can then be extruded into filaments, which can be used in other additive manufacturing processes, such as Fused Deposition Modeling (FDM) [8]. These filaments could be used to produce parts intended for industries such as oil and gas, particularly in applications requiring rapid part replacement.

This approach contributes to more effective waste management and highlights the potential for innovation in the industry. Reusing waste material aligns with the growing demand for sustainable, environmentally responsible manufacturing solutions [9].

Furthermore, this study contributes to the Sustainable Development Goals (SDGs), particularly about responsible consumption and production practices. The alignment of waste reuse with the SDGs is detailed in Table 4, which outlines how this work contributes to developing sustainable practices and environmental stewardship [10].

The results of this study lay the groundwork for future research and practical applications in waste management and additive manufacturing.

Several promising avenues for further investigation and development can be explored to optimize waste management and enhance environmental sustainability within the industry. Future research may focus on developing advanced recycling technologies to process waste materials more efficiently, potentially integrating automated systems to reduce labor and increase throughput. Additionally, exploring biodegradable materials as

Table 3. Quantification of waste generation.

Collection Waste	Percentage Waste	Mass (kg)	Materials
1	12.15%	26.7	PP, PA12, Glass Microsphere
2	5.71%	12.8	PA12, Glass Microsphere
3	4.25%	13.7	PP, PA12, Glass Microsphere
4	3.26%	10.6	PP, Glass Microsphere
5	6.27%	30.1	PP, PA12, Glass Microsphere

Table 4. Main aspects and correlation with the SDGs.

SDG	Key Aspects
Social Responsibility (SDG 8)	Efficiency in additive manufacturing, with reduced waste, contributes to sustainable economic growth.
	It can generate employment opportunities and improve working conditions, promoting SDG 8.
Innovation and Technological Development (SDG 9)	Reducing waste in additive manufacturing stimulates innovation and the development of efficient technologies.
	Aligned with SDG 9, which aims to promote resilient infrastructures and drive innovation.
Environmental Sustainability (SDG 12)	Waste reduction aligns with SDG 12, aiming for sustainable production and consumption patterns.
	Reducing the amount of discarded material preserves natural resources and reduces the environmental impact associated with extraction and processing.
Minimization of Greenhouse Gas Emissions (SDG 13)	The production of materials, such as PA12, often involves significant greenhouse gas emissions.
	Reducing waste in additive manufacturing contributes to a smaller carbon footprint, helping to mitigate climate change.

alternatives to traditional polymers in 3D printing could offer significant environmental benefits.

Another critical research direction is implementing circular practices for the continuous reuse of resources. This could involve creating closed-loop systems where waste is consistently recycled back into the production process, reducing reliance on new raw materials and minimizing overall waste generation.

Moreover, conducting comprehensive environmental impact assessments will be essential to ensure the long-term sustainability of these practices. These assessments allow for identifying potential risks and developing strategies to mitigate any adverse environmental effects associated with waste recycling and new material innovations. These research directions are essential not only for improving the efficiency of the additive manufacturing industry but also for advancing its environmental responsibility, aligning with global sustainability goals.

Conclusion

Reusing polymer waste in industrial processes is an effective strategy for reducing the demand for virgin raw materials, conserving natural resources, and minimizing the emissions associated with production. Recycling polymers transforms these materials into new products, extending their life cycle but also helping reduce the overall volume of waste generated.

Reusing materials to generate filaments through extrusion presents a sustainable and effective solution for industries such as oil and gas. By utilizing these filaments in additive manufacturing, rapid replacement parts can be produced, contributing to a reduction in waste and costs while addressing the dynamic and specific needs of this high-demand sector [10].

This approach enhances production efficiency and underscores the significance of innovation and environmental responsibility. It presents a viable pathway for sustainable practices in the industry, encouraging the adoption of environmentally conscious solutions that support long-term industry growth while mitigating the environmental impact.

Therefore, analyzing the production flow and proposing the reuse of waste generated by the blasting machine are crucial steps to improving the efficiency of the production process and fundamental strategies to promote environmental sustainability and achieve significant savings in operational costs. Ultimately, these initiatives bring economic benefits to the company and contribute to a more sustainable and responsible future for generations to come.

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