Analysis of the influence of advanced materials for aerospace products R&D and manufacturing cost

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Abstract. In this paper, we pointed out the deficiency of traditional cost estimation model about aerospace products Research & Development (R&D) and manufacturing based on analyzing the widely use of advanced materials in aviation products. Then we put up with the estimating formulas of cost factor, which representing the influences of advanced materials on the labor cost rate and manufacturing materials cost rate. The values ranges of the common advanced materials such as composite materials, titanium alloy are present in the labor and materials two aspects. Finally, we estimate the R&D and manufacturing cost of F/A-18, F/A-22, B-1B and B-2 aircraft based on the common DAPCA IV model and the modified model proposed by this paper. The calculation results show that the calculation precision improved greatly by the proposed method which considering advanced materials. So we can know the proposed method is scientific and reasonable.

1. Introduction
As science and technology develop, advanced materials are being widely applied in the fields of aerospace, power generation equipment, numerical control machining, weapon systems, and especially aviation, a field that struggles to reduce every gram of weight [1]. Composite materials, titanium alloy, and other advanced materials are playing an increasingly important role in both civil and military aircraft [2]. For example [3], the American fifth-generation fighter F/A-22, the world's most advanced aircraft, uses composite materials in the most important parts of the fuselage, wings, and tail. In fact, titanium alloy makes up 40% of the total weight of this military aircraft, and composite materials make up 34%. Among civilian aircraft, composite materials make up more than 40% of the total weight of the European Airbus Company’s A380, the world's largest airliner [4-7].

In the early days, metals were the main materials in aircraft manufacturing; later, advanced materials such as titanium alloy and composite materials were incorporated into nonbearing structures. With the continuous development of material properties, modern aircraft use titanium alloy and composite materials more and more widely. Manufacturers have gradually broken the original material-use restrictions and transferred the load bearing structure, moving closer to an all-composite aircraft. Table 1 shows the contrast in material application proportion between the F/A-22 fighter and the early F-15 fighter. Composite material use has greatly increased in the F/A-22, and the amount of titanium alloy used has also risen [8, 9].

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Table 1. Contrast in material application proportions of F-15, F/A-22 fighter and B-2 bomber.

| Type   | Aluminum alloy | Titanium alloy | Alloy steel | Composite materials | Other materials |
|--------|----------------|----------------|-------------|---------------------|-----------------|
| F-15   | 0.50           | 0.34           | 0.02        | 0.02                | 0.12            |
| F/A-22 | 0.15           | 0.40           | 0.06        | 0.34                | 0.05            |
| B-2    | 0.24           | 0.18           | 0.1         | 0.38                | 0.01            |

Material applications in the airframes of modern aircraft represent a significant change from those in early aircraft. This may create a sizeable effect for research and development (R&D) and manufacturing costs of airframes.

Figure 1. Development of composite materials in aircraft.

When estimating R&D and manufacturing costs of new aircraft, we must consider the different amounts of composite materials used in order to modify traditional aircraft cost models appropriately. Figure 1 reflects the evolution of applying composite materials in aircraft. The engineering development prototype of the F/A-22 fighter included 40% titanium alloy, broken down into 37% titanium 6-4 and 3% titanium 6-22-22; 34% composite materials, broken down into 23% thermosetting composite materials, 10% toughened epoxy composite materials, and 1% thermoplastic materials; 15% aluminum alloy; 6% alloy steel; and 5% other materials. With a large number of new technologies, new materials, and new manufacturing processes, aircraft performance has improved rapidly. At the same time, new technologies increase aircraft structures’ complexity and need for precision. Further advances will lead to continued growth in development and production costs. Therefore, when estimating the development and production costs of a model airplane body, we must consider these changes and make corresponding amendments to cost models [10-12].

At present, the best-known cost estimation model is the Development and Procurement Costs of Aircraft (DAPCA) established by America’s Rand Corporation [13], the latest version of which is known as the DAPCA IV model. In this model, the general expression for cost estimation is $y = a_0 + a_1 x_1 + a_2 x_2$, where $y$ is the cost, $x_1$ and $x_2$ are the weight and speed of the aircraft, respectively, and $a_0$, $a_1$, and $a_2$ are the correlation coefficients. The parameter estimation can be achieved by regression using the same aircraft data. This method is simple and practical, but it produces large deviations when used to estimate the cost of an advanced aircraft. The advanced materials’ contribution to the cost represents a major reason behind this error [14, 15].

The German Airbus Company once analyzed the limitations of the DAPCA II model and
introduced a series of cost factors such as materials, stealth, difficulty, and computer-aided design to aid in estimation. Their attempts have strong practical value; however, the correction factor is relatively rough, and the definitions are not sufficiently clear. Also, the use of factors derived from subjective judgment presents obvious defects.

After studying the rules for incorporating advanced materials into planes, this paper puts forward a series of material cost factors using statistical analysis. These factors represent the influence of advanced materials on aircraft development and production costs. We finish by analyzing the validity of material cost factors proposed in this paper through estimating the cost of U.S. military aircraft in service.

2. Calculation of material cost factor
Labor hours and materials costs are the two main elements making up the advanced material cost of an aircraft. The influence of labor hours can be calculated using a working hour’s ratio of advanced materials to whole aluminum alloys. The influence of material costs acts mainly to increase the price of the material itself and decrease the utilization rate.

When analyzing the influence of labor hours, we consider the main materials to be aluminum alloy, aluminum lithium alloy, titanium alloy, alloy steel, carbon-epoxy, carbon-bismaleimide, and carbon thermoplastics, the latter three of which are composite materials. Similarly, we consider the main working hours to be categorized into Nonrecurring Engineering, Nonrecurring Tooling, Recurring Engineering, Recurring Tooling, Recurring Manufacturing, and Recurring Quality Assurance.

The concept of material cost factors plays a role in evaluating the influence of advanced materials for each type of labor hour. These factors are mainly divided into the labor hour cost coefficient and the material cost coefficient. Material cost is the ratio of aircraft cost involving many advanced materials to the cost of a whole aluminum aircraft of the same weight.

2.1. Labor hour cost coefficient
The labor hour cost coefficient can be described by two components: manufacturing process and geometric complexity.

2.1.1. The manufacturing process. Below are the formulas for estimating labor hour costs based on use of advanced materials, derived by statistical analysis.

$$WMCF_l = \sum_{l=1}^{L} \sum_{m=1}^{M} S_m \gamma_l^m$$

(1)

where $WMCF_l$ is the cost factor of $l$ labor hour and $S_m$ is the structural weight percentage of material $m$ in the airframe. Detailed values for $S_m$ are shown in table 2.

| Type                | F-15 | F-16 | F/A-18 | F/A-22 | B-1B | B-2  | C-17  |
|---------------------|------|------|--------|--------|------|------|-------|
| Aluminum alloy      | 50%  | 75%  | 51%    | 15%    | 42.5%| 34%  | 69.3% |
| Titanium alloy      | 34%  | 1%   | 14%    | 40%    | 17.6%| 18%  | 10.3% |
| Alloy steel         | 2%   | 11%  | 12%    | 6%     | 7%   | 10%  | 12.3% |
| Composite material  | 2%   | 2%   | 11%    | 34%    | 32.9%| 38%  | 8.1%  |
| Other materials     | 12%  | 11%  | 12%    | 5%     | —    | —    | —     |

Table 2. Structure weight percentages of airframe materials.

In turn, $\gamma_l^m$ represents the cost ratio of $m$ material to $l$ labor hours. It can be calculated using the following equation:

$$\gamma_l^m = C_i * \sigma_{l,m} + (1 - C_i)$$

(2)
where $C_i$ is the proportion of airframe cost within total cost. The total cost includes not only the airframe cost but also aircraft subsystem costs such as the flight control system and final assembly costs. Values of $C_i$ differ for different types of aircraft and different labor hours. Table 3 shows various values for $C_i$.

**Table 3. Values of $C_i$.**

| Materials | Nonrecurring Engineering | Nonrecurring Tooling | Recurring Engineering | Recurring Tooling | Recurring Manufacturing | Material Cost | Recurring Quality Assurance |
|-----------|--------------------------|----------------------|-----------------------|------------------|-------------------------|--------------|-----------------------------|
| A-6       | 47                       | 80                   | 47                    | 80               | 33                      | —            | —                           |
| A-7       | 20                       | 94                   | 16                    | 92               | 81                      | 83           | 83                          |
| A-10      | 45                       | 88                   | 20                    | 24               | 53                      | —            | —                           |
| B-52      | 24                       | 88                   | 23                    | 92               | 88                      | —            | —                           |
| C-5       | 63                       | 93                   | 63                    | 93               | 75                      | 57           | 57                          |
| C-130     | 61                       | 80                   | 61                    | 80               | 83                      | 83           | 83                          |
| C-141     | 53                       | 80                   | 53                    | 80               | 73                      | 63           | 63                          |
| F-4       | 51                       | 94                   | 51                    | 94               | 50                      | 69           | 69                          |
| F-14      | 58                       | 94                   | 50                    | 94               | 66                      | 35           | 35                          |
| F-15      | 43                       | 87                   | 43                    | 87               | 74                      | —            | —                           |
| F-16      | 12                       | 68                   | 19                    | 69               | 45                      | 16           | 16                          |
| KC-135    | 58                       | 100                  | 57                    | 100              | 88                      | —            | —                           |
| Average   | 45                       | 87                   | 42                    | 82               | 67                      | 58           | 69                          |

*a “—” in the table means the data are not available.

*b Average values present the average values for U.S. active-duty aircraft rather than the average values of the data listed in the table.

**Table 4. Values of $\sigma_{i,m}$ for different materials in late 1980’s.**

| Materials             | Nonrecurring Engineering | Nonrecurring Tooling | Recurring Engineering | Recurring Tooling | Recurring Manufacturing | Recurring Quality Assurance |
|-----------------------|--------------------------|----------------------|-----------------------|------------------|-------------------------|-----------------------------|
| Aluminum alloy        | 1.0                      | 1.0                  | 1.0                   | 1.0              | 1.0                     | 1.0                         |
| Aluminum lithium alloy| 1.1                      | 1.2                  | 1.1                   | 1.1              | 1.1                     | 1.1                         |
| Titanium alloy        | 1.1                      | 1.4                  | 1.4                   | 1.9              | 1.6                     | 1.6                         |
| Alloy steel           | 1.1                      | 1.1                  | 1.1                   | 1.4              | 1.2                     | 1.4                         |
| Carbon-epoxy          | 1.4                      | 1.6                  | 1.9                   | 2.2              | 1.8                     | 2.4                         |
| Carbon-bismaleimide   | 1.5                      | 1.7                  | 2.1                   | 2.3              | 2.1                     | 2.5                         |
| Carbon thermoplastics | 1.7                      | 2.0                  | 2.9                   | 2.4              | 1.8                     | 2.6                         |

In equation (2), $\sigma_{i,m}$ represents the cost factor of $i$ labor hour and $m$ material. These factors are the rates of different materials’ features, price, and utilization to the costs of ordinary aluminum alloy. For example, Table 4 shows values of $\sigma_{i,m}$ as they stood in the late 1980’s.

The category “Other materials” from Table 1 mostly represents nonmetal composite materials. In the following calculations, we consider these to be carbon-epoxy.

When estimating the cost of aircraft, we consider composite materials as a whole because of their
great variety. We can derive $\sigma_{l,m}$ for composite materials using weighted summations from Table 4. Table 5 shows values of $\sigma_{l,m}$ for composite materials.

Table 5. Values of $\sigma_{l,m}$ for composite materials.

| Time       | Nonrecurring Engineering | Nonrecurring Tooling | Recurring Engineering | Recurring Tooling | Recurring Manufacturing | Recurring Quality Assurance |
|------------|--------------------------|----------------------|-----------------------|-------------------|-------------------------|-----------------------------|
| Late 1980’s | 1.53                     | 1.77                 | 2.30                  | 2.30              | 1.90                    | 2.50                        |
| Mid 1990’s  | 1.30                     | 1.50                 | 1.50                  | 2.17              | 1.63                    | 1.97                        |
| Late 1990’s | 1.10                     | 1.30                 | 1.16                  | 1.43              | 1.26                    | 1.44                        |
| Mid 2000’s  | 1.15                     | 1.37                 | 1.18                  | 1.47              | 1.26                    | 1.55                        |

The above expressions combine to yield the labor hour materials cost coefficients for different decades of the last century.

2.1.2. Geometric complexity of component. The geometric complexity of components has a marked impact on costs beyond the influence of materials and manufacturing processes. In fact, for some types of labor hour, geometric complexity is the most important cost-driven factor. However, statistical data on components’ geometric complexity by aviation product manufacturer remain relatively sparse, especially given the contribution of different materials and different accounts to the geometric complexity of the components. Additional statistical data concerning manufacturing labor hours and other labor hours is incomplete as well, preventing comprehensive and effective analysis. Therefore, we propose a more detailed formula regarding manufacturing labor hours.

Table 6. Aircraft body parts by complexity level.

| Complexity     | Name of main components in aircraft |
|----------------|-------------------------------------|
| Simple         | skin, doors, dashboard, accessories, surface smooth skin |
| Medium         | beam, lateral wall of oil tank, equipment tray, ceiling block, rigid skin, tank floor |
| Complex        | horizontal rails, separator, air-intake duct, cabin keel, variable camber skin, pylon, stringers, ribs |
| Extremely complex | bearing, air-intake ports, guide edge |

First, we must quantify the effects of geometric complexity on manufacturing labor hours. Components can be divided into four types: simple components, medium components, complex components, and extremely complex components. Simple components are single blocks or flat surface parts. Medium components incorporate a medium radius of curvature, reinforcing ribs, or a moderate number of unit parts. Complex components include pieces with complex curvature or the main internal structures; they may also involve a large number of subcomponents. Finally, extremely complex components are characterized by complex geometry, with widespread use of multi-dimensional control and high tolerance parts. Table 6 shows examples of this classification system.

Cost ratios of manufacturing labor hours are not identical across different materials, different processes, and different complexities. Table 7 shows the cost ratios of manufacturing labor hours based on medium-complexity aluminum alloy parts. The data in Table 7 suggest the following rules:

- Cost ratios will increase with geometric complexity because the processing time of more complex components is longer than that of simpler components.
• Cost ratios will decrease with automation, especially for composite materials, in which the processing time of automatic fiber placement is shorter than that of manual molding.

**Table 7. Cost ratios of material, manufacturing process, and complexity.**

| Material / Manufacturing Process                  | Simple | Medium | Complex | Extremely complex |
|--------------------------------------------------|--------|--------|---------|-------------------|
| Aluminum alloy / Conventional processing         | 0.7    | 1.0    | 1.5     | 2.3               |
| Aluminum lithium alloy / Conventional processing | 0.7    | 1.0    | 1.6     | 2.5               |
| Titanium alloy / Conventional processing         | 0.7    | 1.2    | 1.7     | 2.9               |
| Alloy steel / Conventional processing            | 0.7    | 1.1    | 1.8     | 2.9               |
| Aluminum alloy / High speed machining            | 0.6    | 0.8    | 1.0     | 1.5               |
| Aluminum lithium alloy / High speed machining    | 0.6    | 0.8    | 1.1     | 1.6               |
| High performance titanium alloy / Processing     | 0.7    | 1.1    | 1.5     | 2.5               |
| Composite / Hand laying                         | 1.3    | 1.8    | 2.2     | 3.0               |
| Composite / Automatic fiber placement            | 0.7    | 1.3    | 1.7     | —                 |
| Composite / Resin transfer molding               | —      | —      | 1.4     | 2.3               |

Therefore, in the manufacturing process of airframes, the labor hour cost factor of the manufacturing process is

\[
WMCF_{lm} = \sum_{l=1}^{L} \sum_{m=1}^{M} S_{lm} \gamma_{lm}^m
\]  

(3)

where \( S_{lm}^m \) is the percentage of airframe structural weight with \( l \) class manufacturing process and \( m \) complexity, and \( \gamma_{lm}^m \) is the percentage of labor hours with \( l \) class manufacturing process and \( m \) complexity. At the same time, we can derive other labor hour cost factors when sufficient statistical data is provided.

2.2. Effect of material costs

Advanced materials costs proceed mainly from two aspects, labor hours and materials costs. The preceding discussion studied labor hours in detail; we will now focus on materials costs, which result largely from increasing prices of materials and declines in utilization rates.

Raw materials costs are related to different types of fiber and resin and their uses in manufacturing and processing. At the same time, material costs are affected by market factors like commercial dosage, purchase quantity, and competition within the industry.

Scrap rate is another important factor that influences the cost of materials. The scrap rate is the weight ratio between the raw materials and the actual manufactured aircraft components. Sources of material loss during manufacturing include material handling loss, processing and cutting loss, scrapping loss, and other operating losses. The scrap rate for automatic fiber placement is lower than for hand operation. The scrap rate of composite materials is related to processing, while the scrap rate of metal materials is closely related to the complexity of the components. The more complex the geometry of the parts, the higher the scrap rate.

Therefore, for \( K \) type of material and \( F \) method of manufacturing, the formula for estimating airframe material cost is

\[
C_m = W_s \cdot \sum_{f=1}^{F} \sum_{k=1}^{K} M_f^k S_f^k \cdot P_k
\]  

(4)
where $W_s$ is the weight of the airframe structure; $M^f_j$ is the weight percentage of $k$ type material and $f$ type manufacturing method; $S^f_j$ is the scrap rate of $k$ type material and $f$ type manufacturing method; and $P_k$ is the unit price of $k$ type material.

When analyzing the material factor, we find that material costs grow based on the factor $\sum_{j=1}^{K} \sum_{f=1}^{F} M^f_j S^f_j$. Therefore, we define $\sum_{j=1}^{K} \sum_{f=1}^{F} M^f_j S^f_j$ as the material cost factor within manufacturing costs of materials. In order to facilitate statistical analysis of data, we simplify the formula as follows:

$$WMCF = \sum S_m \gamma_m$$ (5)

where $\gamma_m$ is the average scrap rate of $m$ material. Table 8 shows specific values:

| Materials         | Aluminum alloy | Aluminum lithium alloy | Titanium alloy | Alloy steel | Composite materials |
|-------------------|----------------|------------------------|----------------|-------------|-------------------|
| Late 1980’s       | 2.5            | 4.2                    | 3.0            | 2.1         | 1.9               |
| Mid 1990’s        | 2.2            | 2.7                    | 3.0            | 2.1         | 1.8               |

Table 8 shows that the scrap rate remained about the same for the common aircraft structure materials over the period covered. Therefore, we can adopt the value from the mid 1990’s to estimate the scrap rate after the 1990’s.

3. Case analysis

In the previous section, we analyzed the impact of advanced materials on labor hour and manufacturing material costs. We then defined and analyzed the material cost factors. In this section, we will consider the use of advanced materials to estimate aircraft R&D and manufacturing costs.

In the case of the B-2 Bomber, the empty weight is 166,579 lb and the maximum speed at the optimum altitude is 489.2 kn. In this aircraft, 34% of the total weight is aluminum alloy and other materials, 10% is alloy steel, 18% is titanium alloy, and 38% is composite materials. The material cost factor can be calculated as follows:

$$WMCF_{NRENGR} = \sum_{l=1}^{L} \sum_{m=1}^{M} S_m \gamma^m_l$$

$$= 0.45 \times (1 \times 0.34 + 1.1 \times 0 + 1.1 \times 0.18 + 1.1 \times 0.1 + 1.7 \times 0.38) + (1 - 0.45) = 1.132$$

$$WMCF_{NRTOL} = 0.87 \times (1 \times 0.34 + 1.2 \times 0 + 1.4 \times 0.18 + 1.1 \times 0.1 + 2 \times 0.38) + (1 - 0.87) = 1.402$$

$$WMCF_{ENGR} = 0.42 \times (1 \times 0.34 + 1.1 \times 0 + 1.4 \times 0.18 + 1.1 \times 0.1 + 2.9 \times 0.38) + (1 - 0.42) = 1.337$$

$$WMCF_{TOOL} = 0.82 \times (1 \times 0.34 + 1.1 \times 0 + 1.9 \times 0.18 + 1.4 \times 0.1 + 2.4 \times 0.38) + (1 - 0.82) = 1.602$$

$$WMCF_{LAB} = 0.67 \times (1 \times 0.34 + 1.1 \times 0 + 1.6 \times 0.18 + 1.2 \times 0.1 + 1.8 \times 0.38) + (1 - 0.67) = 1.289$$

$$WMCF_{MAT} = 0.58 \times (1 \times 0.34 + 2.7 \times 0 + 2.8 \times 0.18 + 0.7 \times 0.1 + 6.5 \times 0.38) + (1 - 0.58) = 2.383$$

$$WMCF_{QUAL} = 0.69 \times (1 \times 0.34 + 1.1 \times 0 + 1.6 \times 0.18 + 1.4 \times 0.1 + 2.6 \times 0.38) + (1 - 0.69) = 1.521$$

Using the DAPCA IV model, the nonrecurring engineering labor hour can be estimated using the following formula:
\[
WHR_{NRENGR} = 0.0168 \times W^{0.747} \times S^{0.8} \times sec \times labor \times 10^{-3} \\
= 0.0168 \times 1665.79^{0.747} \times 489.2^{0.8} \times 1.25 \times 161.66 \times 10^{-3} \\
= 3827.92
\] (6)

However, considering the use of advanced materials, the nonrecurring engineering labor hour can instead be estimated by

\[
WHR_{NRENGR} = WHR_{NRENGR} + 0.0168 \times W^{0.747} \times S^{0.8} \times sec \times labor \times WMCF_{NRENGR} \times 10^{-3} \\
= 3827.92 \times 1.132 = 4334.36
\] (7)

We can take the same approach for other types of labor hours, although we will not detail these in the present article. Table 9 displays the results.

**Table 9.** Labor hour costs from different calculation models.

| Cost                        | DAPCA IV model (millions) | Material cost factor | New model (millions) |
|-----------------------------|---------------------------|----------------------|----------------------|
| Nonrecurring Engineering    | 3827.92                   | 1.132                | 4334.36              |
| Nonrecurring Tooling        | 2009.73                   | 1.402                | 2817.52              |
| Recurring Engineering       | 734.54                    | 1.337                | 982.58               |
| Recurring Tooling           | 264.38                    | 1.602                | 423.51               |
| Recurring Manufacturing     | 1767.05                   | 1.289                | 2278.50              |
| Material Cost               | 433.28                    | 2.383                | 1032.38              |
| Recurring Quality Assurance | 229.72                    | 1.521                | 349.55               |
| Airframe total              | 9266.62                   | —                    | 12218.40             |

**Table 10.** Aircraft R&D and manufacturing costs considering advanced materials.

| Type                        | Actual value | DAPCA IV model | New model |
|-----------------------------|--------------|----------------|------------|
| Actual value                | value        | deviation      | value      | deviation  |
| F/A-18                      | 1.56         | 1.226          | 1.336      | 14.36%     |
| F/A-22                      | 7.47         | 4.92           | 5.978      | 19.97%     |
| B-1B                        | 7.04         | 5.172          | 6.372      | 9.49%      |
| B-2                         | 14.23        | 9.26           | 12.21      | 14.20%     |

| Unit manufacturing cost (millions) | Actual value | DAPCA IV model | New model |
|------------------------------------|--------------|----------------|------------|
| Actual value                       | value        | deviation      | value      | deviation  |
| F/A-18                             | 24.2         | 23.52          | 24.73      | 2.19%      |
| F/A-22                             | 130          | 116.472        | 139.284    | 7.14%      |
| B-1B                               | 283.1        | 239.568        | 283.74     | 0.23%      |
| B-2                                | 840          | 637.764        | 717.576    | 14.57%     |

Table 10 shows the results of estimating R&D and manufacturing costs of the F/A-18, F/A-22, B-1B, and B-2 using the new formula. Figures 2 and 3 provide the estimation error of the DAPCA IV model and the new model.
Figure 2. R&D cost estimate deviations of common aircraft.

Figure 3. Manufacturing cost estimation errors of common aircraft.

Based on the analysis above, the new model appears to offer more accurate estimates than the common DAPCA IV model. We can conclude that it is necessary to consider advanced materials when estimating the cost of a new aircraft.

4. Conclusion

In this article, we studied the relationship between advanced materials and aircraft R&D and manufacturing costs. Ultimately, we proposed a modified formula based on the commonly-used DAPCA IV model to estimate costs while considering advanced materials. Examples performed using US Air Force aircraft data suggest that the estimation accuracy of the new formula exceeds that of the DAPCA IV. For example, the estimation error for the B-2 bomber’s R&D cost improved from 34.93% to 14.2%, and the estimated error in manufacturing cost improved from 24.08% to 14.57%. At the same time, we note that the new estimation model contains some estimation errors, which require further research.

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