Electrothermal Propulsion System Selection for Communication Satellite NSSK Maneuver Using Multi Criteria Decision Making Method

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***Abstract*—Choosing proper space propulsion systems for communication satellites is an important issue for space system engineers. Although there are a lot of alternatives, selection of the system which fits well with the mission requirements depends on many parameters. In this study, thruster selection for the north-south station keeping maneuver of communication satellites is performed. Three kinds of electrothermal thrusters which are resistojet, arcjet and microwave electrothermal thruster considered as alternatives, and properties of the systems are defined. Fuzzy TOPSIS Multi Criteria Decision Making Method is used to evaluate the linguistic variables and their corresponding fuzzy numbers. Specifically, the feasibility of microwave electrothermal thruster for such a mission among the electrothermal thrusters is investigated.**

Keywords—Space Propulsion; Electric Propulsion; Electrothermal Thruster; Communication Satellite; Station Keeping, Fuzzy TOPSİS

I. Introduction

In-space propulsion systems produces thrust that a spacecraft needs to change or maintain its position while performing its mission. Since 1960's various kinds of space propulsion systems have been developing. Cold gas thruster, resistojet, arcjet, ion thruster and Hall Effect thruster is commonly used in space platforms. As there are many alternatives, proper propulsion system selection becomes an issue from the point of view of a space system engineer. One of the ways is used to choose a thruster is comparison of the systems in accordance with their dry mass and specific impulse. Because these two parameters have concrete effect on the system lifetime, over all launch mass and available payload mass. Namely, if the system's dry mass is low, payload margin can be increased or more propellant can be carried instead. In case of more propellant stored in the system the lifetime will be increased. On the other hand higher the specific impulse higher the lifetime is because of the decreasing propellant consumption. In addition to the mass budget power budget, cost, and thrust level is the some other parameters used while choosing a propulsion system. Besides these quantitative criteria more qualitative ones like integration level to space craft, reliability, spacecraft charging risk level, system complexity must be also taken into consideration while choosing a system. Hence multiple parameters must be judged to select propulsion systems for requisite of mission objectives, Multi (or Multiple) Criteria Decision Making (MCDM) can be applied in this process to find the best option. In MCDM the criteria are graded by using linguistic variable for each alternative. Finally the best solution is evaluated by using different kind of MCDM methods.

In this paper, a MCDM process of propulsion system which will be used in a communication satellite North South Station Keeping (NSSK) maneuver is studied. Three kinds of electrothermal systems are chosen as alternatives. These are resistojet, arcjet and microwave electrothermal thruster. One of the aims of the study is to present the strong and the weak sides of the microwave electrothermal thruster in comparison with the resistojets and arcjets.

II. Case Study

The case is issued from the feasibility evaluation of Microwave Electrothermal Thruster (MET) concept which is studied at the Boğaziçi University Space Technologies Laboratory (BUSTLab). Although MET seems to be promising concept of electrothermal propulsion, there is no application of the system on a space platform. So it is hard to see the systems' applicability in the future. To examine the system performance in comparison with the other two concepts in the electrothermal thruster family, MCDM method is performed.

The propulsion system selection is performed to select propulsion system which will be manufactured for a communication satellite. The communication satellites use propulsion systems for orbital maneuvers. For operating sufficiently a communication satellite must maintain its location and attitude roughly in $\pm$ 0.1^{o} deviation case. For North-South Station Keeping (NSSK) nearly 50 m/s velocity increment is needed annually[1]. The most appropriate system is tried to be chosen among three electrothermal systems below by using the attributes defined in section III.

A. Resistojet

Resistojets are the basic and the simplest form of the electrothermal thruster application. In resistojets, propellant is heated using Ohmic heating while passing through heater as in Fig. 1 [2]. Thrust is produced when the hot gas is expelled from a conventional nozzle. In these systems, it is possible to use almost all types of gases as propellant. Moreover using waste water in manned flights is in consideration [3].

Resistojets are the attractive for space propulsion applications because of the simplicity of their power and propellant feeding systems compared to other electric propulsion systems. Besides, they are more compact and lower weight systems. Another advantage of these systems is their ability to continue on a mission as a cold gas system in case of fault in heating subsystem. In addition, interaction of exhaust gases with spacecraft will not cause electric charging as in electric propulsion systems that expels ions [4].

Tendency for the miniaturization of spacecraft to lower cost while maintaining the mission capabilities also affects the propulsion technology. Small scale spacecraft needs micro or mini propulsion systems. To fulfill this requirement, micro resistojets have been developed since 1990’s by using micro-electro-mechanical-systems (MEMS) technology. MEMS based small thrusters are constructed for producing thrust levels of μN and mN levels [5, 6]. Another opportunity of these small thrusters is achieving lower minimum impulse bit which is important for precision in attitude control maneuvers.

Temperature endurance of a resistojet's wall and heater element is the main limiting factor. Wall temperature can be controlled by applying cooling procedures like regenerative cooling as in the chemical thrusters. Even if the walls are cooled, heater element melting point will still be a temperature limiting factor [2]. Thus, maximum available temperature of the propellant is about 3000 K. Even though very light weight hydrogen is used as propellant exhaust velocities cannot reach near 10000 m/s. Another deficiency of these systems is formidable integration of isolation material with heater component [3].

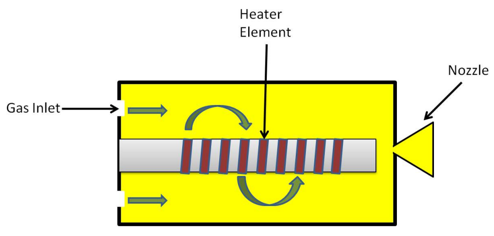

Fig. 1. Schematic view of a resistojet

B. Arcjet

In order to obtain higher specific impulse and exit velocities than chemical thrusters and resistojets, arcjets employs DC or AC arc discharge in the flow region. Arc is generated between tungsten or tungsten alloy cathode and a nozzle which is designed as anode. The arc discharge is produced in the constrictor region of the thruster as shown in Fig. 2. In arcjets, heating of the propellant can materialize in two ways. First one is letting the propellant flow around arc directly. In second one gas energized when swirling around chamber wall which is heated by means of arc. In later mechanism frozen low losses will decrease and efficiency will increase [3]. Energized propellant thermal energy is transferred to kinetic energy when expanding through a nozzle as in other conventional system [7, 8].

Augmented hydrazine arcjets which are commonly used in communication satellites can provide nearly twice as much increase in specific impulse. Thus, reduction in the spacecraft mass and extension of orbital lifetime will be provided [9, 10]. Although arcjets cannot reached specific impulse level of ion or Hall Effect thrusters, their thrust level is significantly higher [8]. Besides, as mentioned in section II.A to take advantage of system miniaturization studies are started in NASA since 1990’s [11].

Cathode erosion is the primary lifetime limiting factor in arcjet thruster. When ions in the discharge strike the surface of the cathode with high speed vaporization occurs. On the other hand electron current will cause the rupturing of the anode surface. And the gap between the cathode and anode will be opened up. At that point the arc cannot be generated in accordance with the Coulomb law. In addition ions’ motion is affected by the magnetic field which is generated by the nature of the high current arc. Because of the magnetic field effect arc becomes unstable and split into many sectors. This formation will have negative effect on the energy transfer to the gas and the electrode erosion [2]. Cathode material, geometry, propellant type have effect on erosion [12]. Even though some measurement are taken like changing the flow pattern, increasing thermal endurance of cathode material by coating to minimize erosion, erosion is an inherited limitation [8]. Besides the erosion problem when compared with a resistojet the power processing unit of the system is much more complex and heavy [4].

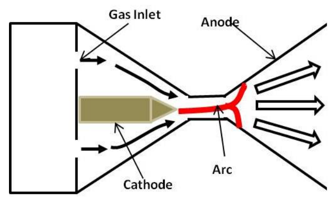

Fig. 2. Schematic view of arcjet

C. Microwave Electrothermal Thruster

Microwave Electrothermal Thruster (MET) which uses free floating plasma to heat up the propellant gas is developed for eliminating the inevitable handicaps of resistojet and arcjet. Namely, in resistojet propellant gas temperature limit is imposed by the filament heater thermal endurance. But in a MET this limit is vanished because no solid heater is used in the system. On the other hand when compared with the Arcjet thruster it is obvious that cathode erosion and the arc instability problem will disappear in the system as a result of the use of a free floating plasma [13].

METs employ microwave radiation to generate discharge. Electromagnetic wave is sent to a resonant cavity which can be considered as heating chamber. The cavity is a closed cylinder with conductor walls. When a wave enters the cavity a standing wave is generated. And the amplitude of the wave increases if microwave continuously transmitted into the cavity. This energy is uses to generate and maintain plasma inside the resonant cavity. On the other hand energy passes to gas through plasma. The operation of the MET systems has three main steps;

- Free electrons in the propellant gas are accelerated via the electric field component of microwave in accordance with the Lorentz Force (F=qE) where q is the elementary charge and E is the electric field.
- Energized electrons transfer their energy to heavy particles (ions, molecules and atoms) after each collision. If the transferred energy is adequate to ionize neutrals, number of electrons will increase. When this number reaches the critical point plasma discharge will start.
- Propellant gas heat up when swirling around free floating plasma as shown in Fig. 3 When gas flows through de Laval nozzle it expands and thermal energy of the gas is transferred into kinetic energy to obtain thrust [14, 15].

One other strong side of the system in comparison with other electrothermal systems is that various gases can be used in these systems. Also, use of water vapor as propellant is performed and approximately 450 s I_{sp} is reached [15–17]. System also gives an opportunity of reduction of system dimensions and impulse bit by changing the electromagnetic field frequency used in the system [13, 18].

The system main handicap is that it has not been used on a space platform yet. So, there is no knowledge about the level of integrations to the spacecraft. Moreover, in the demonstration systems constructed to date system microwave generating and power processing unit is complex and heavier than the thruster itself.

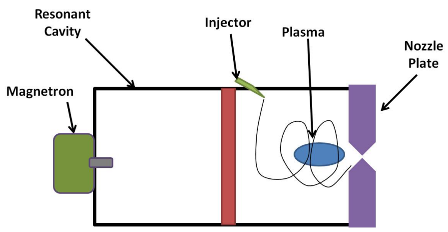

Fig. 3. Schematic view of microwave electrothermal thruster

As mentioned above, three electrothermal systems have very similar characteristics. So, the selection process becomes more complicated and fuzzy. Some quantitative specifications of the systems taken from [19] are tabulated in Table I. The data will be helpful for the experts while evaluating the systems. In addition to these quantitative ones four qualitative parameters defined in Section III are chosen as criteria for MCDM.

TABLE I: SPECIFICATIONS OF THRUSTERS [4, 19]

System	Thrust (mN)	Specific Impulse (s)	Power (kW)	Efficiency
Resistojet	5-500	300-350	0.5-1.5	0.80
Arcjet	5-5000	150-1000	0.005-26	0.35
MET	2-700	150-600	0.07-5	0.50

III. MCDM METHOD AND RESULTS

A. MCDM Method

MCDM problem depends on selecting the best alternative among several alternative possibilities considering desired multiple criteria. The problem can be described with (1). Here, the rows of D matrix represent the alternatives and the columns of D involve the criteria. There are m number of alternatives and n number of criteria in D. The performance rating of alternative i on criteria j is defined as x_{ij} in D. The elements of W array include the importance weights of the criteria.

$$D=\begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \cdots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix}, W=[w_1, \quad w_2, \quad \cdots, \quad w_n] \quad (1)$$

There are various technique used to solve MCDM problem in literature [20] . In this study, Fuzzy "Technique for Order of Preference by Similarity to Ideal Solution" (TOPSIS) method is used to select the best system. The TOPSIS is one of the common methods developed by Hwang and Yoon [21] to solve a MCDM problem. The method bases upon the idea that the selected alternative should have the shortest distance from the positive ideal solution (PIS) and the farthest from the negative ideal solution (NIS) in multidimensional solution space. The method can be easily implemented to any MCDM problem and the steps of the method are not dependent to the number of the criteria.

The performance ratings and the weights of the criteria are given as crisp values in the procedure of TOPSIS. The crisp data are incompetent to model real-life situations in many occasions. Because of the judgments covering decisions or choices of the people are often not clear, they cannot be estimated easily by exact numerical values. Therefore, linguistic assessments instead of numerical values can be used to evaluate the ratings and weights of the criteria in MCDM problems [22, 23]. At this point, fuzzy methods can be preferred [24].

Selection is made by using eight parameters which are commonly used while determining a thruster performance as defined in Table II.

TABLE II : SELECTION CRITERIA [25]

Symbol	Criteria	Definition
C_1	Thrust Level	Achieved level of the force imparted to a space vehicle by propulsion system.
C_2	Specific Impulse	Impulse acting upon a space vehicle per unit weight of propellant.
C_3	Lifetime	The length of the operational time that a propulsion system can work properly.
C_4	Power	Electrical power used by the system to produce some amount of thrust.
C_5	Efficiency	The ratio of the produced kinetic energy to the total energy implemented for operating the system.

Symbol	Criteria	Definition
C_6	Simplicity	Easiness of the system construction and integration to the spacecraft including power supply and propellant feeding system.
C_7	Reliability	Mechanical and operational safety can be provided. Failure risk of the propulsion system and negative effects on the other subsystems are low and well-known.
C_8	Producibility	Easiness of the manufacturing, assembling and testing process is an important parameter while constructing a thruster.

The Fuzzy TOPSIS method used in this paper is revealed by Chen [22] and involves the application of the TOPSIS method in fuzzy environment. Fuzzy TOPSIS procedure is defined in nine steps as shown below:

Step 1. A group of decision makers is formed, and the evaluation criteria are rated using linguistic variables by this group's members. Linguistic variables (LV) in Table III for weighting each criteria are taken from [22] and the criteria are weighted as shown in Table IV by three experts who are represented by E_1, E_2, E_3.

TABLE III : LV FOR WEIGHTING THE CRITERIA [22]

Very Low (VL)	(0,0,0.1)
Low (L)	(0,0.1,0.3)
Medium Low (ML)	(0.1,0.3,0.5)
Medium (M)	(0.3,0.5,0.7)
Medium High (MH)	(0.5,0.7,0.9)
High (H)	(0.7,0.9,1)
Very High (VH)	(0.9,1,1)

TABLE IV : THE IMPORTANCE WEIGHT OF CRITERIA

	E_1	**E_2**	**E_3**
C_1	M	ML	M
C_2	VH	H	H
C_3	H	MH	M
C_4	ML	M	M
C_5	H	M	MH
C_6	L	ML	ML
C_7	H	VH	VH
C_8	ML	L	ML

Step 2. The alternatives are evaluated, using linguistic variables again, with respect to each criterion.

All three systems are rated using the linguistic variables in Table V The rating of three systems are shown in Table VI where resistojet, arcjet and MET are represented by S_1, S_2, S_3 respectively.

TABLE V : LV FOR RATING THE SYSTEMS [22]

Very poor (VP)	(0, 0, 1)
Poor (P)	(0,1,3)
Medium poor (MP)	(1,3,5)
Fair (F)	(3,5,7)
Medium good(MG)	(5,7,9)
Good (G)	(7,9,10)
Very good (VG)	(9,10,10)

TABLE VI: RATINGS OF PROPULSION SYSTEMS

Criteria	**System**	**Experts**		
		E_1	E_2	E_3
C_1	S_1	F	MG	F
	S_2	F	G	G
	S_3	F	MG	F
C_2	S_1	F	P	MP
	S_2	G	F	G
	S_3	MG	G	G
C_3	S_1	MG	G	MG
	S_2	MG	MG	MG
	S_3	G	F	G
C_4	S_1	MG	MP	MG
	S_2	P	P	P
	S_3	MP	MG	MG
C_5	S_1	F	G	MG
	S_2	MP	P	P
	S_3	MG	F	MG
C_6	S_1	VG	G	VG
	S_2	MP	F	F
	S_3	MP	MG	F
C_7	S_1	G	MG	VG
	S_2	G	MP	G
	S_3	P	F	F
C_8	S_1	G	G	G
	S_2	MG	F	MG
	S_3	MP	MP	MP

Step 3. Aggregated fuzzy weight $\tilde{w}_j$ of each criterion Cj is determined using (2). Similarly, aggregated fuzzy rating $\tilde{x}_{ij}$ of alternative S_i under criterion Cj is determined using (3).

$$\tilde{w}_j = \frac{1}{K}\left[\tilde{w}_j^1 (+) \tilde{w}_j^2 (+) \cdots (+) \tilde{w}_j^K\right] \tag{2}$$

$$\tilde{x}_{ij} = \frac{1}{K}\left[\tilde{x}_{ij}^1 (+) \tilde{x}_{ij}^2 (+) \cdots (+) \tilde{x}_{ij}^K\right] \tag{3}$$

where $\tilde{w}_j^K$ denotes the K^{th} decision maker's opinion on the importance of criterion Cj and $\tilde{x}_{ij}^K$ denotes the performance evaluation rating of the K^{th} decision maker for alternative S_i with respect to the criterion Cj .

Step 4. Fuzzy decision matrix (4) is constructed as Table VII, and then normalized (5) as Table VIII.

$$\tilde{\boldsymbol{D}} = \begin{bmatrix} \tilde{x}_{11} & \tilde{x}_{12} & \cdots & \tilde{x}_{1n} \\ \tilde{x}_{21} & \tilde{x}_{22} & \cdots & \tilde{x}_{2n} \\ \vdots & \vdots & \cdots & \vdots \\ \tilde{x}_{m1} & \tilde{x}_{m2} & \cdots & \tilde{x}_{mn} \end{bmatrix}, \tilde{\boldsymbol{W}} = [\tilde{w}_1, \tilde{w}_2, \cdots, \tilde{w}_n] \tag{4}$$

$$\tilde{\boldsymbol{R}} = [\tilde{r}_{ij}]_{m \times n}$$

$$\tilde{r}_{ij} = \left(\frac{a_{ij}}{c_j^*}, \frac{b_{ij}}{c_j^*}, \frac{c_{ij}}{c_j^*}\right) \; if \, j \in B, \; c_j = \max_i c_{ij}$$

$$\tilde{r}_{ij} = \left(\frac{a_j^-}{c_{ij}}, \frac{a_j^-}{b_{ij}}, \frac{a_j^-}{a_{ij}}\right) \; if \, j \in C, \; a_j^- = \min_i a_{ij} \tag{5}$$

Each entry in (4) and (5) is a fuzzy triangular number. B and C are the set of benefit criteria and cost criteria, respectively.

Step 5. Weighted normalized fuzzy decision matrix is constructed using (6) as Table IX.

$$\tilde{V}=\left[\tilde{v}_{ij}\right]_{m\times n},\ i=1,2,...,m,\quad j=1,2,...,n$$
$$\tilde{v}_{ij}=\tilde{r}_{ij}\ (\cdot)\ \tilde{w}_j \tag{6}$$

The elements $\tilde{v}_{ij},\ \forall i,j$ are normalized positive triangular fuzzy numbers and their ranges belong to the closet interval [0,1].

Step 6. Fuzzy positive ideal solution and fuzzy negative ideal solution are determined as in (7).

$$A^{*}=\left(\tilde{v}_1^{*},\tilde{v}_2^{*},\cdots,\tilde{v}_n^{*}\right)$$
$$A^{-}=\left(\tilde{v}_1^{-},\tilde{v}_2^{-},\cdots,\tilde{v}_n^{-}\right) \tag{7}$$

where $\tilde{v}_j^{*}=(1,1,1)$ and $\tilde{v}_j^{-}=(0,0,0)$ are triangular fuzzy numbers for , j =1,2,...,n.

Step 7. The distance of each alternative from fuzzy positive ideal solution (FPIS) and fuzzy negative ideal solution (FNIS) are calculated using (8) and (9) respectively. In these equations, $d(\cdot,\cdot)$ denotes the distance between two triangular fuzzy numbers. This distance is calculated using vertex method as in (10).

$$d_i^{*}=\sum_{j=1}^{n} d\left(\tilde{v}_{ij},\tilde{v}_j^{*}\right),\ i=1,2,\cdots,m \tag{8}$$

$$d_i^{-}=\sum_{j=1}^{n} d\left(\tilde{v}_{ij},\tilde{v}_j^{-}\right),\ i=1,2,\cdots,m \tag{9}$$

$$d(\tilde{m},\tilde{n})=\sqrt{\frac{1}{3}\left[(m_1-n_1)^2+(m_2-n_2)^2+(m_3-n_3)^2\right]} \tag{10}$$

In (10), $\tilde{m}=(m_1,m_2,m_3)$ is the first triangular fuzzy number, and $\tilde{n}=(n_1,n_2,n_3)$ is the second one.

Step 8. Closeness coefficient of each alternative is calculated using (11).

$$CC_i=\frac{d_i^{-}}{d_i^{*}+d_i^{-}},\ i=1,2,\cdots,m \tag{11}$$

An alternative S_i is closer to the FPIS and farther from FNIS as CC_i approaches to 1.

Step 9. According to the closeness coefficient, the ranking order of all alternatives can be determined. The alternative that has the highest CC_i value is said to be the best one. For the case studied according to the closeness coefficients tabulated in Table X Resistojet is determined as the best solution.

TABLE VII : THE FUZZY DECISION MATRIX

Criteria	S_1			S_2			S_3			Weights		
	L	M	U	L	M	U	L	M	U	L	M	U
C_1	3,67	5,67	7,67	5,67	7,67	9,00	3,67	5,67	7,67	0,23	0,43	0,63
C_2	1,33	3,00	5,00	5,67	7,67	9,00	6,33	8,33	9,67	0,77	0,93	1,00
C_3	5,67	7,67	9,33	5,00	7,00	9,00	5,67	7,67	9,00	0,50	0,70	0,87
C_4	3,67	5,67	7,67	0,00	1,00	3,00	3,67	5,67	7,67	0,23	0,43	0,63
C_5	5,00	7,00	8,67	0,33	1,67	3,67	4,33	6,33	8,33	0,50	0,70	0,87
C_6	8,33	9,67	10,00	2,33	4,33	6,33	3,00	5,00	7,00	0,07	0,23	0,43
C_7	7,00	8,67	9,67	5,00	7,00	8,33	2,00	3,67	5,67	0,83	0,97	1,00
C_8	7,00	9,00	10,00	4,33	6,33	8,33	1,00	3,00	5,00	0,07	0,23	0,43

TABLE VIII : THE FUZZY NORMALIZED DECISION MATRIX

Criteria	S_1			S_2			S_3		
	L	M	U	L	M	U	L	M	U
C_1	0,367	0,567	0,767	0,630	0,852	1,000	0,379	0,586	0,793
C_2	0,133	0,300	0,500	0,630	0,852	1,000	0,655	0,862	1,000
C_3	0,567	0,767	0,933	0,556	0,778	1,000	0,586	0,793	0,931
C_4	0,367	0,567	0,767	0,000	0,111	0,333	0,379	0,586	0,793
C_5	0,500	0,700	0,867	0,037	0,185	0,407	0,448	0,655	0,862
C_6	0,833	0,967	1,000	0,259	0,481	0,704	0,310	0,517	0,724
C_7	0,700	0,867	0,967	0,556	0,778	0,926	0,207	0,379	0,586
C_8	0,700	0,900	1,000	0,481	0,704	0,926	0,103	0,310	0,517

TABLE IX : THE FUZZY WEIGHTED NORMALIZED DECISION MATRIX

Criteria	S_1			S_2			S_3		
	L	M	U	L	M	U	L	M	U
C_1	0,086	0,246	0,486	0,147	0,369	0,633	0,089	0,254	0,502
C_2	0,102	0,280	0,500	0,483	0,795	1,000	0,502	0,805	1,000
C_3	0,283	0,537	0,809	0,278	0,544	0,867	0,293	0,555	0,807
C_4	0,086	0,246	0,486	0,000	0,048	0,211	0,089	0,254	0,502
C_5	0,250	0,490	0,751	0,019	0,130	0,353	0,224	0,459	0,747
C_6	0,056	0,226	0,433	0,017	0,112	0,305	0,021	0,121	0,314
C_7	0,583	0,838	0,967	0,463	0,752	0,926	0,172	0,367	0,586
C_8	0,047	0,210	0,433	0,032	0,164	0,401	0,007	0,072	0,224

TABLE X : THE DISTANCE MEASURES AND CLOSENESS COEFFICIENT MATRIX

System	d_i^*	d_i^-	CC_i
S_1	5,087	3,468	0,405
S_2	5,254	3,352	0,390
S_3	5,253	3,308	0,386

IV. CONCLUSION

Selection of propulsion system from among three alternatives of electrothermal systems by using MCDM problem solving method is studied. Weak and strong sides of the three systems are defined. Besides the feasibility analysis of MET is performed as a relatively new concept then the other alternatives.

By using the eight criteria above the resistojet is determined as the best alternative. Although the specific impulse of the resistojet is lower than the other alternatives it comes into prominence as a more reliable and simple system. On the other hand it is obvious that MET is rated very close to arcjet when the closeness coefficient matrix values are compared. Although the MET is an immature concept than the others, it offers curing solutions for life time limiting factors as mentioned above.

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