Thermal Stress Analysis of Several Hundred kW Radiation Cooled Arcjet

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Abstract: With ultra light-weight solar lens array, 170 kWe platform in the orbit will appear on the horizon. In this situation, the specific weight of electric propulsion system becomes almost comparable to that of power sources. Arcjets (including magnetoplasma-dynamic thrusters) are the most promising candidate for light-weight electric propulsion system. Many prototypes up to 500kWe class were tested in the last century, but the attention has not been paid to establish the design guideline taking into consideration the thermal stress. In this study, the prototype design of several hundred kWe arcjet is described and verified in terms of thermal stress.

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Nomenclature

A_0	= universal Richardson constant
A_c	= cathode emission area
E	= Young's modulus
J	= discharge current
k	= boltzmann constant
L_c	= cathode length
$\dot{m}$	= mass flow rate
P	= total input power
Q_{anode}	= heat load to the anode
$Q_{cathode}$	= heat load to the cathode
r_c	= cathode radius
T	= temperature
T_0	= background temperature
T_e	= electron temperature
T_c	= cathode surface temperature
V	= discharge voltage
V_A	= anode fall voltage
V_{conv}	= equivalent voltage drop due to the convection
α	= thermal linear expansion coefficient
ε	= emissivity
λ	= thermal conduction coefficient
λ_R	= correlation factor for the Richardson constant
ϕ	= work function
σ_{ste}	= Stefan-Boltzmann constant

I. Introduction

At the present time, we have already had 15 kWe satellites on the orbit and the spaceship which generates hundreds of kWe appears[1] on the horizon. Especially the stretched lens array (SLA) which has only a few kg/kW of specific weight[2] is the most hopeful candidate. In this situation, much more careful attention has to be paid for the specific weight of the electric propulsion (EP) system.

Up to today, arcjets have been replaced by Hall Effect Thruster(HET) due to their lower thrust efficiency. However they are still the strongest candidate to realize the light-weight EP system. In the end of 20th century, 26 kWe arcjet (ESEX)[3] was demonstrated on the orbit by U.S. team and radiation cooled 100kWe arcjet (HIPARC) was operated on the ground in University of Stuttgart.[4] They are well designed so that the extraordinary heat load can be discharged to the ambient space with very compact body. Especially it seems that the practical arcjet design up to 30 kWe has been almost completely established. This heritage should be taken over to the future multi-hundred kWe class EP system design.

Whenever one consider to design arcjets, temperature distribution analysis is always performed. However, the cause of the destruction is not only due to the melt down of the electrode, but also due to the thermal stress. Little literature is available on the thermal stress analysis of arcjets. It might not be important problem up to 30 kWe, but it becomes principal problem in case of several hundred kWe. In this paper, the design guidelines of multi-hundred kWe arcjets are described paying attention to thermal stress.

II. Basics of Arcjet Design

In this section, we review the basics of arcjet design referring literatures. First of all, the typical operational condition of the arcjets (partially including magnetoplasmadynamic thrusters) is described referring the past literatures. Then, the key points of the practical arcjet design are summarized.

A. General Performance

It is well known that the discharge current J and voltage V of the arc discharge is strongly related to each other. With moderate mass flow rate, we can see the negative correlation up to $J = 100$ A, and then there is a flat voltage region independent of J and positive correlation between J and V can be seen just as shown in Fig.1

In the range of tens of kWe (for example, 500 A time 40 V results 20kWe of input power), the input power increment is achieved only by increasing discharge current because the discharge voltage does not varied. Beyond $J = 1$ kA, the voltage increases with the discharge current. The input power P quadratically increases by increasing discharge current. In the same thruster model, lower mass flow rate gives lower discharge voltage at fixed discharge current (in case of the thermal acceleration).

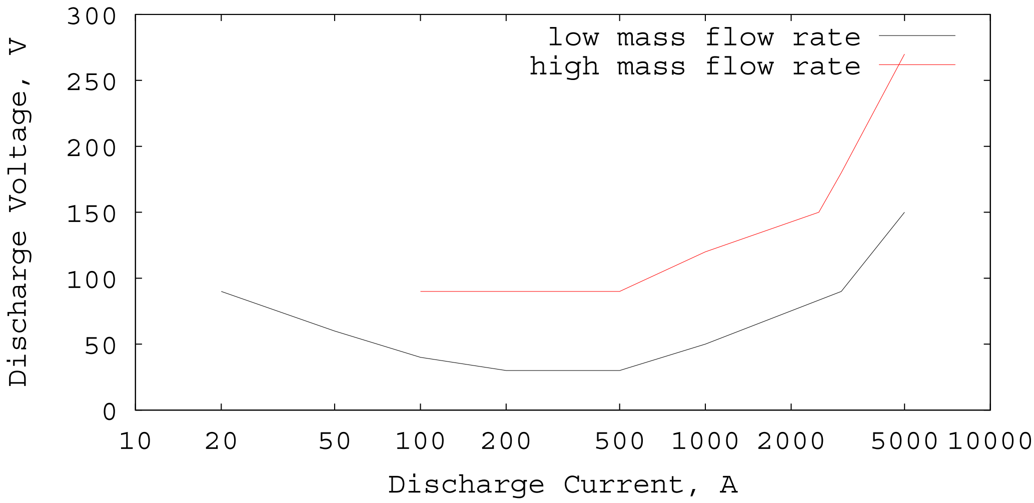

Figure 1. Typical J-V characteristics of arcjets (sample)

B. Anode

Configuration

The largest heat load is applied to the arc attachment area on the anode surface. One of the simple formulation on the anode heat load is described as follows,[5]

$$Q_{anode} = J(V_A + \frac{5}{2}kT_e + \phi + V_{conv}) \tag{1}$$

Q_{anode} is not proportional to the input power P, but to J. Empirically[5] the net anode heat loads run from 9 to 20 V times J, assuming $V_A = 0$ to 10 V, $kT_e = 1.4$ V, $\phi = 4.4$ V for copper and $V_{conv} = 2$V. This is the values for liquid-cooled copper anodes and V_A may be smaller in the case of radiation-cooled anode. We decide to use 15 V times J as a maximum heat load to the anode surface in our analysis.

The biggest issue of the tungsten anode is cracking problem due to the thermal stress at large power input. Careful attention must be paid for the anode configuration design. Tapered fitting to the housing cylinder (or sometimes anode cap is used) is one of the established way to fix the anode. Drilling the holes to the anode body should be avoided because it causes critical stress concentration. (Thread cutting to the tungsten anode body should also be avoided.)

Most of heat load is discharged from the tapered surface in accordance with Stefan-Boltzmann law

$$Q_{rad} = \sigma_{stefan} A(T^4 - T_0^4) \tag{2}$$

In order to minimize the radiator area, it is desirable to locate big radiator next to the hottest area of the anode, but it is not good in the viewpoint of thermal stress since the large temperature difference along the radial direction causes terific hoop stress. The large temperature difference is allowed only along the axial direction. Applied heat to the anode should convect almost parallel to the thruster axis as possible in order to minimize the hoop stress. Resultantly, it is natural that the radiation area is along the lateral face of the tapered anode cylinder. Historically practical 30 kWe arcjet design have followed this rule.[3,6,7]

In the case of magnetoplasmadynamic thruster which enhances Lorentz force acceleration rather than the thermal acceleration, the use of circumferentially divided anode is possible (Tikhonov et al.[8]) This new type of design frees up the hoop stress problem. Thermal arcjet must confine the high pressure ionized gas inside the anode nozzle.

Material

As a material of radiation-cooled anode, only tungsten will be the possible choice because the arc attachment area becomes very high temperature (often higher than the melting point of molybdenum)

Generally the manufacturing process of bulk tungsten is divided to 2 types. One is a "pressed and sintered" tungsten at atmospheric pressure, and the other is "polycrystal" tungsten which is sintered in hydrogen atmosphere at about 2000 K and plastically deformed. The net density of the latter one is almost 100 percent whereas the former one is generally 98-99 percent. Maximum size of rod polycrystal tungsten authors have heard is $d = 250$ mm.[9]

It is quite difficult to have a single crystal of tungsten by usual way. Zone melting with high energy electron beam is the only possible way to have a single crystal of tungsten. The possible maximum size is limited less than $d = 50$ mm at this time. ISAS group had tested small piece of single crystal tungsten for a throat part of an arcjet,[10] but severe crack was recognized after 90 hours operation. In this case, the single-crystal throat was blazed to the surrounding polycrystal tungsten. It is conceivable that the Mo-Ru blaze might cause big temperature gradient in the radial direction or it causes non-uniformity of the heat conduction.

The physical property of the bulk tungsten strongly depends on its manufacturing process below $T =$ 1500 K, especially in terms of fracture strength. It is well known that the bulk tungsten is very brittle material at room temperature except for single crystal tungsten. Single crystal tungsten shows very plastic characteristics even in $T = 100$ K. Beyond $T = 2000$ K, any kind of bulk tungsten shows plastic characteristics regardless of the manufacturing process. However, the fracture strength is drastically decreasing at higher temperature. According to the literature,[11] the fracture strength of "pressed and sintered" tungsten is about 287 MPa at $T = 1650$ K, but it becomes only 65 MPa at $T = 2200$ K. It should be noted that there is a large deviation of the fracture strength. At $T = 2700$ K, it varies from 24.5 to 78.5 MPa among literatures.[11] The order of several tens of MPa is considered to be a threshold of the cracking.

C. Cathode

Configuration

The heat load to the cathode can be defined by neither the total input power P nor the discharge current J. Even in case the P and J are sufficiently small, the cathode surface has to be very high temperature to emit sufficient electron. When the bulk body of the cathode is cold, arc discharge itself makes high density hot spot on the cathode surface, resulting severe erosion of the cathode body. Therefore, it is desirable to keep the bulk body temperature of the cathode high enough to emit sufficient electron required from the source circuit. The relationship between the discharge current and the cathode surface temperature is simply described by Richardson-Dashman equation

$$J = \lambda_R A_0 T_c^2 \exp(\frac{\phi}{kT_c}) \tag{3}$$

where $A_0 = 1.20 \times 10^6$ A/m^{2}K^2 and $\lambda_R = 0.5$. For sustainable operation, the arc attachment must be diffusive (not spotty). Under the diffusive condition, experimentally observed current density is a few kA/cm^2 for ThO_2-W cathode.[5] In kA class operation, the required area from eq.3 is very small, but actually thick cathode (large cross section) is necessary in order to avoid the excessive joule heating in the cathode body.

The cathode length L_c is determined so that the temperature becomes low enough at the connection point to the cathode holder. At the root of the cathode, one has to pay careful attention because this part experiences the most critical thermal stress.

Although the cathode heat load is much smaller than the anode heat load, it is very difficult problem to discharge the heat applied to the cathode.[5] The reason is that the cathode is located in the center axis of the thruster, and it can not have sufficient radiation area. An old NASA report[6] says it is very challenging to realize A.C. arcjet just because of the heat load problem.

USSR group often operated 500 kWe class arcjet successfully.[12] Their thermal design owes alkali-metal propellant used as liquid-cooling fluid in the cathode. Especially lithium is the most promising one. Unfortunately, we can not find any information on the total weight of the liquid-cooling arcjet system as flight model.

The authors think it is also possible to discharge the cathode heat load only by radiation cooling, but it might be difficult to verify this in the limited size of vacuum chamber. Of course some technique of regenerative cooling by propellant (even if it is not alkali metal) is preferable way.

Material

Thoriated tungsten (ThO_2-W) is widely used material because of its low work function and high melting point. La_2O_3-W is alternative non-radio active candidate[13,14,15] , but the long-term durability in steady-state operation is not well verified.

Due to its high melting point, ThO_2-W cathodes tend to have a very concentrated hot point on the tip of the cathode. On the other hand, La_2O_3-W cathodes have its hottest region in wide area.[14] Therefore, the temperature gradient along axial direction of the cathode tends to be smaller with La_2O_3-W cathodes.

The hidden advantageous point of ThO_2-W cathodes is their high fracture strength. It is known that the fracture strength of tungsten is doubled by the addition of thoria.[11] For this reason, ThO_2-W anode in place of pure tungsten is also conceivable choice.

D. Insulator

Boron nitride (BN) is absolutely superior to any other ceramic because of its very low themal expansion coefficient, high thermal conductivity and high melting temperature. Cubical form BN has 3 times larger conductivity than copper.[16] The conductivity of hexagonal form BN, which is normally available, is only about 20 W/m-K. Note that it reveals anisotropic nature (parallel/perpendicular to the hot press direction). The acceptable compression stress depends on the manufacturing process. We used BN 5000 from KENNAMETAL/sintec[17] for JAXA prototype arcjet. The strength of that is shown in Table 1.

Table 1. The strength of BN5000

Maximum withstand temperature in vacuum	2073 K
Compressive strength (para)	30 MPa
Compressive strength (perp)	48 MPa
Flucture strength (para)	12MPa
Flucture strength (perp)	17MPa

BN loses its low thermal expansion coeff. in higher temperature condition. U.S. database[18] shows the thermal expansion coeff. drastically increases in the temperature higher than 1500 K. Since the drastic increase of thermal expansion coeff. causes unexpected cracking, this temperature will be the practical limit of the use of BN insulator although it is much smaller than its melting point.

E. Material Properties

In this study, temperature dependent thermal properties are referred from the famous masterpiece of United States.[18] Figures 2, 3 and 4 show the thermal conductivity, specific heat and linear thermal expansion coefficient of tungsten, molybdenum, copper and BN.

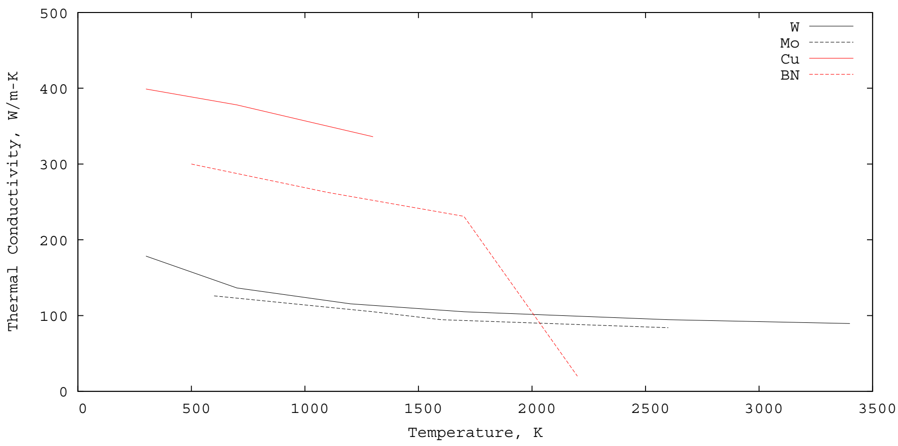

Figure 2. Thermal conductivity of the representative materials[18]

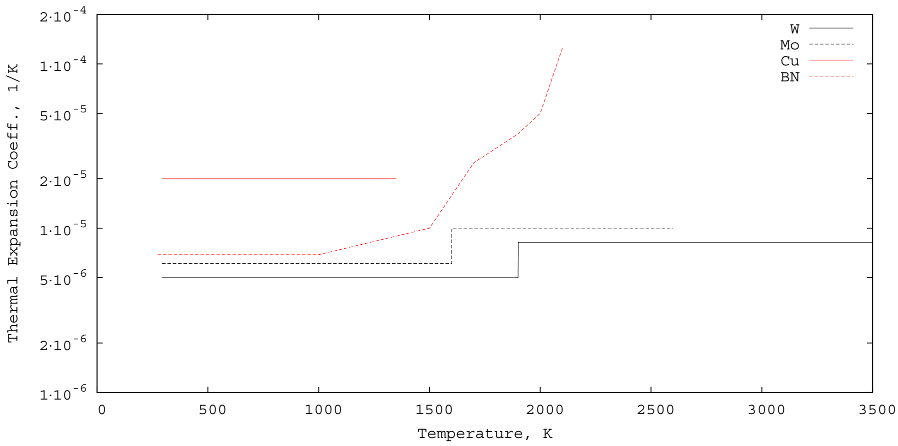

Figure 3. Thermal linear expansion coefficient of the representative materials[18]

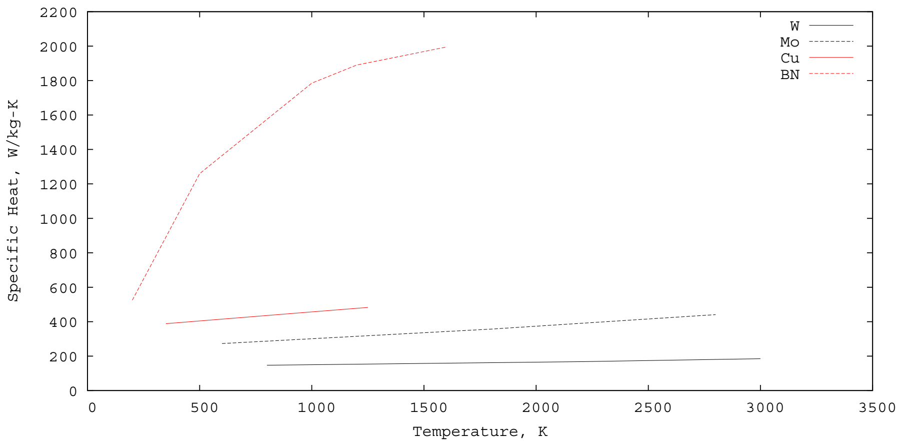

Figure 4. Specific heat of the representative materials[18]

Structural properties (Young's modulus and Poisson's ratio) at high temperature are referred similarly from U.S.S.R. literature.[11]

III. Analysis

A. Basement Model

There are many types of arcjets in the world, and there is too much flexibility when designing arcjet. At the beginning, we use JAXA water cooled 15kWe arcjet as a reference model (Fig.5). This model is developed by the authors' group based on past SAGAMI series[10][19] studied in ISAS. Stable operation was recognized with $J = 170$ A, $V = 61$ V and $\dot{m} = 0.2$ g/s of nitrogen propellant. The heat load to the anode was about 3000 W (estimated by the temperature increment of coolant water), which is corresponding to 30 percent of input power. FEM model shown in the latter section is based on this arcjet in terms of the anode fitting, insulator alignment and the gas-tight sealing.

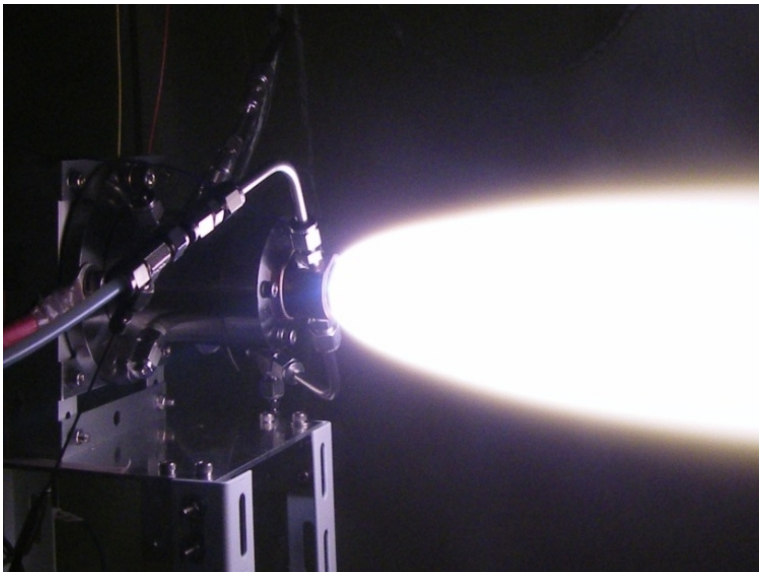

Figure 5. JAXA 15kWe water-cooled arcjet

B. Preliminary Estimation of the Thruster Size

operational characteristics

Although the configuration of the components is based on JAXA 15kWe arcjet, the size of the thruster should be given based on some premises. First of all, the amount of heat load should be defined. As described in eq.1, the heat load does not depend on the total input power. It depends on the discharge current. Whereas Fig.1 shows just a general tendency of *J*-*V* curve, we referred here the data of DT6 thruster studied in University of Stuttgart.[5] Table 2 shows picked-up operational condition of DT6. Arc attachment area is on the exit of the inner surface (exit diam. seems about 14 cm). Anode heat load calculated from eq.1 becomes $Q_{anode} = 45$ kW, 75 kW and 105 kW for $J = 3$ kA, 5 kA and 7 kA respectively. Referring this value, $J =$ 3, 5, 7 kA and $Q_{anode} = 45$ kW, 75 kW, 105 kW is assumed against the input power of $P = 100$, 250, 400 kWe [a].

Table 2. Operational characteristics of kW class arcjet[5]

P [kWe]	J [A]	V [V]	$\dot{m}$ [g/s]
114	3000	38	2.0
250	5000	50	2.0
432	7000	62	2.0

[a] The title of this paper includes the word of "several hundred kW" but the thermal load is rather related to the discharge current. Now we just would like to relate the input power level to the discharge current.

Anode Size

As described in the former section, it is the robust way to discharge the anode heat load from the lateral face of the anode. Table 3 shows rough estimation about the needed radiation area in order to discharge the applied heat load from hot surface. Background temperature is assumed to be 3 K (cosmic microwave background). Of course, this assumption is too simple. Since the radiator temperature decreases along the direction of heat flux, much larger area is needed.

Table 3. Minimum radiation area to discharge the anode heat load

Q_{anode} [W]	Emissivity	Surface temp. [K]	Radiator area [cm^2]
45000	0.6	2000	828
75000	0.6	2000	1380
105000	0.6	2000	1932

There is upper limit of the heat flux which is able to be removed from the hottest area (arc attachment area) to the surrounding area with tolerable temperature gradient. Especially the thermal conductivity of tungsten is not so high (80-90 W/m-K at 3000 K), so the temperature gradient drastically increases with the total heat load around the arc attachment area. Figure 6 is an simple cylinder model 5-cm in diam. Terrific temperature gradient is recognized around the arc attachment area. The only way to solve this is to enlarge the inner diam. of the cylinder and reduce the average heat flux. It is not effective to enlarge the arc attachment area into the axial direction.

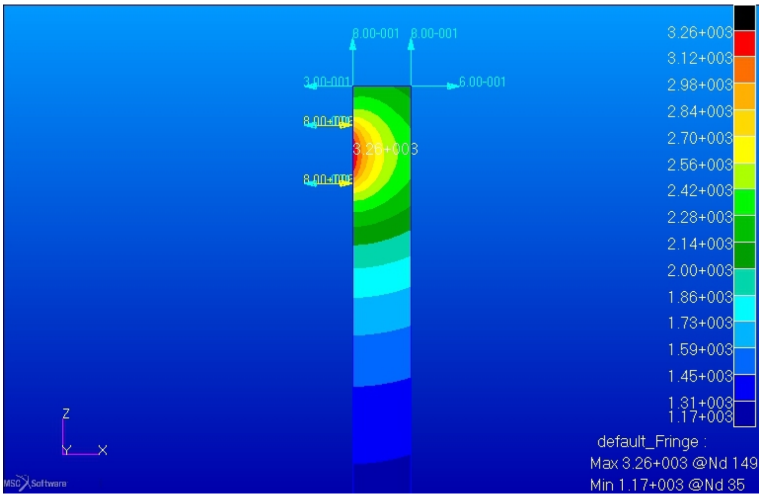

Figure 6. Temperature distribution around the arc attachment area. (simple cylinder model)

Regardless of the thickness of the anode or the axial length of the arc attachment area, minimum inner diam. of the anode is determined not to make the temperature gradient around the heat input area excessively high. As for the 100kWe of heat load to the anode, the inner diam. of the anode should be larger than 10 cm as a result of repeated FEM analysis.

If we use copper instead of tungsten, temperature gradient becomes much smaller because of its high thermal conductivity. However, it is not realistic due to the melting point of copper. The anode block should be made of tungsten, but the upper limit of the anode diam. is d=250 mm as described in the previous section. The anode block should be connected to molybdenum housing where the temperature becomes below 2500 K. (It will be difficult to make housing body with tungsten.) The housing discharges the remaining heat load from its high temperature surface. As for the length of housing, 20-30 cm might be the appropriate value to fulfill the minimum requirement area shown in Table 3 The housing is connected to the base plate made of copper or aluminum, where the temperature becomes the order of several hundred K, *Cathode Size*

Required area of the cathode tip is estimated as shown in Table 4. The work function is assumed to be 2.7 eV, which is widely accepted value for ThO_2. According to the literature,[5] the allowable cathode surface temperature for long time operation is supposed to be 2800 K.

Table 4. Required area of the cathode tip for sufficient electron emission

J [A]	Work function [eV]	Tip temp. [K]	emission area [cm^2]	corresponding r_c [mm]
3000	2.7	2800	0.48	4
5000	2.7	2800	0.80	5
7000	2.7	2800	1.1	6

Although electrons are also emitted from lateral side of the cathode, we only assume the contribution from the tip surface in this study [b]. r_c shown in Table 4 is calculated as ($r_c = \sqrt{(A_c/\pi)}$) assuming the flat tip. Of course the actual cathode tip has conical or hemispherical shape.

The use of the refractory metal for the cathode base would be very difficult (in terms of fitting or blazing) Copper is selected as the cathode base material in this study. Cathode should be connected to the cathode base at the point where the temperature becomes low enough. Specifically, 1000 K would be the safety level as cathode base temperature. Therefore, the temperature drop of 2000 K is assumed from the tip to the root of the cathode. Since the cathode will be extended according to eq.4, too long L_c is not good for the accurate thruster operation design. As is known, the gap between the cathode tip and the throat part is very important factor to define the operational characteristics.

$$\Delta L_c = L_c \alpha dT \tag{4}$$

Substituting L_c = 7 cm, α = 8.0 10^{-6} 1/K ($T > 2000$ K) and dT = 1800 K gives ΔL_c = 1 mm. It depends on the throat size whether this is acceptable level or not. The total heat load which should be discharged from cathode radiator is calcurated by the following equation.

$$Q_c = A_c \lambda \frac{dT}{dL} \tag{5}$$

With L_c = 10 cm, λ = 80 W/m-K and dT = 1800 K, Q_c/A_c becomes 14.4 kW/cm^2. Practically 1cm-diam. cathode is too thin at J = 7000 kA. The voltage drop and joule heating inside the cathode rod are quite large (Table 5). The electrical resistivity of tungsten drastically increases with its body temperature. Here we can refer 8.0 10^{-7} [Ω m] at T = 2700 K.[18]

Table 5. Voltage drop and joule heating of the cathode rod

J [A]	L_c [cm]	A_c [cm^2]	Vdrop [V]	joule heat [kW]
3000	7	3	0.56V	1.7
5000	7	3	0.93V	4.7
7000	7	3	1.3V	9.1

In this study, we defined the tip temperature (= 3000 K) as boundary condition, but it is uncertain whether this assumption is fair or not. Detail discussion and verification based on the real thruster operation are necessary. At least, authors think it is not appropriate to define the cathode heat load as "xx percent of the total input power" because the cathode tip temperature becomes higher than 2500-3000 K in order to emit sufficient electron even if the input power level is small. If the cathode body is too large compared

[b] this assumption is not so wrong because the lateral side of the cathode has lower temperature

to the input power level, the cathode tip temperature becomes very low. In this case, spot arc attachment occur to rise local temperature of the cathode.

The cathode body might receive radiation heat from anode (or vise varsa), but relative temperature difference between the cathode body and the anode is not so large, compared to the assuming level of heat load to the anode/cathode (several tens of kW).

C. FEM model

The FEM analysis to know the thermal stress distribution was performed on Patran 2010 / MD Nastran 2011. Basically this software calculates sparse finite element matrix, but it has been improved with some techniques. SOL 153 was used to calculate temperature distribution and SOL101 was used to calcurate the thermal stress. Authors did some preliminary verification with simple cylinder heat problem comparing to the analytical solution (temperature distribution and thermal stress).

The model was created by CATIA V5 and imported to the Patran 2010. Axisymmetric 2D framework was assumed. The design of the radiator is another problem. Here we attached simple disk shape radiator to the housing and conical shape radiator behind the cathode so that the temperature at the end of the radiators reduces less than 500 K. The model dimension of the thruster is defined summarizing the previous discussion.

Table 6. The model dimension of the thruster

Throat diam.	40 mm
Throat length	20 mm
Anode Exit diam.	140 mm
Cathode diam.	20 mm
Cathode length	100 mm
Housing outer diam.	240 mm
Housing thickness	28 mm
Housing length	240 mm
Anode Radiator diam.	1240 mm
Anode Radiator thickness	20 mm
Cathode Radiator height	380 mm
Cathode Radiator radius	top:100 mm bottom 260 mm

The weight of each component is as follows. In this model, the radiator is not optimized at all (at least, the pudding shape cathode radiator should be improved)

Table 7. The weigth of the components

Components	Material	Weight [kg]
Anode	W	29
Anode Cap	Mo	3.4
Housing	Mo	52
Front Insulator	BN	5.2
Back Insulator	BN	2.1
Cathode Base	Cu	34
Arcjet Total	-	126
Anode Radiator	Cu	213
Cathode Radiator	Cu	518

FEM model is shown in Fig.7. 12000 triangle meshes were pavered on the surface with 2-mm interval. The boudary surfaces between 2 objects is completely contacted to the others. For example, the anode and the anode cap is completely connected. It means infinite thermal conductivity and no allowable displacement between them. We put on gaps between insulators and housing on purpose because they are not tightly pressed to the radial direction. In this case, no thermal conduction and no phisical restraints are assumed between them.

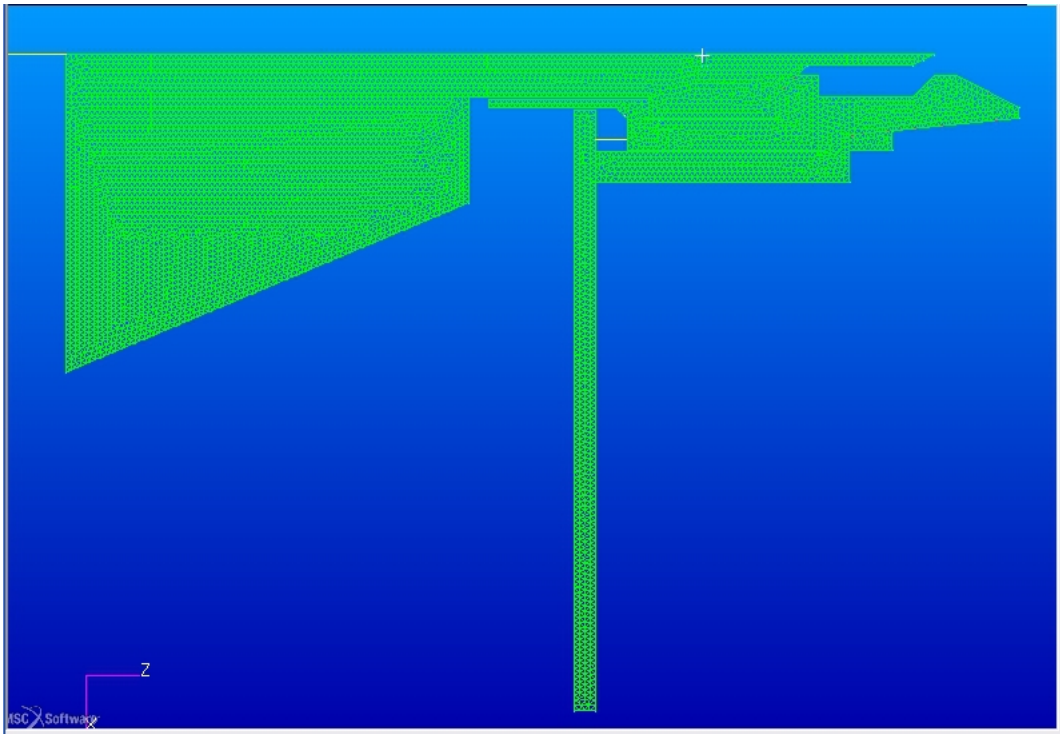

Figure 7. FEM model for thermal stress analysis

The boundary condition is shown in Table 8. Figures 8 and 9 show the application area of heat load B.C.s and radiation B.C.s. Except for the inner anode surface, $\varepsilon = 0.6$ was assumed with the prospect that the surface is covered by high emission material (e.g. TaC).

We put on the heat load of 105 kW at first, but reduced to 35 kWe because it seems that the heat load of 105 kWe was too high. [c]

Table 8. Boundary condition of the FEM model

BCs	J [A]
Heat load to the anode	105 kW/ 35 kW
Temperature of the cathode tip	3000 K
Radiation from inner anode	$\varepsilon = 0.3$
Radiation from outer anode	$\varepsilon = 0.6$
Radiation from housing	$\varepsilon = 0.6$
DOF at the root of the thruster	[0 0 0 0 0 0]

[c]To be honest to the readers, the thermal analysis calculation in case of 105 kWe heat input was not successfully converged at this time. In higher input power condition, we have to modify iteration parameters and matrix update method appropriately.

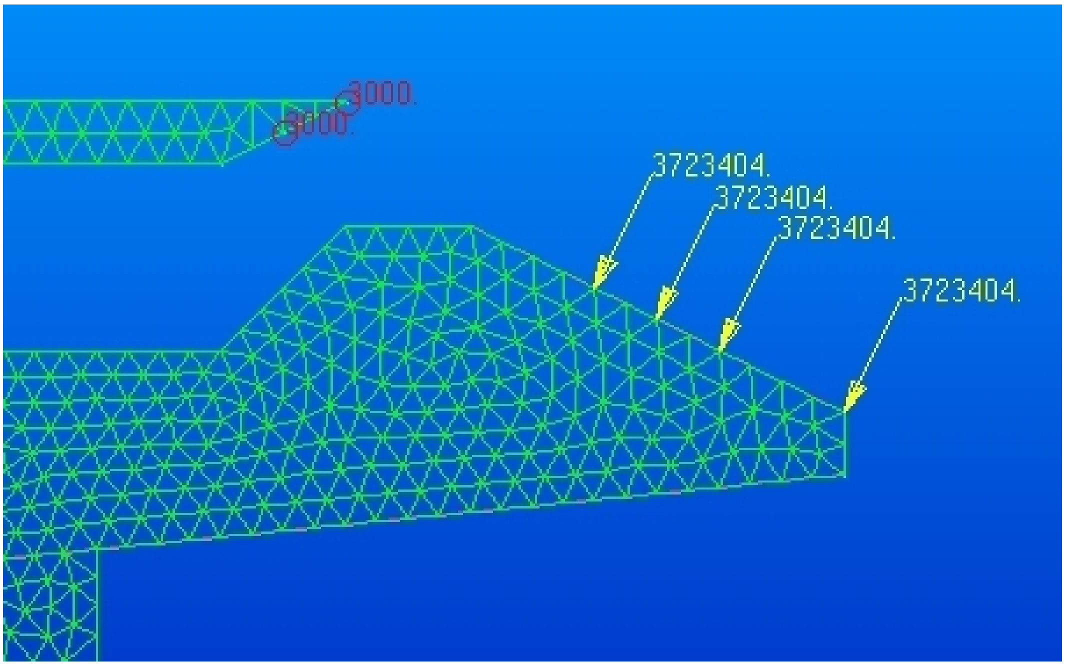

Figure 8. The application area of heat load B.C.s

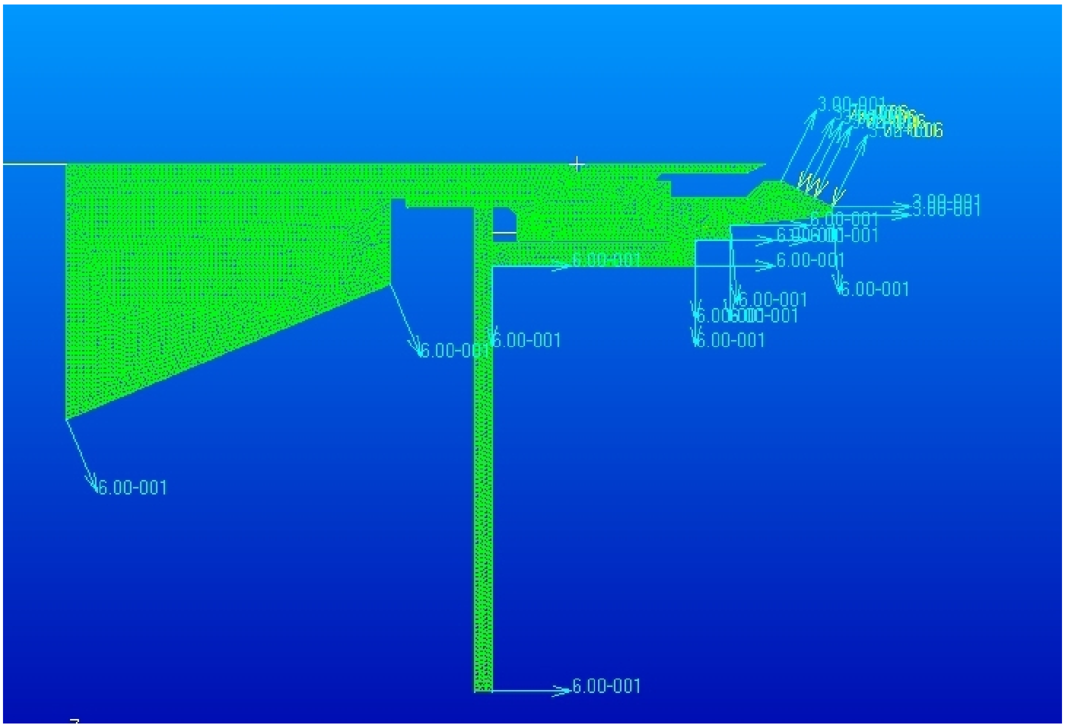

Figure 9. The application area of radiation B.C.s

IV. Results and Discussion

Figure 10 shows the temperature distribution of the arcjet with 105 kWe of the heat load to the anode (J =7.0 kA) . The temperature is 3000 K on the tip of the cathode(this is boundary condition), 2640 K at the arc attachment area on the anode, 1250 K on the anode cap, 1080 K on the top surface of the insulator and 650 K at the root of the cathode (connection point of the cathode and the cathode base). This is acceptable level judging from the melting point of each material. With reduced input heat load (J = 2.3kA, 35 kWe to the anode), the temperature distribution is as shown in Fig. 11. The temperature is 1800 K at the arc attachment area on the anode, 930 K on the top surface of the insulator and 600 K at the root of the cathode. Figure 12 is the magnitude of the heat flux.

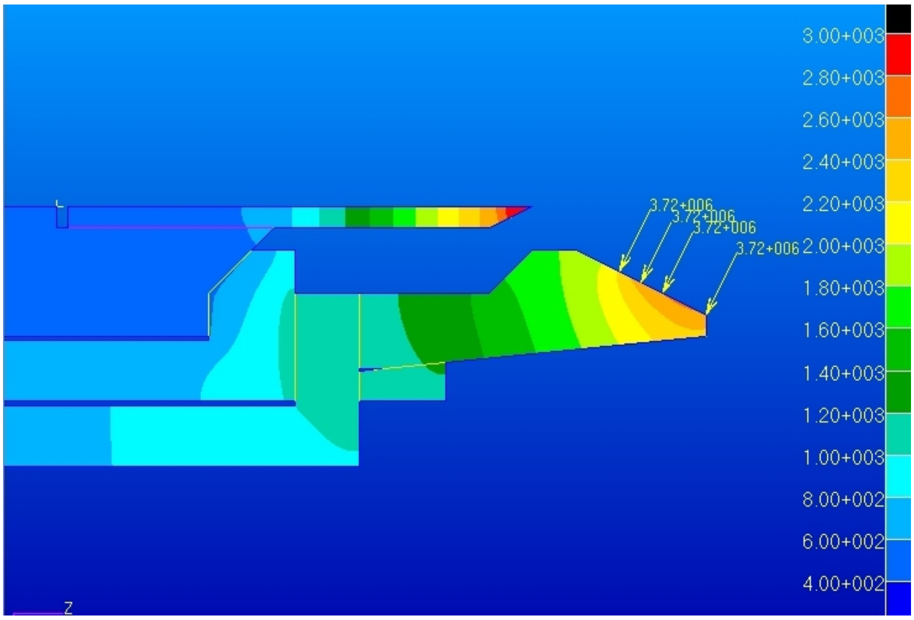

Figure 10. Temperature distribution at J=7.0 kA

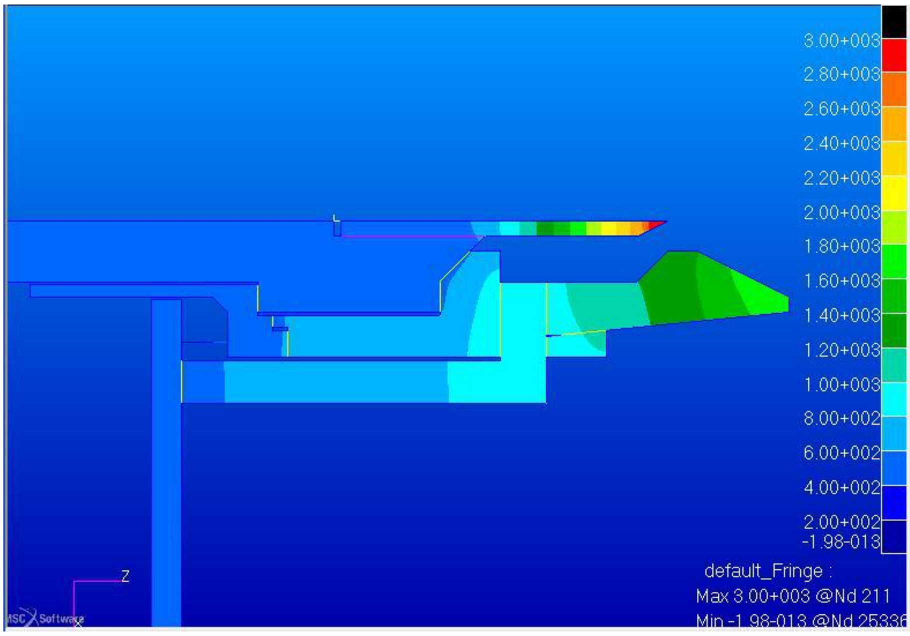

Figure 11. Temperature distribution at J=2.3 kA

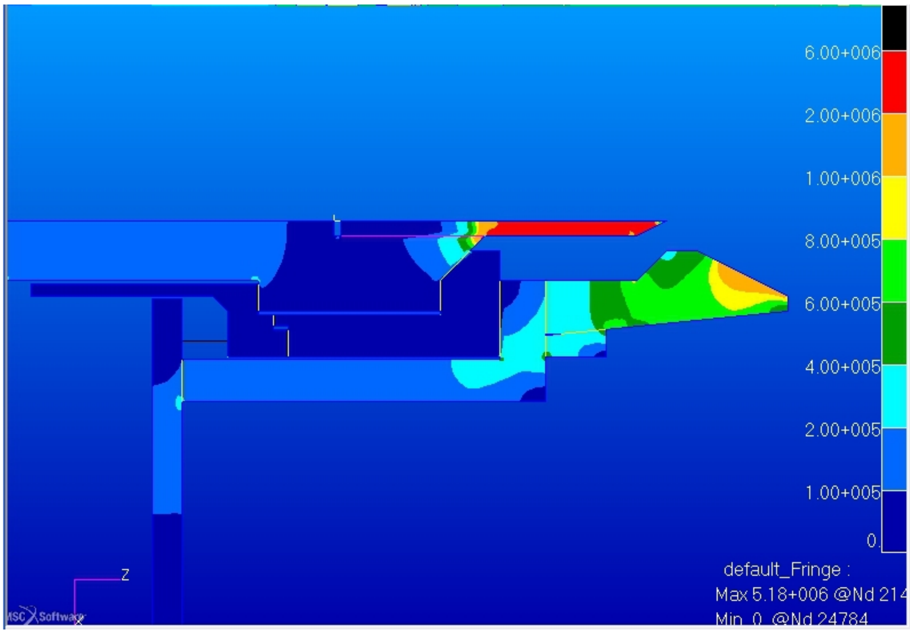

Figure 12. Heat flux distribution at J=2.3 kA

With the temperature distribution shown in Fig.11 as a thermal load, the thermal stress distribution was analyzed. Figure 13 shows the Mises stress distribution. The most remarkable stress is recognized in the root of the cathode. In this case, the cathode is tightly fixed by pressed fitting or blazing. The use of collet attachment might relax the stress to a certain extent. The Mises stress was 20 MPa, which is almost critical value for tungsten at high temperature[11] (T = 2000 K), but here the bulk temperature is sufficiently low, and the critical value is much higher (200-300 MPa).

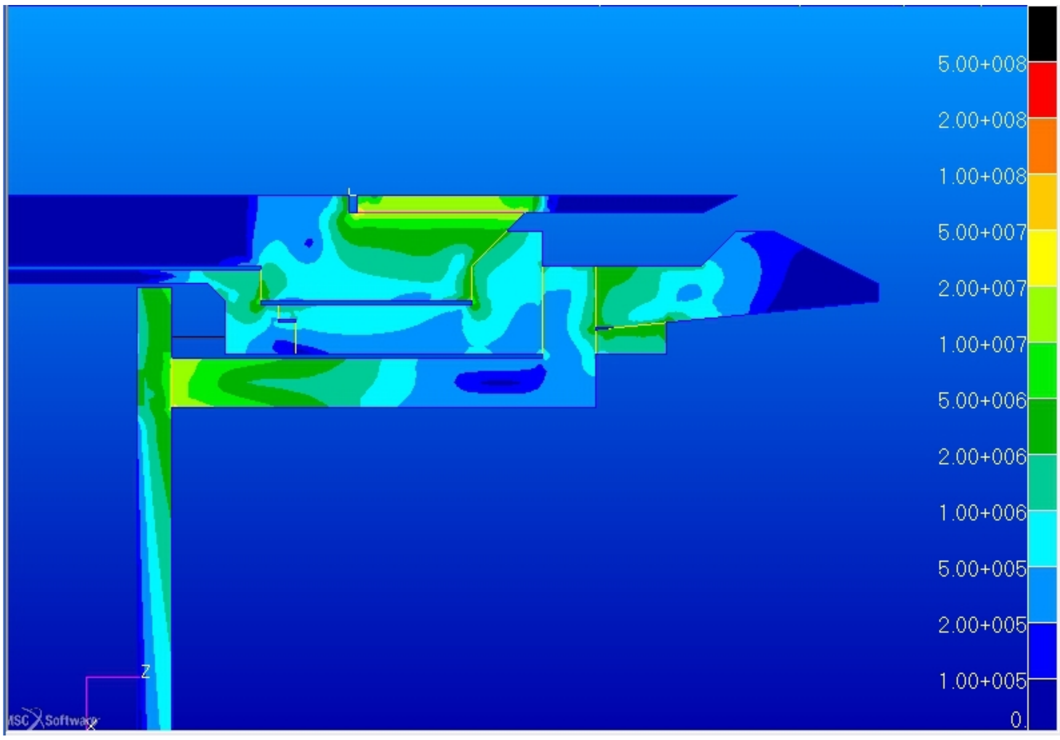

Figure 13. Mises stress distribution at J = 2.3 kA

In the anode block, no severe stress is not recognized because the heat flux is almost parallel to the axial direction and the anode block can expand toward the exit. Considerable stress is rather recognized at the contact area of the anode cap and the root of the housing. Disk shape radiator makes large temperature difference along the radial direction, causing considerable Mises stress. However, it is not a big problem here because the temperature is sufficiently low (the strength of the material is high enough).

Figures 14, 15 and 16 show 3-axis stress distribution. Considerable level of z-axis stress is observed at the root of the cathode. The cathode extention due to the large temperature difference is strongly restrained in the cathode base.

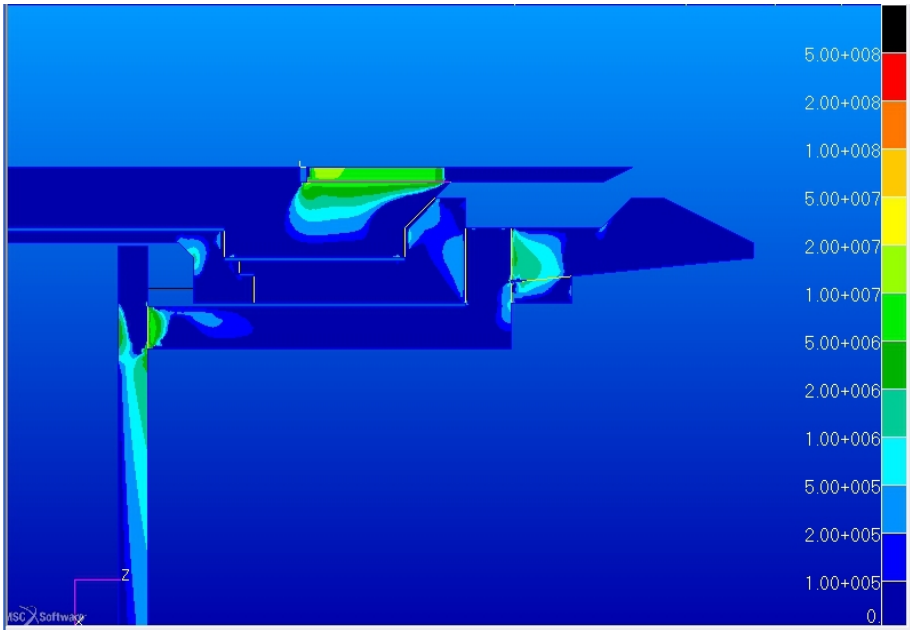

Figure 14. Thermal stress distribution along X-axis at J = 2.3kA

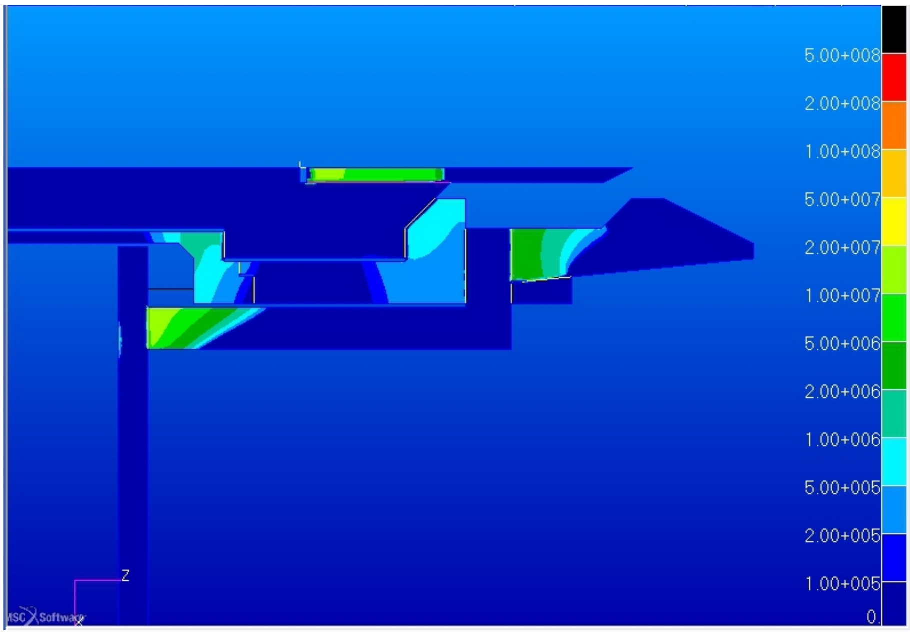

Figure 15. Thermal stress distribution along Y-axis at J = 2.3kA

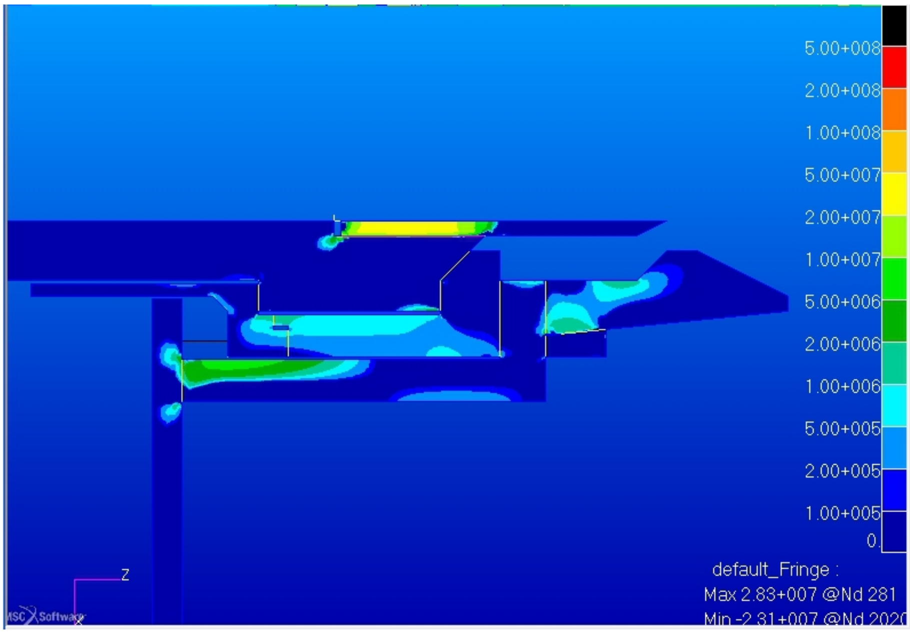

Figure 16. Thermal stress distribution alond Z-axis at J = 2.3kA

Here we conclude the model of which the weight is about 120 kg will stand for the heat load of 35kWe in terms of thermal stress. It seems that this model likely to stand for 50 kWe, although it is suspicious for 100 kW of anode heat load. Corresponding specific weight will be less than 1kg / kWe without radiators.

In this study, the volumetric heat generation and enclosure radiation is neglected. The authors think the latter one might be negligible, but the joule heating of the electrode has to be included hereafter.

V. Summary

Arcjets are promising candidate in terms of light-weight EP system design since it has very large thrust density and it can discharge the heat load from very high temperature surface.

In this study, several hundred kWe class arcjet was designed based on simple 1-D analysis and the thermal stress analysis was performed. Severe stress was recognized in the cathode root, anode cap and the bottom of the housing. All of them are located on the area where the large temperature difference along the radial direction exist. Although the model used in this study is not optimized, sophisticated design will reduce the thruster weight much more. Here we conclude 1kg/kWe (without the radiator) is possible as a specific weight of the arcjet for several hundreds of input power level.

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