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# DESIGN STUDIES ON ADVANCED SELF-COOLED LIQUID TEST BLANKET MODULES FOR JA DEMO

T. TANAKA
National Institute for Fusion Science
Oroshi/Toki, Japan
Email: tanaka.teruya@nifs.ac.jp

Y. SOMEYA
National Institutes for Quantum Science and Technology
Rokkasho/Aomori, Japan

M. KONDO
Institute of Science Tokyo
O-okayama/Meguro-ku, Japan

S. EBARA
Tohoku University
Aoba-ku/Sendai, Japan

S. ITO
Tohoku University
Aoba-ku/Sendai, Japan

K. KATAYAMA
Kyushu University
Kasuga-koen/Kasuga, Japan

R. KASADA
Tohoku University
Aoba-ku/Sendai, Japan

N. H. OONO
Tohoku University
Aoba-ku/Sendai, Japan

Y. SAKAMOTO
National Institutes for Quantum Science and Technology
Rokkasho/Aomori, Japan

**Abstract**

Comprehensive design studies on self-cooled liquid test blanket module (TBM) for a DEMO reactor of Japan (JA DEMO) are being conducted aiming for showing the prospects of high-efficiency power generation in future reactors. A LiPb self-cooled concept has been selected as the first candidate after investigating the neutronics performance, i.e. tritium breeding ratio >1, and the feasibility was studied mainly from the viewpoint of MHD effects on the LiPb coolant flows. Numerical calculations indicated that angular misalignment between the first wall cooling channel and magnetic field induces high velocity flow layers in the coolant flow, and this MHD effect is essential to enhance the heat removal performance and keep the first wall temperature acceptable. On the other hand, the magnitude of MHD pressure drop in the TBM system could be suppressed to an acceptable level with appropriate electrical insulation.

## 1. INTRODUCTION

In the strategy of Japan's fusion demonstration reactor (JA DEMO), electricity generation will be demonstrated with the water-cooled solid breeder blanket system [1, 2]. However, in the later period of the operation, advanced blanket concepts which could achieve higher efficiency power generation are planned to be tested by installing test blanket modules (DEMO-TBMs). Since long-term studies on materials, technologies and designs for self-cooled liquid metal and molten salt blanket concepts have conducted mainly by universities and National Institute for Fusion Science (NIFS) in Japan, selection of the first candidate of an advanced liquid blanket concept for DEMO-TBM and design studies have also been conducted under a research collaboration program for fusion DEMO led by National Institutes for Quantum Science and Technology (QST).

Although the number of test blanket modules installed in JA DEMO would be one or few, the selected blanket concept must have prospects to be operated with adequate performances in heat removal, tritium fuel breeding, coolant circulation control, etc. in future fusion reactors. At the beginning of the study, tritium breeding ratios (TBRs) of the candidate liquid blanket concepts were investigated assuming all the original water-cooled solid breeder blanket modules are replaced by the liquid metal or molten salt blanket modules. After confirming the concepts with TBRs > ~1.10, a self-cooled LiPb blanket concept has been selected as the first candidate concept for DEMO-TBM considering material properties, possibility for simple structure, and situation of the long-term research activities for liquid blanket technologies in Japan. In the present paper, the proposed structure of the self-cooled LiPb DEMO-TBM and the feasibility investigation mainly from the viewpoint of first wall cooling and MHD pressure drop are described.

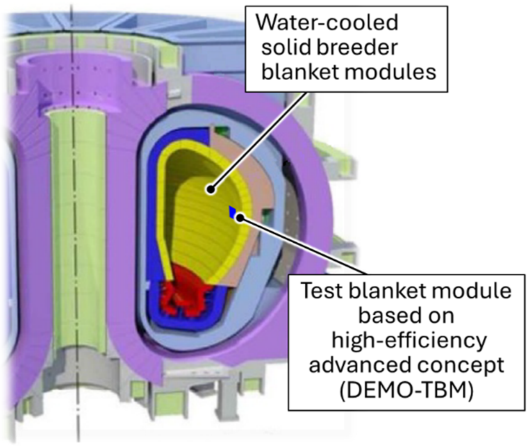


*FIG. 1. Test blanket module for JA DEMO (DEMO-TBM). (Position and dimensions have not been decided.)*

## 2. TRITIUM BREEDING PERFORMANCES OF SELF-COOLED LIQUD BLANKET CONCEPTS

Tritium breeding ratios (TBRs) of self-cooled liquid blanket concepts were evaluated by the MCNP-5 code [3] and JENDL-4.0 nuclear data library [4] for the 3-D calculation geometry of JA DEMO (Fig.2). Part of the original input data defining water-cooled solid breeder blanket modules were replaced by structure and material data for the self-cooled liquid blanket modules as shown in Figs. 2 (a) and (b). For the concepts without a solid neutron multiplier, the first wall and breeding zone (mixture of 80 vol.% liquid metal or molten salt breeder/coolant and 20 vol.% structural material) are simulated. For the concepts requiring solid Be multiplier, an additional layer with mixture of a breeder/coolant, structural material and Be neutron multiplier is placed at the rear side of the first wall cooling channel of 2 cm in width. Table 1 shows the evaluated TBRs. Since the blanket space is adequate both at the inboard and outboard regions, all the blanket concepts could achieve the TBRs>~1.10 in JA DEMO.

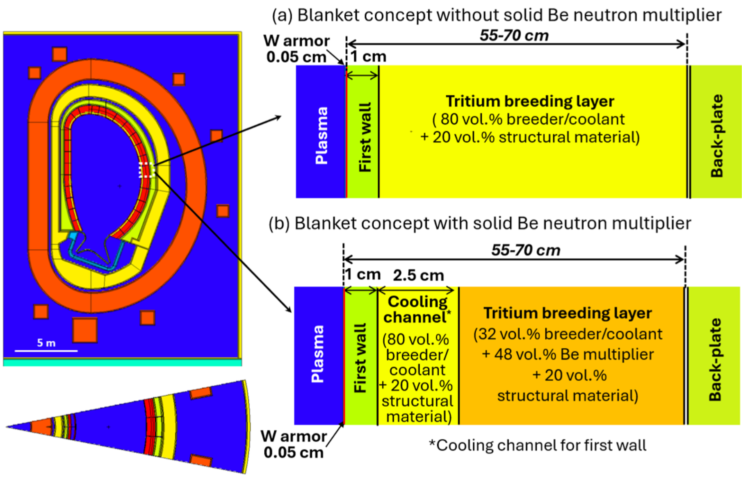


*FIG. 2. Evaluation of tritium breeding performances of liquid blanket concepts in JA DEMO geometry.*

TABLE 1. TRITIUM BREEDING PERFORMANCES OF LIQUID BLANKET CONCEPTS

| Blanket concept | Tritium breeding ratio |
|---|---|
| Li/V* (Enrichment of $^6$Li: 7.5%) | 1.08 |
| Li/V (35%) | 1.18 |
| Li+Be/V (7.5%) | 1.43 |
| Li+Be/V (90%) | 1.50 |
| LiPb/RAFMs** (90%) | 1.13 |
| FLiBe+Be/RAFMs (90%) | 1.31 |
| FLiNaBe+Be/RAFMs (90%) | 1.25 |

* Vanadium alloy, ** Reduced activation ferritic/martensitic steel

## 3. SELF-COOLED LIPB TEST BLANKET MODULE FOR JA DEMO

### 3.1. Selection of blanket concept

Development of the fusion blanket technologies for the DEMO reactor in Japan has steadily been conducted with the water-cooled solid breeder concept for many decades by QST (previously by Japan Atomic Energy Agency (JAEA) and Japan Atomic Energy Research Institute (JAERI)). In contrast, research groups in Japanese universities have been conducting academic studies on advanced liquid metal and molten salt blanket technologies, i.e., evaluation and suppression of MHD pressure drop [5, 6], tritium behaviours and recovery [7, 8], corrosion behaviours [9-11], material development [12], component designs [13, 14], etc. for more than 40 years. Those long-term activities have been focusing especially on self-cooled concepts rather than double cooled concepts with He or water coolants. The studies on the self-cooled concepts are aiming at a high efficiency and low-pressure blanket system with a simple structure for future commercial fusion reactors. Considering the history and present situation of the development of liquid blanket technologies, a self-cooled LiPb concept has been selected as the first candidate for DEMO-TBM. The chemical stability, low melting point (235°C) and high heat removal performance are the preferable properties of LiPb as blanket breeder/coolant among the candidates.

### 3.2. Module structure

Fig. 3 shows a proposed structure of the self-cooled LiPb DEMO-TBM. After preliminary investigation on the first wall cooling performances was performed by thermo-fluid calculations including MHD effects, the configuration has been proposed aiming for a simple structure as possible. Considering the licensing as a nuclear component, F82H (reduced activation ferritic/martensitic steel) is adopted as the structural material similar to the original water-cooled blanket modules of JA DEMO. The dimensions are approximately 1.4 x 0.9 x 0.7 $m^3$ and these are same as those of the outboard blanket module of JA DEMO. LiPb breeder/coolant enters the module at 300°C. The coolant reaches the first wall cooling channels at ~320°C and cools the first wall with the average velocity of 1.45 m/s. The first wall thickness is 6 mm, and the cross-sectional dimensions of the cooling channels are 7.5 x 25 mm$^2$. After the first wall cooling, LiPb flows slowly in the module and goes out at ~500°C. The module is heated up with surface heat load of 0.5 MW/m$^2$ and neutron wall loading of 1.5 MW/m$^2$. To obtain the temperature difference of ~200°C between the inlet and outlet, the flow rate of LiPb required for the TBM is ~0.008 m$^3$/s. Electrical insulation using a ceramic channel insert will be required at least for the side flow channel connecting the inlet and first wall channels, since an intense magnetic field penetrates perpendicularly. The first wall cooling channels are not insulated to make the design simple and robust as possible. By keeping the angular misalignment between the cooling channel and magnetic field small, the magnitude of the MHD pressure drop at the first wall channels would be suppressed to an acceptable level. W armor of 0.5 mm in thickness is attached to the surface of the F82H first wall similar to the original water-cooled blanket modules [2].

Since the magnetic field lines in the reactor are curved along the toroidal direction of the torus, the first wall cooling channels in the actual blanket modules will also be curved along the magnetic field lines for efficient cooling. However, straight magnetic field lines and cooling channels are assumed in the present investigation to obtain the perspectives on feasibility of the proposed TBM design. An example of additional analysis with curved first wall channels and a curved magnetic field appears in the next section to support the validity of the analysis.

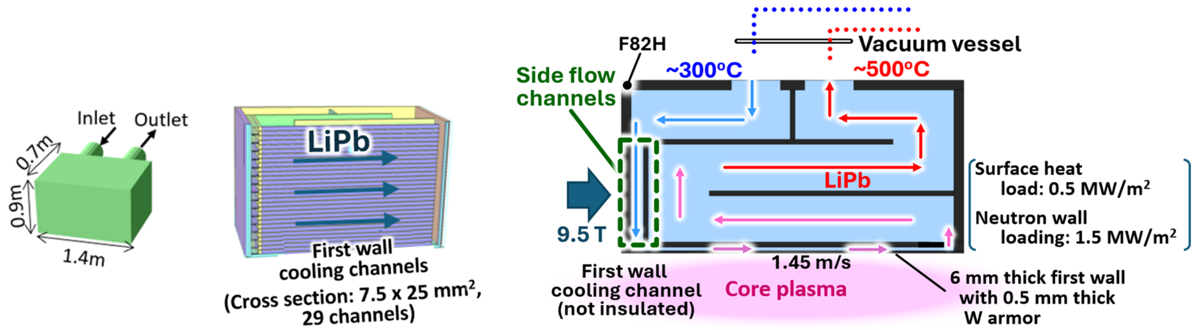


*FIG. 3. Self-cooled LiPb DEMO-TBM proposed for JA DEMO.*

## 4. THERMO-FLUID ANALYSIS

### 4.1. MHD pressure drop in TBM

The thermo-fluid analysis for the module was performed by the STREAM code [15] which can simulate MHD effects on a liquid metal flow, i.e., MHD pressure drop and velocity distribution. According to the 3-D magnetic field distribution analysed for the steady state operation of JA DEMO, the maximum magnetic field strength is ~9.5 T and the angle to the horizontal plane of the torus is ~6° at an inboard blanket module position as shown in Fig. 4 (a). Those are ~4.7 T and ~13° at an outboard blanket module. Although DEMO-TBM would be placed at the outboard side, the feasibility of the proposed design was investigated for the highest magnetic field condition in JA DEMO, i.e., ~9.5 T and ~6°.

If no ceramic electrical insulator is inserted or attached in the module, the total magnitude of the pressure drop exceeds 6 MPa almost due to MHD pressure drop. With the condition that the side flow channels are electrically insulated, the total magnitude is suppressed to 2.3 MPa. If the all the channels in TBM except for the first wall channels are insulated, the total magnitude of the pressure drop could be suppressed to ~1.0 MPa (Fig.4(b)).

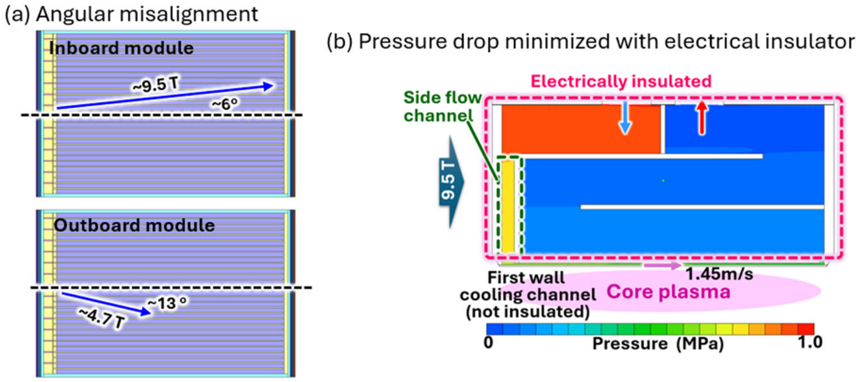


*FIG. 4. (a) Magnetic field strength and angular misalignment with cooling channels (front view of module), (b) Pressure drop inside module.*

### 4.2. First wall cooling of TBM

Calculated temperature distributions of the first wall surface are shown in Fig. 5. Since influence of the 0.5 mm thick W amor on temperature control in the first wall layer is considerably small as shown in the next section, only the 6 mm thick F82H first wall layer is simulated. The results indicate the importance of heat removal enhancement utilizing the characteristics of a liquid metal flow under an intense magnetic field. When the directions of the cooling channel and magnetic field are completely aligned, ~1/3 of the first wall exceeds 580℃ as shown in Fig. 5 (a). In the result shown in Fig. 5 (d), the simulated misalignment between the magnetic field and first wall channel is 5.5° in the vertical direction and 0.3° in the horizontal direction, which is derived from analysis of the 3-D magnetic field distribution in JA DEMO. In this condition, the maximum temperature of the surface is ~580°C at ends of the channels. The velocity distributions in the cooling channels are compared in Figs. 5 (b) and (e). When the magnetic field has a vector component penetrating a liquid metal flow in a metal channel perpendicularly, high velocity flow layers are induced near the walls parallel to the perpendicular component as shown in Fig. 5 (e). Since these layers enhances the heat removal performance, the maximum temperature of the first wall surface is suppressed as compared in Figs. 5 (c) and (f). On the other hand, the angular misalignment induces MHD pressure drop. For the magnetic field of 9.5 T with the misalignment of 5.5°, the vertical component of the magnetic field vector is 0.91 T. Although this vertical component induces the pressure drop of ~ 0.5 MPa at the first wall cooling channel, the magnitude would be acceptable. The heat removal enhancement by the angular misalignment has also been confirmed by calculations simulating the curved first wall channels and a curved magnetic field as shown in Fig. 5 (g).

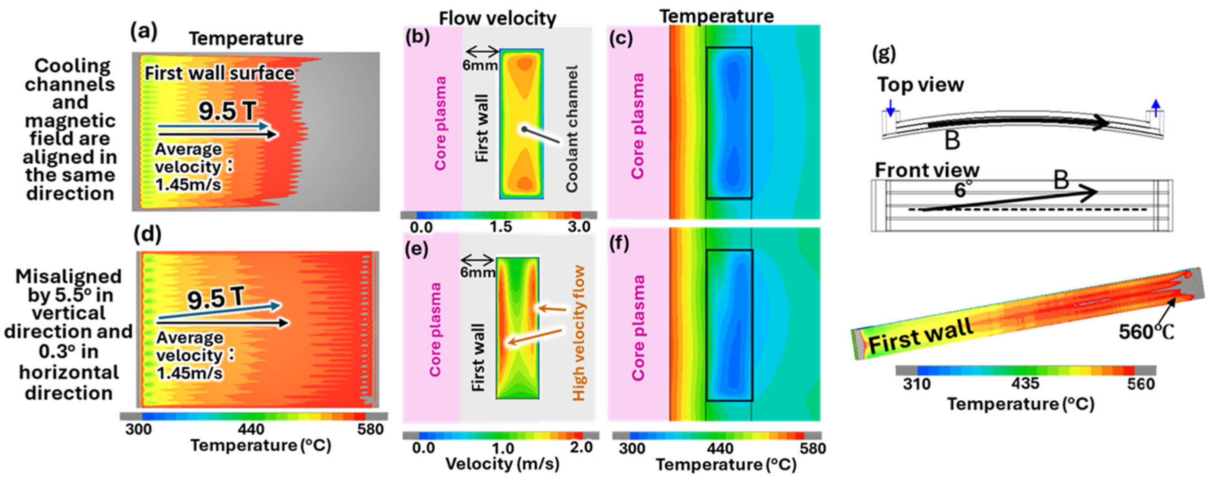


*FIG. 5. (a-c) Surface temperature distribution, flow velocity distribution and cross-sectional temperature distribution for channels and magnetic field with no angular misalignment, (d-f) those with angular misalignment. (d) Example of temperature distribution calculated with curved cooling channels and magnetic field.*

### 4.3. Material and corrosion issues

It is commonly recognized that the maximum acceptable temperature is 550℃ for F82H. The temperature distribution obtained by one-dimensional analytic calculation according to the Fourier's law (Fig. 6 (a)) shows that the temperature difference in the 6 mm thick F82H first wall layer is ~125℃. Therefore, assuming the surface temperature is 580℃, the front region within ~2 mm from the first wall surface exceeds 550℃ and the rear layer of ~4 mm in thickness could be kept below 550℃. Considering the thickness reduction due to corrosion and erosion by LiPb flows, thicker first wall would be preferable. Further discussions considering irradiation effects on F82H, mechanical stress analysis, etc. are needed for the final decision of the thickness.

Corrosion of the F82H first wall channels due to the high velocity LiPb flows [16] has been one of important concerns in the present design study. As the design effort to mitigate the issue, modification of the inner structure is considered as shown in Fig. 6 (b). Although the structure becomes complicated by making the two flow paths in the module, the average flow velocity could be suppressed to ~1/2, i.e., ~0.7 m/s. Another effort is experimental studies to develop an anti-corrosion material. Recently, an $Al_2O_3$ layer produced on an FeCrAl alloy substrate by a preoxidation process indicated the superior corrosion resistance in a stirred LiPb flow [17]. The thickness reduction of the first wall could be suppressed by attaching the peroxidized FeCrAl alloy liner inside the cooling channel. Although the two sides of the channel will be electrically insulated by the $Al_2O_3$ layer, it has been confirmed that high velocity flow layers will be induced similar to Fig. 5 (e).

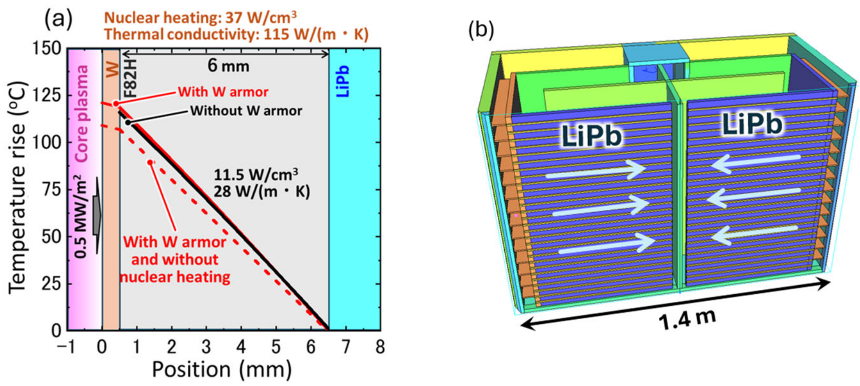


*FIG. 6. (a)Temperature distribution in first wall layer calculated according to the Fourier's law. (b) Design effort to suppress corrosion of first wall.*

### 4.4. MHD pressure drop at LiPb transport ducts

When the self-cooled LiPb blanket modules are installed in a tokamak fusion reactor, the maximum magnetic field of ~10 T will be applied to long LiPb transport ducts located at the back side of the inboard blanket modules. To ensure the feasibility of the present design proposal in future reactors, the magnitude of MHD pressure drop at the transport ducts were also evaluated. Assuming that the inner diameter of the duct is ~210 mm which is same as that in the water-cooled blanket
system of JA DEMO, the average velocity of a LiPb flow would be ~1.85 m/s to obtain the temperature difference of 200℃ in all the modules. An example of the magnetic field strength distribution along a transport duct are shown in Fig. 7. Since a magnetic field of 7.5 - 10.0 T is applied on the ~15 m long inboard LiPb transport duct, the magnitude of MHD pressure drop in a LiPb coolant is calculated to be 417 MPa. However, if the duct is electrically insulated by ceramic inserts, etc., the MHD pressure drop could be suppressed to ~1.5 MPa. The magnitudes of MHD pressure drop in other LiPb transport ducts would be more moderate because of the smaller magnetic field strength. Since further reduction of the pressure drop could be possible by increasing the number of transport ducts and decreasing the flow velocities, issues on the LiPb coolant circulation for the self-cooled concept could be mitigated by electrical insulation and duct configurations.

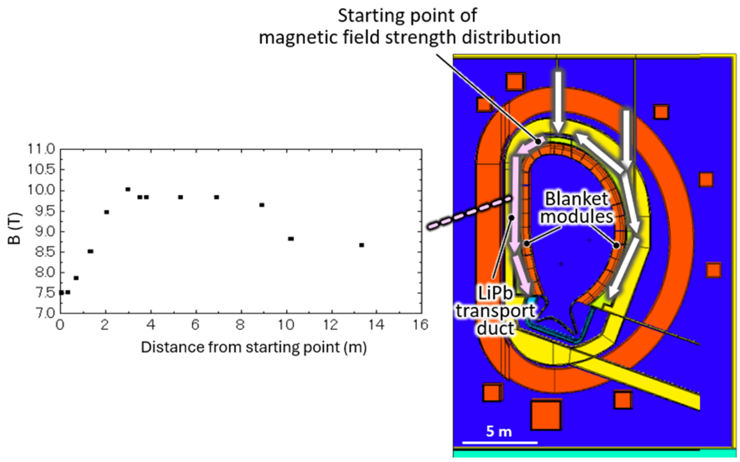


*FIG. 7. Distribution of magnetic field strength at the back side of inboard blanket modules.*

## 5. EXPERIMENTAL STUDIES ON LIPB TECHNOLOGIES

In Japanese universities, corrosion behaviours of materials [17], ceramic coating development [18, 19] tritium transport and recovery technique with the vacuum sieve tray (VST) method [20], etc. are actively conducted at present. The designs of DEMO-TBM can be updated by reflecting the latest experimental results.

## 6. CONCLUSION

Design studies on advanced self-cooled liquid test blanket modules for JA DEMO (DEMO-TBM) are being conducted aiming for performance tests in the later period of the DEMO program. After evaluation of tritium breeding performances of candidate liquid blanket concepts in a tokamak fusion reactor (JA DEMO geometry) and preliminary investigation of MHD pressure drop in a liquid metal coolant, a self-cooled LiPb concept was selected as the first candidate, and the TBM design with a simple structure has been proposed. Especially in the first wall cooling, high velocity flow layers induced by magnetic fields beside the cooling channel walls considerably enhance the heat removal performances. However, the average LiPb velocity required for keeping the maximum temperature of F82H first wall ~550°C is ~1.5 m/s in the present design and this value would be a concern from the viewpoint of material corrosion. Both the design and material development efforts are being continued for mitigation of the corrosion issue. Regarding the magnitudes of MHD pressure drop, those could be suppressed within an acceptable level with electrical insulation of coolant channels and ducts, and by modification of the duct configuration.

Detailed modification of the module design on wall thicknesses, edge shapes of the module and inside the coolant channels, etc. is planned to be performed based on temperature control and mechanical stress analysis. Recently, investigation of self-cooled molten salt TBM, i.e., FLiBe and FLiNaBe, has also been started for a similar TBM structure.

## ACKNOWLEDGEMENTS

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