*EM

The *EM keyword cards provide input for the electromagnetism module. This module is for solving 3D eddy-current, inductive heating or resistive heating problems. It can be coupled with the mechanical and thermal solvers. Typical applications include magnetic metal forming and welding. This module also includes coupling the boundary element method to the finite element method coupling. We intend this coupling for simulations involving a conductor interacting with air so that the air does not need to be meshed. The conductor is modeled with finite elements while the air is modeled with boundary elements.

    *EM_2DAXI

    *EM_BOUNDARY

    *EM_BOUNDARY_PRESCRIBED

    *EM_CIRCUIT

    *EM_CIRCUIT_CONNECT

    *EM_CIRCUIT_ROGO

    *EM_CIRCUIT_SOURCE

    *EM_CONTACT

    *EM_CONTACT_RESISTANCE

    *EM_CONTACT_SUBDOM

    *EM_CONTROL

    *EM_CONTROL_CONTACT

    *EM_CONTROL_COUPLING

    *EM_CONTROL_EROSION

    *EM_CONTROL_MAGNET

    *EM_CONTROL_SOLUTION

    *EM_CONTROL_SWITCH

    *EM_CONTROL_SWITCH_CONTACT

*EM_CONTROL_TIMESTEP

*EM_DATABASE_CIRCUIT

*EM_DATABASE_CIRCUIT0D

*EM_DATABASE_CIRCUITSOURCE

*EM_DATABASE_ELOUT

*EM_DATABASE_FIELDLINE

*EM_DATABASE_GLOBALENERGY

*EM_DATABASE_NODOUT

*EM_DATABASE_PARTDATA

*EM_DATABASE_POINTOUT

*EM_DATABASE_ROGO

*EM_DATABASE_TIMESTEP

*EM_EP_CELLMODEL_DEFINE_FUNCTION

*EM_EP_CELLMODEL_FENTONKARMA

*EM_EP_CELLMODEL_FIZHUGHNAGUMO

*EM_EP_CELLMODEL_TENTUSSCHER

*EM_EP_CELLMODEL_TOMEK

*EM_EP_CELLMODEL_TOR_ORD

*EM_EP_CELLMODEL_USERMAT

*EM_EP_CREATEFIBERORIENTATION

*EM_EP_ECG

*EM_EP_EIKONAL

*EM_EP_ISOCH

*EM_EP_LAPLACE_DIRICHLET

*EM_EP_PURKINJE_NETWORK

*EM_EP_TENTUSSCHER_STIMULUS

*EM_EOS_BURGESS

*EM_EOS_MEADON

*EM_EOS_PERMEABILITY

*EM_EOS_TABULATED1

*EM_EOS_TABULATED2

*EM_EXTERNAL_FIELD

*EM_ISOPOTENTIAL

*EM_ISOPOTENTIAL_CONNECT

*EM_ISOPOTENTIAL_ROGO

*EM_MAT_001

*EM_MAT_002

*EM_MAT_003

*EM_MAT_004

*EM_MAT_005

*EM_MAT_006

*EM_OUTPUT

*EM_OUTPUT_FORCES

*EM_OUTPUT_VTK

*EM_PERMANENT_MAGNET

*EM_POINT_SET

*EM_RANDLES_BATMAC

*EM_RANDLES_EXOTHERMIC_REACTION

*EM_RANDLES_MESHLESS

*EM_RANDLES_TSHELL

*EM_RANDLES_SHORT

*EM_RANDLES_SOLID

*EM_ROTATION_AXIS

*EM_SOLVER_BEM

*EM_SOLVER_BEMMAT

*EM_SOLVER_FEM

*EM_SOLVER_FEMBEM

*EM_SOLVER_FEMBEM_MONOLITHIC

*EM_2DAXI

Purpose: Sets up the electromagnetism solver as 2D axisymmetric instead of 3D, on a given part, in order to save computational time as well as memory.

The electromagnetism is solved in 2D on a given cross section of the part (defined by a segment set), with a symmetry axis defined by its direction (at this time, it can be the x, y, or z axis). The EM forces and Joule heating are then computed over the full 3D part by rotations. The part needs to be compatible with the symmetry, i.e. each node in the part needs to be the child of a parent node on the segment set, by a rotation around the axis. Only the conductor parts (with a *EM_MAT_… of type 2 or 4) should be defined as 2D axisymmetric.

Card 1	1	2	3	4	5	6	7	8
Variable	PID	SSID			STARSSID	ENDSSID	NUMSEC	
Type	I	I			I	I	I	
Default	none	none			none	none	none	

VARIABLE	DESCRIPTION
PID	Part ID of the part to be solved using 2D axisymmetry
SSID	Segment Set ID : Segment that will define the 2D cross section of the part where the EM field is solved
STARSSID, ENDSSID	Used by the 2D axisymmetric solver to make the connection between two corresponding boundaries on each side of a slice when the model is a slice of the full 360 circle.
NUMSEC	Number of Sectors. This field gives the ratio of the full circle to the angular extension of the mesh. This has to be a power of two. For example, NUMSEC = 4 means that the mesh of the part represents one fourth of the total circle. If this value is set to 0, then the value from *EM_ROTATION_AXIS is used instead.

Remarks:

1. At this time, *either* all or none of the conductor parts should be 2D axisymmetric. In the future, a mix between 2D axisymmetric and 3D parts will be allowed.

*EM_BOUNDARY

Purpose: Define some boundary conditions for the electromagnetism problems.

Include as many cards as needed. This input ends at the next keyword ("*") card.

Card 1	1	2	3	4	5	6	7	8
Variable	SSID	BTYPE						
Type	I	I						
Default	none	none						

VARIABLE	DESCRIPTION
SSID	Segment Set Id
BTYPE	EQ.9: The faces of this segment set are eliminated from the BEM calculations (used for example for the rear or side faces of a workpiece).

*EM_BOUNDARY_PRESCRIBED

Purpose: Prescribe a local boundary condition applied on nodes.

Card 1	1	2	3	4	5	6	7	8
Variable	BPID	BPTYPE	SETTYPE	SETID	VAL	LCID		SYSTYPE
Type	I	I	I	I	F	I		I
Default	none	none	none	none	0.	0		0

Optional Card.

Card 2	1	2	3	4	5	6	7	8
Variable	BIRTHT	DEATHT			VAL2	LCID2		
Type	F	F			F	I		
Default	0.	1.e28			0.	0		

VARIABLE	DESCRIPTION
ISOID	ID of the prescribed boundary
BPTYPE	Prescribed boundary type:
	EQ.1: Short (scalar potential set to 0.)
	EQ.2: Prescribed resistance (Robin B.C.)
	EQ.3: Prescribed scalar potential (Dirichlet B.C.)
	EQ.4: Prescribed current density (Neumann B.C.)
SETTYPE	Set type:
	EQ.1: Segment set
	EQ.2: Node set
	EQ.3: Fluid part (see *ICFD_PART)
SETID	Set ID

VARIABLE	DESCRIPTION
VAL	Value of the resistance, current density or potential depending on BPTYPE. Ignored if LCID is defined.
LCID	Load curve ID defining the value of the resistance, voltage, or current as a function of time. If a negative value is entered, a *DEFINE_FUNCTION will be expected. The following parameters are allowed: f(time, emdt, curr, pot, cond, temp, potglob, currglob, areaglob, area, x, y, z). Pot/curr/area and potglob/currglob/areaglob are the local value of the scalar potential/current/area and the global averaged value on the prescribed boundary, respectfully. Cond is the local electrical conductivity, and x, y, and z are the local coordinates.
SYSTYPE	Flag for the type of system on which the boundary condition is applied (applies only for cardiac electrophysiology when *EM_BOUNDARY_PRESCRIBED is used with EMSOL = 11 or 12):
	EQ.0: Applied on extracellular potential
	EQ.1: Applied on transmembrane potential
BIRTHT / DEATHT	Birth and death times for that prescribed boundary
VAL2	Value of the impedance in radiofrequency problems to be used in conjunction with BPTYE = 2.
LCID2	Load curve ID for defining the impedance value as a function of time. It is only available in radiofrequency problems with BPTYPE = 2.

Remarks:

1. **Supported solvers.** This keyword is currently only available for the resistive heating solver (EMSOL = 3) and the electrophysiology solvers (EMSOL = 11, 12, and 13).

***EM_CIRCUIT**

Purpose: Define an electrical circuit.

The solver type, set with EMSOL of *EM_CONTROL, determines how the current density in a circuit is modeled. For example, for an eddy current solver, the diffusion of the current in the circuit is considered. To model a circuit with uniform current through its cross-section, see *EM_CIRCUIT_SOURCE.

Card 1	1	2	3	4	5	6	7	8
Variable	CIRCID	CIRCTYP	LCID	R/F	L/A	C/T0	V0	T0
Type	I	I	I	F	F	F	F	F
Default	none	none	none	none	none	none	none	0.

Card 2	1	2	3	4	5	6	7	8
Variable	SIDCURR	SIDVIN	SIDVOUT	PID				
Type	I	I	I	I				
Default	none	none	none	none				

Optional Card. This card is only read if CIRCTYP = 30.

Card 3	1	2	3	4	5	6	7	8
Variable	VCUT	R3	L3	R2				
Type	F	F	F	F				
Default	0.	0.	0.	0.				

VARIABLE	DESCRIPTION
CIRCID	Circuit ID

VARIABLE	DESCRIPTION
CIRCTYP	Circuit type :

        EQ.1: Imposed current as a function of time set by a load curve.

        EQ.2: Imposed voltage as a function of time specified by a load curve. If a negative value is entered for LCID, its absolute value will refer to a DEFINE FUNCTION for a user-defined circuit equation. If a DEFINE_FUNCTION is used, the following parameters are accepted: f(time, emdt, curr, curr1, curr2, pot1, pot2). emdt is the current timestep; curr, curr1, and curr2 refer to the current value at t, $t - 1$, and $t - 2$, respectfully; and pot1 and pot2 refer to the scalar potential at $t - 1$ and $t - 2$, respectfully.

        EQ.3: R, L, C, V0 circuit.

        EQ.11: Imposed current defined by an amplitude A, frequency F and initial time t_0: $I = A\sin[2\pi F(t - t_0)]$

        EQ.12: Imposed voltage defined by an amplitude A, frequency F and initial time t_0: $V = A\sin[2\pi F(t - t_0)]$

        EQ.21: Imposed current defined by a load curve over one period and a frequency F. See Remark 3.

        EQ.22: Imposed voltage defined by a load curve over one period and a frequency F. See Remark 3.

        EQ.30: Modified version of R, L, C, V0 circuit that includes a diode. See Figure 6-1.

VARIABLE	DESCRIPTION
LCID	Load curve ID for CIRCTYP = 1, 2, 21, and 22
R/F	Value of the circuit resistance for CIRCTYP = 3 and 30. For CIRCTYP = 30, this part of the circuit is labeled R1 in Figure 6-1.
	Value of the frequency for CIRCTYP = 11, 12, 21, and 22. For CIRCTYP = 11 and 12, to have the frequency specified as a function of time with a load curve, a negative value can be entered with the absolute value corresponding to the load curve ID.
L/A	Value of the circuit inductance for CIRCTYP = 3 and 30. For CIRCTYP = 30, this part of the circuit is labeled L1 in Figure 6-1.
	Value of the amplitude for CIRCTYP = 11 and 12. To have the amplitude specified as a function of time with a load curve, a negative value can be entered with the absolute value corresponding to the load curve ID.
C/T0	Value of the circuit capacity for CIRCTYP = 3 and 30. For CIRC-

VARIABLE	DESCRIPTION
	TYP = 30, this part of the circuit is labeled C1 in Figure 6-1.
	Value of the initial time t_0 for CIRCTYP = 11 and 12.
V0	Value of the circuit initial voltage for CIRCTYP = 3 and 30.
T0	Starting time for CIRCTYP = 3. The default is the beginning of the run.
SIDCURR	Segment set ID for the current. It uses the orientation given by the normal of the segments. To use the opposite orientation, use a '–' (minus) sign in front of the segment set ID.
	CIRCTYP.EQ.1/11/21: The current is imposed through this segment set.
	CIRCTYP.EQ.3/30: The current needed by the circuit equations is measured through this segment set.
	CIRCTYP.EQ.2/12/22: Optional segment set that the current is forced through. See Remark 2.
SIDVIN	Segment set ID for input voltage when CIRCTYP = 2, 3, 30, 12, or 22 or for input current when CIRCTYP = 1, 11, or 21. The input voltage or current is oriented to enter the structural mesh, irrespective of the orientation of the segments.
SIDVOUT	Segment set ID for output voltage when CIRCTYP = 2, 3, 30, 12, or 22 or for output current when CIRCTYP = 1, 11, or 21. The output voltage or current is oriented to leave the structural mesh, irrespective of the orientation of the segment.
PID	Part ID associated with the circuit. It is only mandatory when including the second line of *EM_ROTATION_AXIS for the EM 2D axisymmetric solver.
VCUT	Cut off voltage for the diode, allowing the current to flow or not. Setting this field to a very large negative value effectively means that the diode circuit branch is never triggered, causing CIRCTYP = 30 to revert to an R, L, C circuit with behavior similar to CIRCTYP = 3. See Figure 6-1.
R3/L3/R2	Optional circuit resistance and inductance values for the different branches for CIRCTYP = 30. See Figure 6-1.

Table 6-1. Correspondence between circuit type and card entries. "M" indicates mandatory, "M*" mandatory with exceptions (see Remark 1), "O" optional, and "-" ignored.

Variable	1: Imposed current	2: Imposed voltage	3: R, L, C	11: F, A, t0	12: F, A, t0
LCID	M	M	-	-	-
R/L/C/V0	-	-	M	-	-
F	-	-	-	M	M
A/T0	-	-	-	M	M
SIDCURR	M	O	M	M	O
SIDVIN	M*	M	M	M*	M
SIDVOUT	M*	M	M	M*	M

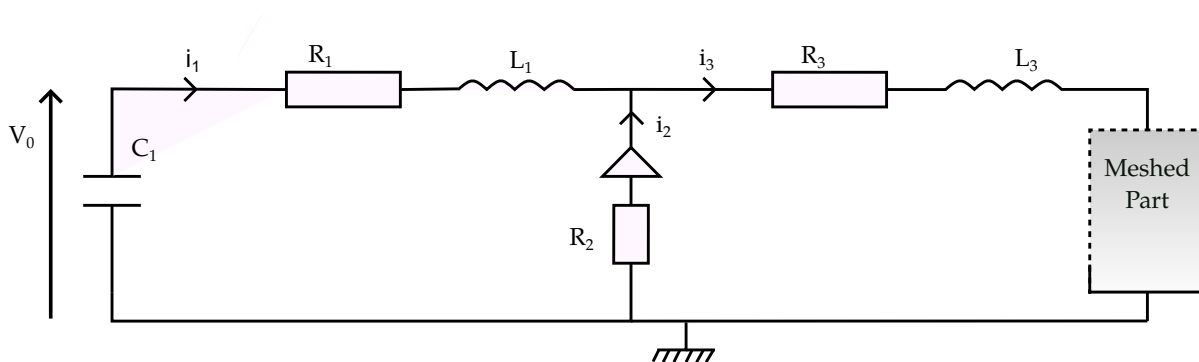| Variable	21: LCID, F	22: LCID, F	30: R, L, C with diode
LCID	M	M	-
R/L/C/V0	-	-	M
F	M	M	-
A/T0	-	-	-
SIDCURR	M	O	M
SIDVIN	M*	M	M
SIDVOUT	M*	M	M

Figure 6-1. CIRCTYP = 30 circuit sketch

Remarks:

1. **Imposed current with closed loop geometry.** For a circuit with an imposed current (CIRCTYP 1, 11, or 21) in a closed loop geometry (torus), SIDVIN and SIDVOUT cannot be specified. Thus, only SIDCURR is necessary.

2.   **SIDCURR with imposed tension.** For a circuit with an imposed tension (CIRC-TYP 2, 12, 22), it is also possible to set SIDCURR. This can be useful in circuits where various flow paths are possible for the current to force the entire current to go through SIDCURR.

3.   **CIRCTYP = 21 and 22.** Circuit types 21 and 22 are for cases where the periodic current/tension does not exactly follow a perfect sinusoidal. You must provide the frequency and the shape of the current/tension over one period through a load curve.

4.   **EMSOL = 4.** Only CIRCTYP = 1 and 2 are available for the frequency-based Eddy current solver. The values in the load curve represent the norm of the amplitude. A time shift can optionally be defined using T0.

5.   **CIRCTYP = 30.** This circuit type is only available for the Eddy current solver. When used, the output includes the current and voltage values of the different branches.

*EM_CIRCUIT_CONNECT

Purpose: Connect several circuits together by imposing a linear constraint on the global currents of circuit pairs.

$$c_1 i_1 + c_2 i_2 = 0.$$

This feature is especially useful for 2D axisymmetric models involving spiral or helical coils.

Card 1	1	2	3	4	5	6	7	8
Variable	CONID	CONTYPE	CIRC1	CIRC2	C1	C2		
Type	I	I	I	I	F	F		
Default	none	none	none	none	none	none		

VARIABLE	DESCRIPTION
CONID	ID of the circuit connect
CONTYPE	Connection type between circuits:

        EQ.1: If CIRC2 already has a global condition on its current, i_2, (see *EM_CIRCUIT), that global condition takes precedence over the constraint defined by the circuit connect.

        EQ.2: The condition defined by circuit connect takes precedence in the case of conflicting constraints (for example CIRC2 also has an imposed current defined by *EM_CIRCUIT).

VARIABLE	DESCRIPTION
CIRC1	ID of the first circuit
CIRC2	ID of the second circuit
C1/C2	Values of the linear constraints

*EM_CIRCUIT_ROGO

Purpose: Define Rogowsky coils to measure a global current versus time through a segment set or a node set.

Include as many cards as needed. This input ends at the next keyword ("*") card.

Card 1	1	2	3	4	5	6	7	8
Variable	ROGID	SETID	SETTYPE	CURTYP	PID			
Type	I	I	I	I	I			
Default	0	0	0	0	0			

VARIABLE	DESCRIPTION
ROGID	Rogowsky coil ID
SETID	Segment or node set ID
SETTYPE	Type of set: EQ.1: Segment set EQ.2: Node set (not available yet}
CURTYP	Type of current measured: EQ.1: Volume current EQ.2: Surface current (not available yet} EQ.3: Magnetic field flux (B field times Area)
PID	Part ID. It is only available for 2D axisymmetric Eddy current cases. See Remark 2.

Remarks:

1. **Output.** An ASCII file em_rogo_*xxx*, with *xxx* being the ROGID, is generated for each *EM_CIRCUIT_ROGO card. This file contains the value of the current or the magnetic field versus time for that Rogowsky coil.

2. **Special input for 2D axisymmetric Eddy current problems.** When the second line of *EM_ROTATION_AXIS is used, a simplified input for 2D axisymmetric

Eddy current problems becomes available. This case does not require specifying segment sets through the cross sections. Instead, if segment sets are unavailable, provide the part ID of the 2D axisymmetric part as PID to associate it with a Rogowsky coil.

*EM_CIRCUIT_SOURCE

Purpose: Define a circuit with uniform current through its cross-section.

This feature generally helps model stranded conductors carrying a source current (in which case Amperes become Ampere-turns). This feature can also help save computational time in models with a low-frequency current and where the diffusion of the EM fields is a very fast process. In contrast, when using *EM_CIRCUIT, the current density in a circuit is modeled in accordance with the solver type defined in EMSOL of *EM_CONTROL. For example, using an eddy current solver causes considering the diffusion of the current in the circuit. See Remark 2 for a discussion of the available circuit types for source circuits.

Card 1	1	2	3	4	5	6	7	8
Variable	CIRCID	CIRCTYP	LCID	R/F	T/A	T0		
Type	I	I	I	F	F	F		
Default	none	none	none	none	none	none		

Card 2	1	2	3	4	5	6	7	8
Variable	SIDCURR	SIDVIN	SIDVOUT	PARTID	IFREQST			
Type	I	I	I	I	I			
Default	none	none	none	none	1			

VARIABLE	DESCRIPTION
CIRCID	Circuit ID
CIRCTYP	Circuit type :

        EQ.1: Imposed current as a function of time specified by a load curve.

        EQ.2: Imposed voltage as a function of time given by a load curve.

VARIABLE	DESCRIPTION
	EQ.11: Imposed current defined by an amplitude A, frequency F and initial time t_0: $I = A\sin[2\pi F(t - t_0)]$
LCID	Load curve ID for CIRCTYP = 1 or 2. See Remark 3.
R/F	Value of the frequency for CIRCTYP = 11. To have the frequency specified as a function of time with a load curve, a negative value can be entered with the absolute value corresponding to the load curve ID.
	Value of the resistance when using an imposed voltage (CIRC-TYPE = 2).
T/A	Value of the amplitude for CIRCTYP = 11. To have the amplitude specified as a function of time with a load curve, a negative value can be entered with the absolute value corresponding to the load curve ID. See Remark 3.
	Number of turns when using an imposed voltage (CIRCTYPE = 2).
T0	Value of the initial time, t_0, for CIRCTYP = 11
SIDCURR	Segment set ID for the current. It uses the orientation given by the normal of the segments. To use the opposite orientation, use a '–' (minus) sign in front of the segment set ID or reorient the face normals.
SIDVIN	Segment set ID for input voltage when CIRCTYP = 2 or for input current when CIRCTYP = 1 or 11. This field must be left blank if the stranded conductor is a torus shape (see Remark 1).
SIDVOUT	Segment set ID for output voltage when CIRCTYP = 2 or for output current when CIRCTYP = 1 or 11. This field must be left blank if the stranded conductor is a torus shape (see Remark 1).
PARTID	Part ID associated with the circuit
IFREQST	Frequency for recomputing the source terms. The source terms are recalculated every IFREQST time steps. By default, the source terms are recomputed every EM time step. See Remark 4.
	LT.0: |IFREQST| is a load curve ID giving the frequency for recomputing as a function of time.

Remarks:

1. **Imposed current with closed loop geometry.** For a closed loop geometry (torus), SIDVIN and SIDVOUT cannot be defined. Thus, only SIDCURR is necessary.

2. **Circuit types for source circuits.** Source circuits with imposed currents (CIRCTYP = 1 or 11) can be associated with an insulator material (MTYPE = 1) in *EM_MAT_001. In this case, the solver relies on the Biot-Savart integration method to retrieve the influence of the source circuit on other conductors. This method is fast, but it is not possible to calculate the force on the coil. Circuits conforming to these conditions can be used with both the Richardson (*EM_-SOLVER_FEMBEM) and Monolithic solvers (*EM_SOLVER_FEMBEM_MON-OLITHIC) for coupling the FEM-BEM solvers.

    To extract the magnetic force on the coil when using imposed current, the source circuit must be associated with a conductor material (MTYPE = 2) that has a 0. value for the conductivity. In this case, the stranded circuit becomes part of the FEM/BEM system, and resolution might be slower. This approach is only valid with the monolithic solver (see *EM_SOLVER_FEMBEM_MONOLITHIC).

    Source circuits also support imposed voltage with CIRCTYP = 2 (associated to a resistance value and a number of turns or windings). The source circuit must be used with the monolithic solver (*EM_SOLVER_FEMBEM_MONOLITHIC) and become part of the FEM/BEM system. Therefore, it must be associated with a conductor material (MTYPE = 2) with a 0. value for the conductivity in its associated EM material (see *EM_MAT_001). Defining source circuits by their voltage instead of their current is very useful in cases where the current is unknown, such as for actuators or electric motors.

3. **Ampere versus Ampere-turns.** For an imposed current (CIRCTYP = 1 or 11), the number of windings can be directly applied by multiplying the current value by the number of turns. The imposed current value corresponds to Ampere-turns. For example, a stranded coil with ten turns and a current of two Amperes means that imposing a value of twenty in the load curve (if CIRCTYP = 1) or its periodic amplitude (if CIRCTYP = 11). For imposed voltage, providing Ampere-turns is not available. Thus, the number of turns must be specified directly in the keyword (as well as the total resistance of the circuit).

4. **When to change IFREQST.** In cases where conductors are not moving with respect to one another, using high values of IFREQST avoids recomputing the source fields which can save some calculation time.

5. **EMSOL = 4.** For the frequency-based Eddy current solver, only CIRCTYPE = 1 and 2 are available. The values contained in the load curve represent the norm of the amplitude while a time shift can optionally be defined using T0.

*EM_CONTACT

Purpose: Optional define and specify options on electromagnetic contacts between two sets of parts. Generally, it is used with the *EM_CONTACT_RESISTANCE. Fields left empty on this card default to the value of the equivalent field for *EM_CONTROL_CONTACT.

Contact Definition Cards. Include one card for each contact definition. This input ends at the next keyword ("*") card.

Card 1	1	2	3	4	5	6	7	8
Variable	CONTID	DTYPE	PSIDR	PSIDT	EPS1	EPS2	EPS3	D0
Type	I	I	I	I	F	F	F	F
Default	none	0	none	none	0.3	0.3	0.3	none

VARIABLE	DESCRIPTION
CONTID	Electromagnetic contact ID
DTYPE	Detection type (see remarks):
	EQ.0: Contact type 0 (default)
	EQ.1: Contact type 1
PSIDR	Reference surface part set ID
PSIDT	Tracked surface part set ID
EPSi	Contact coefficients for contact detection conditions. See the discussion below.
D0	Parameter for contact condition 3 when DTYPE = 1 (see remarks)

Remarks:

In these remarks, we discuss the conditions for contact detection. For reference, Figure 0-1 illustrates which geometric values help determine contact. In this figure and discussion, f_r is a face of the reference surface, and f_t is a face of the tracked surface. Contact is detected when *all of the following three conditions are satisfied*:
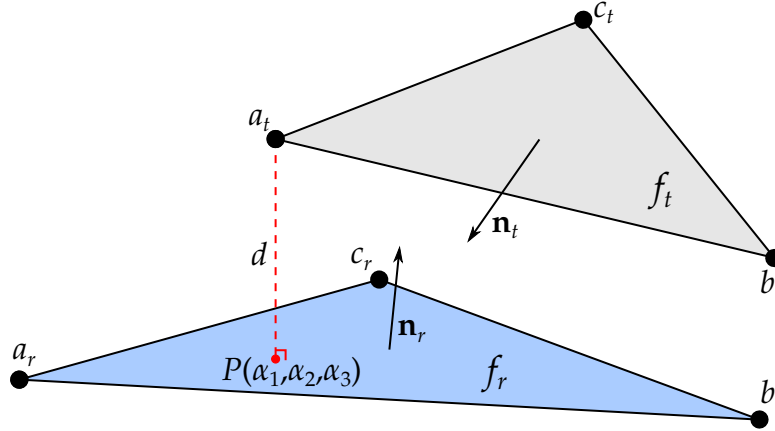
Figure 0-1. Contact detection conditions between two faces.

1. Contact condition 1:

$$\mathbf{n}_r \cdot \mathbf{n}_t \leq -1 + \varepsilon_1$$

Here $\mathbf{n}_r$ and $\mathbf{n}_t$ are the normal vectors of faces f_r and f_t, respectively, and ε_1 is an input parameter. See Figure 0-1.

2. Contact condition 2:

$$-\varepsilon_2 \leq \alpha_1 \leq 1 + \varepsilon_2$$
$$-\varepsilon_2 \leq \alpha_2 \leq 1 + \varepsilon_2$$
$$-\varepsilon_2 \leq \alpha_3 \leq 1 + \varepsilon_2$$

$(\alpha_1, \alpha_2, \alpha_3)$ are the local coordinates of point P (see Figure 0-1). P is the projection of point a_2 on face f_r. ε_2 is an input parameter.

3. Contact condition 3 depends on the contact type. For either possible condition, let d be the distance between P and a_t (see Figure 0-1).

   a) For contact type 0:

   $$d \leq \varepsilon_3 S_r \ ,$$

   where ε_3 is an input parameter and S_r is the minimum side length for f_r:

   $$S_r = \min[d(a_r, b_r), d(b_r, c_r), d(c_r, a_r)] \ .$$

   b) For contact type 1:

   $$d \leq D_0 \ ,$$

   where D_0 is an input parameter.

***EM_CONTACT_RESISTANCE**

Purpose: Calculate the electric contact resistance of a previously defined EM contact in *EM_CONTACT.

Card 1	1	2	3	4	5	6	7	8
Variable	CRID	CONTID	CTYPE		JHRTYPE			
Type	I	I	I		I			
Default	none	none	none		none			

Cards 2	1	2	3	4	5	6	7	8
Variable	DFID							
Type	I							
Default	none							

VARIABLE	DESCRIPTION
CRID	Resistive contact ID
CONTID	EM contact ID defined in *EM_CONTACT
CTYPE	Contact resistance type:
	EQ.1: Electric contact resistance defined by user defined define function.
DFID	Define function ID (see Remark 1)
JHRTYPE	Indicates how the Joule heating calculated by the contact resistance shall be taken into account:
	EQ.0: No addition. The Joule heating calculated by the contact resistance is not taken into account.

Figure 6-2. Electrode coming into contact with workpiece (RSW application).

VARIABLE	DESCRIPTION
	EQ.1: The Joule heating coming from the contact resistance is divided and distributed evenly among all elements neighboring the contact surface.

Remarks:

1. **Define Function Parameters.** In the *DEFINE_FUNCTION, the following parameters are allowed: f(time, emdt, arealoc, areatot, ctdist, currloc, currglob, rho_mst, rho_slv, cond_mst, cond_slv, ctpress_mst, ctpress_slv, temp_mst, temp_slv, vmstress_mst, vmstress_slv, press_mst, press_slv). Here,

time	current time step
emdt	EM time step
arealoc	Local area associated with each face in contact
areatot	Total contact area
ctdist	Contact distance between the two faces in contact
currloc	Local current density at the contact area
currglob	Total current flowing through the contact area

rho_mst	Density of the elements associated with the reference surface side of the contact
rho_slv	Density of the elements associated with the tracked surface side of the contact
cond_mst	Electrical conductivity of the elements associated with the reference surface side of the contact
cond_slv	Electrical conductivity of the elements associated with the tracked surface side of the contact
ctpress_mst	Contact pressure of the elements associated with the reference surface side of the contact
ctpress_slv	Contact pressure of the elements associated with the tracked surface side of the contact
temp_mst	Temperature of the elements associated with the reference surface side of the contact
temp_slv	Temperature of the elements associated with the tracked surface side of the contact
vmstress_mst	von Mises stress of the elements associated with the reference surface side of the contact
vmstress_slv	von Mises stress of the elements associated with the tracked surface side of the contact
press_mst	Pressure of the elements associated with the reference surface side of the contact
press_slv	Pressure of the elements associated with the tracked surface side of the contact

*EM_CONTACT_SUBDOM

Purpose: Optional card used for defining a specific region where EM contact will be active. This allows saving some calculation time by limiting the contact search area. Must be used in conjunction with *EM_CONTROL_CONTACT.

Card 1	1	2	3	4	5	6	7	8
Variable	SDTYPE	MVTYPE	LCIDX/NID	LCIDY	LCIDZ			
Type	I	I	I	I	I			
Default	none	0	none	none	none			

Card 2	1	2	3	4	5	6	7	8
Variable	R	PMINX	PMINY	PMINZ	PMAXX	PMAXY	PMAXZ	
Type	F	F	F	F	F	F	F	
Default	none	none	none	none	none	none	none	

VARIABLE	DESCRIPTION

SDTYPE   Subdomain definition type :

> EQ.1: Defined by box.
>
> EQ.2: Defined by cylinder.
>
> EQ.3: Defined by sphere.

MVTYPE   Movement type of subdomain :

> EQ.0: Static subdomain (Default).
>
> EQ.1: Domain translates in the three directions by the velocities given by LCIDX,LCIDY,LCIDZ.
>
> EQ.2: Domain follows the displacements of the node ID given by NID.

VARIABLE	DESCRIPTION
LCIDX/NID	Time dependent load curve ID for the translational velocity in the X direction for MVTYPE = 1, Node ID for MVTYPE = 2.
LCIDY/Z	Time dependent load curve IDs for MVTYPE = 1 in the Y and Z directions.
R	Radius of the sphere if SDTYPE = 3 or the cylinder if SDTYPE = 2.
PMINX/Y/Z	Point of minimum coordinates if SDTYPE = 1. Origin point if SDTYPE = 3. Axis head point if SDTYPE = 2.
PMAXX/Y/Z	Point of maximum coordinates if SDTYPE = 1. Axis tail point if SDTYPE = 2.

*EM_CONTROL

Purpose: Enable the EM solver and set its options.

Card 1	1	2	3	4	5	6	7	8
Variable	EMSOL	NUMLS		DIMTYPE	NPERIO		NCYLFEM	NCYLBEM
Type	I	I		I	I		I	I
Default	none	100		0	2		5000	5000

VARIABLE	DESCRIPTION

<div>

  VARIABLE   DESCRIPTION

</div>

EMSOL   Electromagnetism solver selector:

     EQ.-1: Turns the EM solver off after reading the EM keywords.

     EQ.1: Eddy current solver

     EQ.2: Periodic inductive heating solver (see Remark 3)

     EQ.3: Resistive heating solver

     EQ.4: Frequency-based Eddy current solver (see Remark 3)

     EQ.5: Periodic resistive heating solver (see Remark 3)

     EQ.11: Electrophysiology monodomain

     EQ.12: Electrophysiology bidomain

     EQ.13: Electrophysiology monodomain coupled with bidomain

     EQ.14: Pure eikonal model. Activation times are computed and output in VTK format to the /vtk directory. See *EM_EP_EIKONAL.

     EQ.15: Reaction eikonal (RE) model based on [1]. See *EM_EP_EIKONAL.

NUMLS   Number of local EM steps in a whole period for EMSOL = 2. Global frequency for EMSOL = 4. If a negative value is entered, it gives the value as a function of the macro time.

DIMTYPE   EM dimension type:

     EQ.0: 3D solve

     EQ.1: 2D planar with zero thickness shell elements

VARIABLE	DESCRIPTION
	EQ.2: 2D axisymmetric (Y-axis only) with zero thickness elements
NPERIO	Number of periods for which the last is used to calculate the average Joule heat rate when EMSOL = 2. NPERIO = 2 means that two periods of NUMLS steps will be calculated. Only the last period of NPERIO is used for the average Joule heat calculation. See Remark 1.
NCYLFEM	Number of electromagnetism cycles between the recalculation of FEM matrices. If negative, the absolute value refers to a load curve that gives the number of electromagnetism cycles as a function of time. See Remark 2.
NCYLBEM	Number of electromagnetism cycles between the recalculation of BEM matrices. If negative, the absolute value refers to a load curve that gives the number of electromagnetism cycles as a function of time. See Remark 2.

Remarks:

1. **Number of periods and the average Joule heating calculation.** The purpose of using more than one period to calculate the average Joule heating is to allow the different fields to adopt the correct amplitude and time shift when starting from 0.0 at $t = 0$. NPERIO = 2 means that two periods are calculated, of which only last one, being the second one in this case, is used for the average Joule heat calculation. In some cases, larger values might be required to achieve good accuracy, and conversely, in others, NPERIO = 1 might yield sufficient accuracy.

2. **Order of precedence for NCYLFEM and NCYLBEM.** You can set NCYLFEM and NCYLBEM with *EM_CONTROL_SOLUTION, *EM_SOLVER_FEM/BEM, or *EM_CONTROL. *EM_CONTROL_SOLUTION has the highest priority for setting these fields, while *EM_CONTROL has the lowest priority. If a field is left as the default on *EM_CONTROL_SOLUTION, LS-DYNA looks at the setting of that field on *EM_SOLVER_FEM/BEM. If left as default on *EM_-SOLVER_FEM/BEM, LS-DYNA looks at the setting on *EM_CONTROL.

3. **Solver for inductive heating.** Both EMSOL = 2 and 4 can be used for inductive heating problems. EMSOL = 4 requires using the monolithic solver. It is a frequency-based solver, so the solve is usually faster than solving EM quantities in the time domain over the full period. However, only EMSOL = 2 is available for nonlinear magnetic permeability cases. EMSOL = 5 is similar to EMSOL = 2 but

restricted to resistive-heating-type applications because it does not consider inductive-diffusive effects.

References:

[1]   A. Neic et al, " Efficient computation of electrograms and ECGs in human whole heart simulations using a reaction-eikonal model", Journal of Computational Physics 346 (2017) 191–211

*EM_CONTROL_CONTACT

Purpose: Activate the electromagnetism contact algorithms, which detect contact between conductors. Electromagnetic fields flow from one conductor to another when found to be in contact.

Card 1	1	2	3	4	5	6	7	8
Variable	EMCT	CCONLY	CTYPE	DTYPE	EPS1	EPS2	EPS3	D0
Type	I	I	I	I	F	F	F	F
Default	0	0	0	0	0.3	0.3	0.3	none

VARIABLE	DESCRIPTION

EMCT   EM contact activation flag:

>   EQ.0: No contact detection

>   EQ.1: Contact detection

CCONLY   Determines parts for which EM contact is active:

>   EQ.0: Contact detection between all active parts associated with a conducting material. (Default)

>   EQ.1: Only look for EM contact between parts associated through the *EM_CONTACT card. In some cases, this option can reduce the calculation time.

CTYPE   Contact type:

>   EQ.-1: Node-to-node contact based on constraints on the scalar potential. See Remark 1.

>   EQ.0: Node-to-node penalty-based contact on the scalar potential.

>   EQ.1: Discrete mortar penalty contact on the scalar potential.

>   EQ.2: Continuous mortar penalty contact on the scalar potential and the vector potential (when active).

DTYPE   Detection type. If *EM_CONTACT is not defined, the solver will look for global contact options in *EM_CONTROL_CONTACT. See *EM_CONTACT for details.

VARIABLE	DESCRIPTION
	EQ.0: Contact type 0 (default).
	EQ.1: Contact type 1.
EPS*i*	Global contact coefficients used if the equivalent fields in *EM_-CONTACT are empty. See *EM_CONTACT for details.
D0	Global parameter for contact condition 3 when DTYPE = 1. See *EM_CONTACT for details.

Remarks:

1. **Contact types.** In versions prior to R12, CTYPE = 0 was the default EM contact for the resistive heating solver, while CTYPE = -1 was the default EM contact for the Eddy current solver. In versions R12 and later, CTYPE = 0 became the default for all solvers. We recommend CTYPE = 1 and 2 for the best accuracy.

2. **Contact between BEM surfaces with the Eddy current solver.** When the Eddy current solver is active and contact occurs between BEM surfaces, the solver automatically removes the faces on the contact surface and internally stitches the two BEM surfaces together to achieve a continuous closed BEM mesh.

*EM_CONTROL_COUPLING

Purpose: Control couplings between various solvers with the EM solver.

Card 1	1	2	3	4	5	6	7	8
Variable	THCPL	SMCPL	THLCID	SMLCID	THCPLFL	SMCPLFL		
Type	I	I	I	I	I	I		
Default	0	0	0	0	0	0		

Optional Card.

Card 2	1	2	3	4	5	6	7	8
Variable	SMMOD	DFX	DFY	DFZ		FSIB	INTERP	
Type	I	I	I	I		I	I	
Default	0	none	none	none		0	0	

Optional Card.

Card 3	1	2	3	4	5	6	7	8
Variable	NID1	NID2	NID3					
Type	I	I	I					
Default	0	0	0					

VARIABLE	DESCRIPTION
THCPL	Coupling to the thermal solver. When turned on, the EM solver will transfer the Joule heating terms to the solid mechanics thermal solver. EQ.0: Coupling on.

VARIABLE	DESCRIPTION
	EQ.1: Coupling off.
	EQ.2: Coupling on. It forces all EM heating terms to be expressed at the element level. See Remark 2.
SMCPL	Coupling to the solid mechanics solver. When turned on, the EM solver will transfer forces to the solid mechanics solver.
	EQ.0: Coupling on. Lorentz force density is transferred.
	EQ.1: Coupling off.
	EQ.2: Coupling on. Magnetic force surface density is transferred. More accurate representation of EM forces in cases involving magnets or nonlinear ferromagnets. See *EM_SOLVER_FEMBEM_MONO-LITHIC.
	EQ.3: Coupling on. Magnetic force surface density is transferred to magnets and ferromagnets, while Lorentz force density is transferred to regular conductors.
THLCID	Optional load curve ID. When defined, the heat rate transferred to the thermal solver will be scaled by the value returned by THLCID.
SMLCID	Optional load curve ID. When defined, the forces transferred to the solid mechanics solver will be scaled by the value returned by SMLCID.
THCPLFL	Coupling to the heat equation when EM quantities are solved on fluid elements. When turned on, the EM solver will transfer the Joule heating terms to the ICFD solver.
	EQ.0: Coupling off.
	EQ.1: Coupling on.
SMCPLFL	Interaction between the solid mechanics solver and the ICFD solver when EM quantities are solved on fluid elements.
	EQ.0: The fluid pressure will be passed to the solid mechanics solver (default).
	EQ.1: The fluid pressure is replaced by the electrostatic pressure.
	EQ.2: The fluid and electrostatic pressure are passed on to the solid mechanics solver.

VARIABLE	DESCRIPTION
	EQ.4: The EM solver will send the Lorentz Force as a volumetric source term to the fluid solver.
SMMOD	Coupling to the solid mechanics solver. When turned on, the EM solver will transfer forces to the solid mechanics solver.
	EQ.0: Off.
	EQ.1: Force calculation at the element level is decided by *DEFINE_FUNCTION. See DFX, DFY and DFZ.
	EQ.2: Force calculation at the element level is decided by the usermat routine. See dyn21em.f and user_getEMForceArray routine.
DFX/DFY/DFZ	*DEFINE_FUNCTION IDs for the force three components if SMMOD = 1. Arguments for the *DEFINE_FUNCTIONs are the same as in *EM_EOS_TABULATED2. See Remark 2 of *EM_EOS_TABULATED2.
FSIB	Solid mechanics – ICFD FSI boundaries. When turned on, the EM solver uses the coupled FSI interface to impose the continuity of the scalar potential between the two domains. See Remark 1.
	EQ.0: Off
	EQ.1: On
INTERP	Flag for EM force interpolation by the solid mechanics solver. By default, the solid mechanics solver interpolates at each time the EM force from the last two EM steps. See Remark 3.
	EQ.0: Time interpolation on (default)
	EQ.1: No time interpolation. Use the force from the last EM solve.
NID1/NID2/NID3	Three node IDs defining a local coordinate system. See Remark 4.

Remarks:

1.   **FSI coupling.** *ICFD_CONTROL_FSI and *ICFD_BOUNDARY_FSI control the coupling between the ICFD and the solid mechanics solvers. When FSI exists and the FSIB flag is turned on, the EM solver reuses those boundaries to impose the necessary constraints on the scalar potential to ensure continuity. The solid

and fluid domains must have been previously defined as conductors (see *EM_-MAT_001).

2. **Heating term at the element level.** By default, the EM-thermal heat rate is expressed at the node level before being sent to the thermal solver. However, for some applications where sharp gradients are present, such as battery applications involving Randles circuits, an alternative approach is to express the heat rate term at the element level using THCPL = 2. THCPL = 2 results in a smoother and more diffusive solution.

3. **Force interpolation.** In typical EM Eddy current applications, such as magnetic metal forming or welding, the mechanical time step is much smaller than the EM time step. The EM solver completes its solve with its larger time step and waits for the mechanical solver to catch up. During each of its solves, the mechanical solver interpolates the force between the two last EM steps. However, for specific magnetostatic problems (specifically rotating problems), this time interpolation can introduce errors. INTERP, therefore, exists to turn off the time interpolation and have the mechanical solver use the force from the last EM solve.

4. **Rotating problems.** In conjunction with INTERP = 1 described in Remark 3, optional Card 3 enables defining a local reference frame. If the frame is rotating, the mechanical solver applies the corresponding rotation to the force vectors obtained from the EM solver. This feature was developed specifically for magnetostatic rotating problems and is subject to further development.

*EM_CONTROL_EROSION

Purpose: Allows the EM solver to take eroded elements into account

Card 1	1	2	3	4	5	6	7	8
Variable	ECTRL							
Type	I							
Default	0							

VARIABLE	DESCRIPTION

ECTRL   Erosion search :

                 EQ.0:   Off. This means that the EM solver will ignore eroded elements and still consider them part of the EM problem.

                 EQ.1:   On. The EM solver will look for potential elements that are eroded and remove them from the EM solve by updating its matrix system.

*EM_CONTROL_MAGNET

Purpose: Control how often the magnetization vector for magnets is recomputed. By default, the magnetization vector for each magnet is computed only once at the beginning of the calculation (see Remark 1).

Card 1	1	2	3	4	5	6	7	8
Variable	MCOMP	NCYCM						
Type	I	I						
Default	0	0						

VARIABLE	DESCRIPTION
MCOMP	Flag controlling whether the magnetization vector is recomputed.
	EQ.0: Magnetization vector not recomputed (see Remark 1).
	EQ.1: Magnetization vector recomputed at the frequency controlled by NCYCM.
NCYCM	Magnetization vector recomputation frequency. A value of 1 means recomputation at every EM time step. If a negative value is entered, |NCYCM| is the ID of a load curve giving the value as a function of time.

Remark:

1. **MCOMP.** In most applications involving magnets, the magnetization vector associated to each magnet needs only to be calculated once at the beginning of the analysis. The magnetization direction is then scaled by the Coercive force value (See EM_PERMANENT_MAGNET) to correctly estimate the contribution of each magnet. In certain specific applications, for examples in cases involving magnet deformations or changes in magnet boundary conditions, it may be needed to periodically update the initially computed magnetization vector. This can be achieved by setting MCOMP to 1 and defining NCYCM.

*EM_CONTROL_SOLUTION

Purpose: Specify different conditions under which reassembly of the FEM and BEM matrices occurs.

Card 1	1	2	3	4	5	6	7	8
Variable	NCYLFEM	NCYLBEM	AUTOFEM	AUTOBEM	TOL1FEM	TOL2FEM	TOL1BEM	TOL2BEM
Type	I	I	I	I	F	F	F	F
Default	5000	5000	0	0	0.3	0.1	0.3	0.1

Optional Card.

Card 2	1	2	3	4	5	6	7	8
Variable	NID1	NID2	NID3	NID4	NID5	NID6	ANG	DIST
Type	I	I	I	I	I	I	F	F
Default	0	0	0	0	0	0	1.e16	1.e16

VARIABLE	DESCRIPTION
NCYLFEM	Number of electromagnetism cycles between the recalculation of FEM matrices. See Remark 1.
	LT.0: |NCYLFEM| refers to a load curve, giving the number of cycles as a function of time.
NCYLBEM	Number of electromagnetism cycles between the recalculation of BEM matrices. See Remark 1.
	LT.0: |NCYLBEM| refers to a load curve, giving the number of cycles as a function of time.
AUTOFEM	In addition to NCYLFEM, AUTOFEM triggers an automatic recomputation of the FEM matrices based on an error calculation of the conductors' relative deformation and electrical conductivity changes. See TOL1FEM and TOL2FEM. See Remark 2.
	EQ.0: Autorecomputation off

VARIABLE	DESCRIPTION
	EQ.1: Autorecomputation on
AUTOBEM	In addition to NCYLBEM, AUTOBEM triggers an automatic recomputation of the BEM matrices based on an error calculation of the conductors' relative displacements. See TOL1BEM and TOL2BEM. See Remark 2.
	EQ.0: Autorecomputation off
	EQ.1: Autorecomputation on
TOL1FEM	Only used if AUTOFEM = 1. If a conducting element experiences a deformation or a conductivity change that reaches an error larger than TOL1FEM, the solver reassembles the FEM matrices. If negative, the absolute value refers to a load curve that gives the tolerance as a function of time.
TOL2FEM	Only used if AUTOFEM = 1. If (number of conducting elements) × TOL2FEM elements experience a deformation or a conductivity change that reaches an error larger than TOL2FEM, the solver recomputes the FEM matrices. If negative, the absolute value refers to a load curve that gives TOL2FEM as a function of time.
TOL1BEM	Only used if AUTOBEM = 1. If a conducting element experiences a displacement that reaches an error larger than TOL1BEM, then LS-DYNA reassembles the BEM matrices. If negative, the absolute value refers to a load curve that gives the tolerance as a function of time.
TOL2BEM	Only used if AUTOBEM = 1. If (number of conducting elements) × TOL2BEM elements experience a displacement that reaches an error larger than TOL2BEM, then the BEM matrices are recomputed. If negative, the absolute value refers to a load curve that gives TOL2BEM as a function of time.
NID1, NID2, NID3	Local coordinate system specified with NID1, NID2, and NID3. See Remark 3.
NID4, NID5, NID6	Local coordinate system specified with NID4, NID5, and NID6. See Remark 3.
ANG	Angle (in degrees) tolerance criterion that triggers a BEM matrix recomputation. See Remark 3.
	LT.0.0: |ANG| is a load curve ID giving the angle tolerance criterion as a function of time.

VARIABLE	DESCRIPTION
DIST	Distance tolerance criterion that triggers a BEM matrix recomputation. See Remark 3.

> LT.0.0: |DIST| is a load curve ID giving the distance tolerance criterion as a function of time.

Remarks:

1. **Order of precedence for NCYLFEM and NCYLBEM.** You can set NCYLFEM and NCYLBEM with *EM_CONTROL_SOLUTION, *EM_SOLVER_FEM/BEM, or *EM_CONTROL. *EM_CONTROL_SOLUTION has the highest priority for setting these fields, while *EM_CONTROL has the lowest priority. If you leave one of these fields as the default value on *EM_CONTROL_SOLUTION, LS-DYNA then looks at the setting of that field on *EM_SOLVER_FEM/BEM. If left as the default on *EM_SOLVER_FEM/BEM, LS-DYNA looks at the setting on *EM_CONTROL.

2. **EM contact with recomputation.** When EM contact occurs and you have enabled automatic FEM or BEM matrix recomputation, LS-DYNA simultaneously reassembles both the FEM and BEM matrices when any criterion is reached to maintain consistency. When you do not enable automatic recomputation, we recommend the FEM and BEM systems have the same value for the recomputation cycle.

3. **Rotating and translating parts.** The optional second line triggers a BEM matrix recomputation only if the rotation or distance between the system composed of NID1/NID2/NID3 and NID4/NID5/NID6 exceeds ANG (in degrees) or DIST. This feature is useful in cases when one conductor part rotates or translates based on another part and an automatic criterion is desired.

*EM_CONTROL_SWITCH

Purpose: Create a control "switch" that will shut down the solver based on information from a load curve. LS-DYNA supports complex types of curves (See *DEFINE_CURVE_- FUNCTION) that allow the setting up of complex on/off switches, for instance, by using a nodal temperature value.

Card 1	1	2	3	4	5	6	7	8
Variable	LCID	FEMCOMP	BEMCOMP					
Type	I	I	I					
Default	0	0	0					

VARIABLE	DESCRIPTION
LCID	Load curve or define curve function ID. Negative values switch the solver off; positive values switch it back on.
FEMCOMP	Flag to determine if LS-DYNA recomputes the FEM matrices each time the EM solver is turned back on:
	EQ.0: Recompute FEM matrices.
	EQ.1: Do not recompute FEM matrices.
BEMCOMP	Flag to determine if LS-DYNA recomputes the BEM matrices each time the EM solver is turned back on:
	EQ.0: Recompute BEM matrices.
	EQ.1: Do not recompute the BEM matrices.

*EM_CONTROL_SWITCH_CONTACT

Purpose: It is possible to active a control "switch" that will shut down the electromagnetic contact detection. This can be useful in order to save some calculation time in cases where the user knows when contact between conductors will occur or stop occurring.

Card 1	1	2	3	4	5	6	7	8
Variable	LCID	NCYLFEM	NCYLFEM					
Type	I	I	I					
Default	0	0	0					

VARIABLE	DESCRIPTION
LCID	Load Curve ID.
	Negative values switch the contact detection off, positive values switch it back on.
NCYLFEM	Determines the number of cycles before FEM matrix recomputation. If defined this will overwrite the previous NCYCLFEM as long as the contact detection is turned on.
NCYLBEM	Determines the number of cycles before BEM matrix recomputation. If defined this will overwrite the previous NCYCLBEM as long as the contact detection is turned on.

*EM_CONTROL_TIMESTEP

Purpose: Controls the EM time step and its evolution.

Card 1	1	2	3	4	5	6	7	8
Variable	TSTYPE	DTCONST	LCID	FACTOR	TSMIN	TSMAX	RLCSF	MECATS
Type	I	F	I	F	F	F	I	I
Default	none	none	none	1.0	none	none	25	0

VARIABLE	DESCRIPTION
TSTYPE	Time step type:

      EQ.1: Constant time step given in DTCONST

      EQ.2: Time step as a function of time given by a load curve specified in LCID

      EQ.3: Automatic time step computation, depending on the solver type. This time step is then multiplied by FACTOR

      EQ.5: EM time step forced to be the same as the thermal time step in problems with the EM solver coupled to the thermal solver. In other words, the thermal solver determines the EM time step.

VARIABLE	DESCRIPTION
DTCONST	Constant value for the time step for TSTYPE = 1
LCID	Load curve ID giving the time step as a function of time for TSTYPE = 2
FACTOR	Multiplicative factor applied to the time step for TSTYPE = 3
TSMIN	Minimum time step. When TSMIN is defined, the EM time step cannot drop below TSMIN. A negative value will refer to a time-dependent load curve.
TSMAX	Maximum time step. When TSMAX is defined, the EM time step cannot increase beyond TSMAX. A negative value will refer to a time-dependent load curve.
RLCSF	RLC Circuit time step scale factor. See Remark 2.

VARIABLE	DESCRIPTION
MECATS	Mechanical time step handling in cases where the EM solver time step becomes smaller (see Remark 3):

> EQ.0: Default. The EM time step will go below the solid mechanics timestep, and several EM solves will occur between two solid mechanics time steps to ensure time consistency.

> EQ.1: The solid mechanics time step will adapt and decrease to the EM time step value so that only one EM solve occurs between two solid mechanics solves.

Remarks:

1. **Automatic time step for Eddy current solvers.** For eddy current solvers, the automatic time step is based on the diffusion equation for the magnetic field:

$$\sigma \frac{\partial \vec{A}}{\partial t} + \vec{\nabla} \times \frac{1}{\mu} \vec{\nabla} \times \vec{A} + \sigma \vec{\nabla} \varphi = \vec{j}_S \ .$$

It is computed as the minimal elemental diffusion time step over the elements. For a given element, the elemental diffusion time step is given as $dt_e = l_e^2/(2D)$, where:

- D is the diffusion coefficient $D = 1/(\mu_0 \sigma_e)$,
- σ_e is the element's electrical conductivity,
- μ_0 is the permeability of free space,
- l_e is the minimal edge length of the element (minimal size of the element).

2. **Automatic time step with RLC circuit.** When an automatic time step is defined and an RLC circuit is present, the EM solver will perform an additional check and calculate an approximation of the first current period based on a 0-D circuit solve. It will then limit the timestep by a factor $T_{\text{period}}/(4 \times \text{RLCSF})$. The default value of RLCSF ensures that 25 EM timesteps will be calculated for the first quarter period.

3. **MECATS.** In general, we recommend avoiding scenarios where the EM time step becomes smaller than the solid mechanics time step, a situation often resulting from ill-defined input decks and parameters. However, this can happen when conducting elements have large deformations and an automatic EM time step is selected. For this case, choose between the two MECATS options.

4. **Macro time step.** If EMSOL = 2 or 4 in *EM_CONTROL, the EM time step defined here represents a "macro" time step, meaning the time when new time-

averaged quantities such as Joule heating Power or Magnetic Forces are up-dated. If material properties are constant and no displacement of parts is expected, this macro time step can be equal to the termination time.

*EM_DATABASE_CIRCUIT

Purpose: Enable the output of EM data for every circuit defined.

Output options card

Card 1	1	2	3	4	5	6	7	8
Variable	OUTLV	DTOUT						
Type	I	F						
Default	1	0.						

VARIABLE	DESCRIPTION
OUTLV	Determines if LS-DYNA creates the output file:
	EQ.0: Do not generate the output file.
	EQ.1: Generate the output file.
DTOUT	Time interval to print the output. If DTOUT is equal to 0.0, LS-DYNA uses the EM timestep.

Remarks:

1. **File name.** The file name for this database is em_circuit_*XXX*.dat with *XXX* as the circuit ID.

2. **ResistanceD.** LS-DYNA calculates *ResistanceD* in the following way:

    a) Imposes a scalar potential difference of 1 at the circuit's boundaries SIDVIN and SIDVOUT.

    b) Solves $\nabla^2 \varphi = 0$ with $\varphi_{\text{SIDVIN}} = 1$ and $\varphi_{\text{SIDVOUT}} = 0$ at SIDCURR. We do not consider diffusive effects, meaning the current density can be written as $\mathbf{j} = \nabla\varphi$ and the total current as $I = \mathbf{j} \cdot \mathbf{n}dA$.

    c) Estimates the resistance using $R_D = U/I$. U is the potential difference between φ_{SIDVIN} and and φ_{SIDVOUT}, that is, equal to 1. The circuit's geometry and conductivity solely determine this R_D resistance. It is, therefore, equivalent to the resistance as commonly defined in the circuit equations:

$$R_D = L/\sigma S \ ,$$

where L is the length of the circuit and S is its surface area.

3. **ResistanceJ.** LS-DYNA calculates *ResistanceJ* with the data provided during the EM solve: $R_J = J/I^2$ where J and I are, respectively, the joule heating and the current. Compared with *ResistanceD, ResistanceJ* is not so much a resistance calculation since it accounts for the resistive effects (when using the Eddy current solver). Rather, it corresponds to the resistance that the circuit would need in order to get the same Joule heating in the context of a circuit equation. If all EM fields are diffused or you are using the resistive heating solver, *ResistanceJ* should be close to *ResistanceD*.

4. **Mutual inductances.** Only the mutual inductances between the first three circuits defined are output.

*EM_DATABASE_CIRCUIT0D

Purpose: Enable the output of 0D EM data for every circuit defined.

Output options card

Card 1	1	2	3	4	5	6	7	8
Variable	OUTLV	DTOUT						
Type	I	F						
Default	0	0.						

VARIABLE	DESCRIPTION
OUTLV	Determines if LS-DYNA creates the output file. EQ.0: Does not generate the output file. EQ.1: Generates the output file.
DTOUT	Time interval to print the output. If DTOUT equals 0.0, then LS-DYNA uses the EM time step.

Remarks:

1. **File name.** The file name for this database is em_circuit0D_*XXX*.dat with *XXX* as the circuit ID.

2. **0D solution.** At the start of the run, based on the initial values of the meshes resistances and inductances, the solver calculates the results for a so-called "0D" solution, which does not consider the current's diffusion, the part's displacements, or the EM material property changes. It is, therefore, a crude approximation. LS-DYNA extrapolates the initial results through time which it outputs at DTOUT intervals. This result can be useful in some cases, especially in RLC circuits if you need a rough idea of how the source current will behave.

3. **Cost.** Since the calculation of this 0D circuit can take time depending on the size of the problem, you should only use it in cases where the output results help with comprehension of the analysis.

4. **Effect of this keyword.** This keyword does not influence the results of the EM run itself.

***EM_DATABASE_CIRCUITSOURCE**

Purpose: Output additional data specific to source circuits.

Card 1	1	2	3	4	5	6	7	8
Variable	CIRCID	IMP						
Type	I	I						
Default	none	0						

VARIABLE	DESCRIPTION
CIRCID	Source circuit ID for which total magnetic flux is calculated and output to em_CircuitSource_CIRCID.dat. See Remark 1.
IMP	Include the source circuit with ID CIRCID in the impedance matrix calculation and output:

> EQ.0: Not included.
>
> EQ.1: Included. See Remark 2.

Remarks:

1. **Magnetic flux.** This keyword causes an additional vector product operation on the current density and vector potential to give the magnetic flux for the specified source circuits. For the frequency domain solver, the output is decomposed into its real and imaginary components. This output is useful for retrieving coil inductance variations and resistance variations or induced voltage. It is frequently used in crack detection problems in conjunction with the frequency domain Eddy current solver. Since it relies on the vector potential output, the source circuit coil must be defined as a conductor. See Remark 2 in *EM_CIRCUIT_SOURCE).

2. **Impedance matrix.** IMP = 1 only applies when the frequency domain solver is also activated (EMSOL = 4 in *EM_CONTROL). For each CIRCID for which IMP = 1, the solver performs a separate solve with each CIRCID considered in turn as an emissive and receptive coil. This method enables establishing the complete impedance matrix. Its real and imaginary parts are output in ASCII files em_indMtx.dat and em_resMtx.dat, respectively. The results of em_resMtx.dat are multiplied by ω, where $\omega = 2\pi F$, for convenience purposes.

*EM_DATABASE_ELOUT

Purpose: Enable the output of EM data on elements.

Output Options Card.

Card 1	1	2	3	4	5	6	7	8
Variable	OUTLV	DTOUT						
Type	I	F						
Default	0	0.						

Include as many cards as needed. This input ends at the next keyword ("*") card.

Card 2	1	2	3	4	5	6	7	8
Variable	ELSID							
Type	I							
Default	none							

VARIABLE	DESCRIPTION
OUTLV	Determines if LS-DYNA creates the output file: EQ.0: Does not generate the output file. EQ.1: Generates the output file.
DTOUT	Time interval to print the output. If DTOUT equals 0.0, LS-DYNA uses the EM time step.
ELSID	Solid elements set ID

Remarks:

1. **File name.** The file name for this database is em_elout.dat.

*EM_DATABASE_FIELDLINE

Purpose: The EM solver uses a BEM method to calculate the EM fields between conductors. With this method, the magnetic field in the air or vacuum between conductors is therefore not explicitly computed. However, in some cases, it may be interesting to visualize some magnetic field lines for a better analysis. This keyword allows the output of field line data. It has no influence on the results of the EM solve.

Output Options Card.

Card 1	1	2	3	4	5	6	7	8
Variable	FLID	PSID	DTOUT	NPOINT				
Type	I	I	F	I				
Default	none	none	0.	100				

Remaining cards are optional.[†]

Card 2	1	2	3	4	5	6	7	8
Variable	INTEG	H	HMIN	HMAX	TOLABS	TOLREL		
Type	I	F	F	F	F	F		
Default	2	0.	0.	1E10	1E-3	1E-5		

Card 3	1	2	3	4	5	6	7	8
Variable	BTYPE							
Type	I							
Default	2							

VARIABLE	DESCRIPTION
FLID	Field line set ID
PSID	Point Set ID associated to the field line set (See *EM_POINT_SET). The coordinates given by the different points will be the starting points of the field lines.
DTOUT	Time interval to print the output. If DTOUT is equal to 0.0, then the EM time step will be used.
NPOINT	Number of points per field line. The points are regularly spaced.
INTEG	Type of numerical integrator used to compute the field lines :
	EQ.1: RK4, Runge Kutta 4. See Remark 2.
	EQ.2: DOP853, Dormand Prince 8(5,3). See Remark 2.
H	Value of the step size. In case of an integrator with adaptive step size, it is the initial value of the step size.
HMIN	Minimal step size value. Only used in the case of an integrator with adaptive step size.
HMAX	Maximal step size value. Only used in the case of an integrator with adaptive step size.
TOLABS	Absolute tolerance of the integrator. Only used in the case of an integrator with adaptive step size.
TOLREL	Relative tolerance of the integrator. Only used in the case of an integrator with adaptive step size.
BTYPE	Method to compute the magnetic field :
	EQ.1: Direct method (every contribution is computed by the Biot Savart Law and summed up : very slow).
	EQ.2: Multipole method (approximation of the direct method using the multipole expansion).
	EQ.3: Multicenter method (approximation of the direct method using a weighted subset of points only in order to compute the magnetic field).

Remarks:

    1.   **File Names.** The file name for this database is em_fieldLine_*XX_YYY*.dat where *XX* is the field line ID and *YYY* is the point set ID defined in *EM_POINT_SET.

    2.   **Integrators.** The Runge Kutta 4 integrator is an explicit iterative method for solving ODEs. It is a fourth order method with a constant step size. The Dormand Prince 8(5,3) integrator is an explicit iterative method for solving IDEs. Particularly, this integrator is an embedded Runge Kutta integrator of order 8 with an adaptive step size. This integrator allows a step size control which is done though an error estimate at each step. The Dormand Prince 8(5,3) is a Dormand Prince 8(6) for which the 6th order error estimator has been replaced by a 5th order estimator with 3rd order correction in order to make the integrator more robust.

*EM_DATABASE_GLOBALENERGY

Purpose: Enable the output of global EM energies.

Output Options Card.

Card 1	1	2	3	4	5	6	7	8
Variable	OUTLV	DTOUT						
Type	I	F						
Default	0	0.						

VARIABLE	DESCRIPTION
OUTLV	Determines if the output file should be dumped.
	EQ.0: No output file is generated.
	EQ.1: The output file is generated.
DTOUT	Time interval to print the output. If DTOUT is equal to 0.0, then the EM timestep will be used.

Remarks:

1. **Database Name.** The file name for this database is em_globEnergy.dat.

2. **Output Data.** The output file includes the global EM energies of the mesh, the air, and the source circuit. It also includes the global kinetic energy and the global plastic work energy.

*EM_DATABASE_NODOUT

Purpose: This keyword enables the output of EM data on nodes.

Output Options Card.

Card 1	1	2	3	4	5	6	7	8
Variable	OUTLV	DTOUT						
Type	I	F						
Default	0	0.						

Include as many cards as needed. This input ends at the next keyword ("*") card.

Card 2	1	2	3	4	5	6	7	8
Variable	NSID							
Type	I							
Default	none							

VARIABLE	DESCRIPTION
OUTLV	Determines if the output file should be dumped.
	EQ.0: No output file is generated.
	EQ.1: The output file is generated.
DTOUT	Time interval to print the output. If DTOUT is equal to 0.0, then the EM timestep will be used.
NSID	Node Set ID.

Remarks:

1. The file name for this database is em_nodout.dat.

*EM_DATABASE_PARTDATA

Purpose: This keyword enables the output of EM data for every part defined. .

Output Options Card.

Card 1	1	2	3	4	5	6	7	8
Variable	OUTLV	DTOUT						
Type	I	F						
Default	0	0.						

VARIABLE	DESCRIPTION
OUTLV	Determines if the output file should be dumped.
	EQ.0: No output file is generated.
	EQ.1: The output file is generated.
DTOUT	Time interval to print the output. If DTOUT is equal to 0.0, then the EM timestep will be used.

Remarks:

1. The file name for this database is em_partData_*XXX*.dat with *XXX* the part ID.

2. Outputs the part EM energies of the part as well as the Lorentz force. Also outputs the part kinetic energy and the part plastic work energy.

*EM_DATABASE_POINTOUT

Purpose: Enable the output of EM data on point sets.

Output Options Card.

Card 1	1	2	3	4	5	6	7	8
Variable	OUTLV	DTOUT						
Type	I	F						
Default	0	0.						

Include as many cards as needed. This input ends at the next keyword ("*") card.

Card 2	1	2	3	4	5	6	7	8
Variable	PTSID							
Type	I							
Default	none							

VARIABLE	DESCRIPTION
OUTLV	Determines if LS-DYNA creates the output file:
	EQ.0: Do not generate the output file.
	EQ.1: Generate the output file.
DTOUT	Time interval to print the output. If DTOUT equals 0.0, LS-DYNA uses the ICFD time step.
PTSID	Point set ID (See *EM_POINT_SET card).

Remarks:

1. **File name.** The file name for this database is em_pointout.dat.

***EM_DATABASE_ROGO**

Purpose: This keyword enables the output of EM data for every circuit defined. .

Output Options Card.

Card 1	1	2	3	4	5	6	7	8
Variable	OUTLV	DTOUT						
Type	I	F						
Default	1	0.						

VARIABLE	DESCRIPTION
OUTLV	Determines if the output file should be dumped.
	EQ.0: No output file is generated.
	EQ.1: The output file is generated.
DTOUT	Time interval to print the output. If DTOUT is equal to 0.0, then the EM timestep will be used.

Remarks:

1. The file name for this database is em_rogoCoil_*XXX*.dat where *XXX* is the rogo Coil ID.

*EM_DATABASE_TIMESTEP

Purpose: This keyword enables the output of EM data regarding the EM timestep.

Output options card.

Card 1	1	2	3	4	5	6	7	8
Variable	OUTLV							
Type	I							
Default	0							

VARIABLE	DESCRIPTION
OUTLV	Determines if the output file should be dumped.
	EQ.0: No output file is generated.
	EQ.1: The output file is generated.

Remarks:

1. The file name for this database is em_timestep.dat.

2. Outputs the run's EM tim estep versus the time step calculated using the EM CFL condition as criteria (autotimestep). This can be useful in cases with big deformations and/or material property changes and a fixed time step is being used in case that time step becomes to big compared to the stability time step.

***EM_EP_CELLMODEL_DEFINE_FUNCTION**

Purpose: Define a user-defined ionic cell model for Electro-Physiology.

Card 1	1	2	3	4	5	6	7	8
Variable	MID	NSTATE	FSWITCH					
Type	I	I	I					
Default	none	none	none					

Card 2	1	2	3	4	5	6	7	8
Variable	DVDT	DU1DT	DU2DT	DU3DT	DU4DT	DU5DT	DU6DT	DU7DT
Type	I	I	I	I	I	I	I	I
Default	none	none	none	none	none	none	none	none

Card 3	1	2	3	4	5	6	7	8
Variable	V0	U1	U2	U3	U4	U5	U6	U7
Type	I	I	I	I	I	I	I	I
Default	none	none	none	none	none	none	none	none

VARIABLE	DESCRIPTION
MID	Material ID defined in the *MAT section. If a negative value is entered, the cell model is defined on a node set instead of a part, and -MID is the node set where the cell model is defined.
FSWITCH	Flag for the ODE definition (see Remark 1):

                                 EQ.0: Functions

                                 EQ.1: Derivatives

VARIABLE	DESCRIPTION
NSTATE	Number of state variables $u_1, u_2, \ldots, u_n$. The maximum value is 7 (see Cards 2 and 3).
DVDT	Function ID (see *DEFINE_FUNCTION) for evolution of V (function g in the equations in Remark 1).
DUiDT	Function ID (see *DEFINE_FUNCTION) for evolution of u_i (function f_i in the equations in Remark 1)
V0	Function ID (see *DEFINE_FUNCTION) for initial value of $V(x, y, z)$
Ui	Function ID (see *DEFINE_FUNCTION) for initial value of $u_i(x, y, z)$

Remarks:

1. **Model.** This keyword enables specifying a user-defined cell model through defined functions (see *DEFINE_FUNCTION). This model traces the evolution of the transmembrane potential, V, and n state variables: $u_1, u_2, \ldots u_n$. Their temporal evolution depends upon FSWITCH.

   a) If FSWITCH = 0:

   $$V(t) = g\big(t, dt, V(t-1), u_1(t-1), u_2(t-1), \ldots, u_n(t-1)\big)$$
   $$u_1(t) = f_1\big(t, dt, V(t-1), u_1(t-1), u_2(t-1), \ldots, u_n(t-1)\big)$$
   $$u_2(t) = f_2\big(t, dt, V(t-1), u_1(t-1), u_2(t-1), \ldots, u_n(t-1)\big)$$
   $$\vdots$$
   $$u_n(t) = f_n\big(t, dt, V(t-1), u_1(t-1), u_2(t-1), \ldots, u_n(t-1)\big)$$

   b) If FSWITCH = 1:

   $$\frac{\partial V(t)}{\partial t} = g\big(t, dt, V(t-1), u_1(t-1), u_2(t-1), \ldots, u_n(t-1)\big)$$
   $$\frac{\partial u_1(t)}{\partial t} = f_1\big(t, dt, V(t-1), u_1(t-1), u_2(t-1), \ldots, u_n(t-1)\big)$$
   $$\frac{\partial u_2(t)}{\partial t} = f_2\big(t, dt, V(t-1), u_1(t-1), u_2(t-1), \ldots, u_n(t-1)\big)$$
   $$\vdots$$
   $$\frac{\partial u_n(t)}{\partial t} = f_3\big(t, dt, V(t-1), u_1(t-1), u_2(t-1), \ldots, u_n(t-1)\big)$$

2. **Benchmarks.** You can use this model to perform the electrophysiology benchmarks presented in Pathmanathan and Gray [2014].

References:

[1]   Pathmanathan, P. and R.A. Gray, "Verification of computational models of cardiac electro-physiology," Int J Numer Method Biomed Eng, vol. 30, No. 5, pp. 524-544, (2014).

*EM_EP_CELLMODEL_FENTONKARMA

Purpose: Define a Fenton-Karma ionic cell model for Electro-Physiology.

Card 1	1	2	3	4	5	6	7	8
Variable	MID							
Type	I							
Default	none							

Card 2	1	2	3	4	5	6	7	8
Variable	TAUD	TAUR	TAUSI	TAU0	TAUVP	TAUVM	TAUWP	TAUWM
Type	F	F	F	F	F	F	F	F
Default	none	none	none	none	none	none	none	none

Card 3	1	2	3	4	5	6	7	8
Variable	UC	UCSI	K					
Type	F	F	F					
Default	none	none	none					

Card 4	1	2	3	4	5	6	7	8
Variable	U0	V0	W0					
Type	F	F	F					
Default	none	none	none					

VARIABLE	DESCRIPTION
MID	Material ID defined in *MAT. If a negative value is entered, the cell model is defined on a node set instead of a part, and -MID is the node set where the cell model is defined.
TAUD	Time constant τ_d described in Equation 5
TAUR	Time constant τ_r described in Equation 6
TAUSI	Time constant τ_{si} described in Equation 7
TAU0	Time constant τ_0 described in Equation 6
TAUVP	Time constant τ_{vp} described in Equation 3
TAUVM	Time constant τ_{vm} described in Equation 3
TAUWP	Time constant τ_{wp} described in Equation 4
TAUWM	Time constant τ_{wm} described in Equation 4
UC	Threshold potential, u_c for activation of J_{fi} (the fast inward current) in Equations 3, 4, 5, and 6
UCSI	Threshold potential u_c^{si} for activation of J_{si} (the slow inward current) in Equation 7
K	Constant k in Equation 7
U0/V0/W0	Initial values of u, v, and w, respectively

Remarks:

The Fenton-Karma model is a simplified ionic model with three membrane currents that approximates well the restitution properties and spiral wave behavior of more complex ionic models of cardiac action potential (Beeler-Reuter and others). It was introduced in [1].

The total current flowing through the membrane is given by:

$$I_{ion} = -C_m \frac{\partial V}{\partial t} = -J_{fi} \tag{1}$$

where V is the transmembrane potential, C_m is the specific capacitance of the cell membrane, and J_{fi} is the fast inward current.

The model depends on three state variables, u, v, and w, and three membrane currents, J_{fi}, J_{so} (slow outward current), and J_{si} (slow inward current), through the following equations:

$$\frac{du}{dt} = -J_{fi} - J_{so} - J_{si} \tag{2}$$

$$\frac{dv}{dt} = \frac{\Theta(u_c - u)(1 - v)}{\tau_{vm}} - \frac{\Theta(u - u_c)v}{\tau_{vp}} \tag{3}$$

$$\frac{dw}{dt} = \frac{\Theta(u_c - u)(1 - w)}{\tau_{wm}} - \frac{\Theta(u - u_c)w}{\tau_{wp}} \tag{4}$$

$$J_{fi} = -\frac{\Theta(u_c - u)(1 - u)(u - u_c)}{\tau_d} \tag{5}$$

$$J_{so} = \frac{u\,\Theta(u_c - u)}{\tau_o} + \frac{u\,\Theta(u - u_c)}{\tau_r} \tag{6}$$

$$J_{si} = -\frac{w(1 + \tanh[k(u - u_c^{si})])}{2\tau_{si}} \tag{7}$$

In the above Θ is the Heaviside step function.

References:

[1]   Fenton, F. & A. Karma, "Vortex dynamics in three-dimensional continuous myocardium with fiber rotation. Filament instability and fibrillations," *Chaos, Solitons, and Fractals*, Vol. 8, No. 1, pp. 661-686, (1998).

[2]   https://www.ibiblio.org/e-notes/html5/fk.html

*EM_EP_CELLMODEL_FITZHUGHNAGUMO

Purpose: Define a Fitzhugh-Nagumo ionic cell model for Electro-Physiology.

Card 1	1	2	3	4	5	6	7	8
Variable	MID							
Type	I							
Default	none							

Card 2	1	2	3	4	5	6	7	8
Variable	ALPHA	BETA	GAMMA	C	MU1	MU2		
Type	F	F	F	F	F	F		
Default	none	none	none	none	none	none		

Card 3	1	2	3	4	5	6	7	8
Variable	V	R						
Type	F	F						
Default	none	none						

VARIABLE	DESCRIPTION
MID	Material ID defined in *MAT. If a negative value is entered, the cell model is defined on a node set instead of a part, and -MID is the node set where the cell model is defined.
ALPHA	Excitation constant α described in Equation 1
BETA	Excitation constant β described in Equation 2

VARIABLE	DESCRIPTION
GAMMA	Excitation constant γ described in Equation 2
C	Excitation constant c described in Equation 1
MU1	Excitation constant μ_1 described in Equation 2
MU2	Excitation constant μ_2 described in Equation 2
V	Initial value of V
R	Initial value of r

Remarks:

In the Fitzhugh-Nagumo model, the excitation is defined by a cubic polynomial along with one recovery variable, r. The transmembrane current, I_{ion}, is given by:

$$I_{\text{ion}} = -C_m \frac{\partial V}{\partial t} = -cV\,(V - \alpha)(V - 1) - rV \qquad (1)$$

Here V is the transmembrane potential, C_m is the specific capacitance of the cell membrane, and c and α are excitation constants.

The recovery variable r evolves according to:

$$\frac{dr}{dt} = (\gamma + \frac{r\mu_1}{\mu_2 + V})(-r - cV(V - \beta - 1)) \qquad (2)$$

where β, γ, μ_1 and μ_2 are excitation constants.

References:

[1]   Aliev, R.R. and Panfilov, A.V., "A simple two-variable model of cardiac excitation," *Chaos, Solitons, and Fractals*, Vol 7, No 3, pp 293-301, (1996).

[2]   Pullan, A.J., Cheng, L.K., and Buist, M.L., Mathematically Modelling the Electrical Activity of the Heart, World Scientific Publishing Co. Pte. Ltd., Singapore, pp 132-133, (2005).

[3]   Baillargeon, B. et al., "The Living Heart Project: A robust and integrative simulator for human heart function," *European Journal of Mechanics - A/Solids*. Vol 48, pp 38-47, (2014).

*EM_EP_CELLMODEL_TENTUSSCHER

Purpose: Define a ten Tusscher ionic cell model for Electro-Physiology.

Card Summary:

Card 1. This card is required.

MID							

Card 2. This card is required.

R	T	F	CM	VC	VSR	VSS	PKNA

Card 3. This card is required.

KO	NAO	CAO					

Card 4. This card is required.

GK1	GKR	GKS	GNA	GBNA	GCAL	GBCA	GTO

Card 5. This card is required.

GPCA	GPK						

Card 6. This card is required.

PNAK	KMK	KMNA	KNACA	KSAT	ALPHA	GAMMA	KMCA

Card 7. This card is required.

KMNAI	KPCA						

Card 8. This card is required.

K1	K2	K3	K4	EC	MAXSR	MINSR	

Card 9. This card is required.

VREL	VLEAK	VXFER	VMAXUP	KUP			

Card 10. This card is required.

BUFC	KBUFC	BUFSR	KBUFSF	BUFSS	KBUFSS		

Card 11. This card is required.

V	KI	NAI	CAI	CASS	CASR	RPRI	

Card 12. This card is required.

XR1	XR2	XS	M	H	J	D	F

Card 13. This card is required.

F2	FCASS	S	R				

Data Card Definitions:

Card 1	1	2	3	4	5	6	7	8
Variable	MID							
Type	I							
Default	none							

VARIABLE	DESCRIPTION
MID	Material ID defined in *MAT section. If a negative value is entered, the cell model is defined on a node set instead of a part, and -MID is the node set where the cell model is defined.

Card 2	1	2	3	4	5	6	7	8
Variable	R	T	F	CM	VC	VSR	VSS	PKNA
Type	F	F	F	F	F	F	F	F
Default	none	none	none	none	none	none	none	none

VARIABLE	DESCRIPTION
R	Gas constant ($J \times K^{-1} \times Mol^{-1}$)

VARIABLE	DESCRIPTION
T	Temperature (K)
F	Faraday constant (C × mmol^{-1})
CM	Cell capacitance for unit surface area (μF × Cm^{-2})
VC	Cytoplasmic volume (μm^3)
VSR	Sarcoplasmic reticulum volume (μm^3)
VSS	Subspace volume (μm^3)
PKNA	Relative I_{Ks} permeability to Na$^+$

Card 3	1	2	3	4	5	6	7	8
Variable	K0	NAO	CAO					
Type	F	F	F					
Default	none	none	none					

VARIABLE	DESCRIPTION
KO	Extracellular K$^+$ concentration (mM)
NAO	Extracellular Na$^+$ concentration (mM)
CAO	Extracellular Ca^{2+} concentration (mM)

Card 4	1	2	3	4	5	6	7	8
Variable	GK1	GKR	GKS	GNA	GBNA	GCAL	GBCA	GTO
Type	F	F	F	F	F	F	F	F
Default	none	none	none	none	none	none	none	none

Card 5	1	2	3	4	5	6	7	8
Variable	GPCA	GPK						
Type	F	F						
Default	none	none						

VARIABLE	DESCRIPTION
GK1, GKR, GKS, GNA, GBNA, GCAL, GB-CA, GTO, GPCA, GPK	Maximal I_{K1}, I_{Kr}, I_{Ks}, I_{Na}, I_{bNa}, I_{CaL}, I_{bCa}, I_{to}, I_{pCa}, and I_{pK} conductance, respectively (units: nS × pF^{-1})

Card 6	1	2	3	4	5	6	7	8
Variable	PNAK	KMK	KMNA	KNACA	KSAT	ALPHA	GAMMA	KMCA
Type	F	F	F	F	F	F	F	F
Default	none	none	none	none	none	none	none	none

Card 7	1	2	3	4	5	6	7	8
Variable	KMNAI	KPCA						
Type	F	F						
Default	none	none						

VARIABLE	DESCRIPTION
PNAK	P_{NaK}, parameter for calculating the Na$^+$/K$^+$ pump current (units: pA × pF^{-1}). See Reference [1].

VARIABLE	DESCRIPTION
KMK, KMNA	K_{mK} and K_{mNa}, parameters for calculating the Na$^+$/K$^+$ pump current (units: millimolar). See Reference [1].
KNACA, KSAT, AL-PHA, GAM-MA, KMNAI	k_{NaCa}, k_{sat}, α, γ, and K_{mNai}, parameters for calculating the Na$^+$/Ca^{2+} exchanger current (units: millimolar). See Reference [1].
KPCA	K_{pCa}, parameter for calculating Ca^{2+} pump current (units: millimolar). See Reference [1].

Card 8	1	2	3	4	5	6	7	8
Variable	K1	K2	K3	K4	EC	MAXSR	MINSR	
Type	F	F	F	F	F	F	F	
Default	none	none	none	none	none	none	none	
Ref	2	2	2	2	2	2	2	

VARIABLE	DESCRIPTION
K1	R to O and RI to I I_{rel} transition rate (mM^{-2} × ms^{-1})
K2	O to I and R to RI I_{rel} transition rate (mM^{-1} × ms^{-1})
K3	O to R and I to RI I_{rel} transition rate (ms^{-1})
K4	I to O and RI to I I_{rel} transition rate (ms^{-1})
EC	Ca$_{SR}$ half-saturation constant of k_{casr} (mM)
MAXSR/MINSR	Maximum and minimum values of k_{casr}

Card 9	1	2	3	4	5	6	7	8
Variable	VREL	VLEAK	VXFER	VMAXUP	KUP			
Type	F	F	F	F	F			
Default	none	none	none	none	none			

VARIABLE	DESCRIPTION
VREL, VLEAK, VXFER, VMAXUP	Maximal I_{rel}, I_{leak}, I_{xfer}, and I_{up} conductance (mM × ms^{-1}), respectively. See Reference [2].
KUP	Half-saturation constant of I_{up} (mM). See Reference [2].

Card 10	1	2	3	4	5	6	7	8
Variable	BUFC	KBUFC	BUFSR	KBUFSF	BUFSS	KBUFSS		
Type	F	F	F	F	F	F		
Default	none	none	none	none	none	none		
Ref	2	2	2	2	2	2		

VARIABLE	DESCRIPTION
BUFC	Total cytoplasmic buffer concentration (mM)
KBUFC	Ca_i half-saturation constant for cytoplasmic buffer (mM)
BUFSR	Total sarcoplasmic buffer concentration (mM)
KBUFSR	Ca_{SR} half-saturation constant for sarcoplasmic buffer (mM)
BUFSS	Total subspace buffer concentration (mM)
KBUFSS	Ca_{SS} half-saturation constant for subspace buffer (mM)

Card 11	1	2	3	4	5	6	7	8
Variable	V	KI	NAI	CAI	CASS	CASR	RPRI	
Type	F	F	F	F	F	F	F	
Default	none	none	none	none	none	none	none	
Ref	2	1	1	2	2	2	2	

VARIABLE	DESCRIPTION
V	Initial value of transmembrane potential (mV)
KI	Initial value of K_i, used in potassium dynamics (mM)
NAI	Initial value of Na_i, used in sodium dynamics (mM)
CAI	Initial value of Ca_i. used in calcium dynamics (mM)
CASS	Initial value of Ca_{SS}, used in calcium dynamics (mM)
CASR	Initial value of Ca_{SR}, used in calcium dynamics (mM)
RPRI	Initial value of R′, used in calcium dynamics

Card 12	1	2	3	4	5	6	7	8
Variable	XR1	XR2	XS	M	H	J	D	F
Type	F	F	F	F	F	F	F	F
Default	none	none	none	none	none	none	none	none
Ref	1	1	1	1	1	1	2	2

VARIABLE	DESCRIPTION
XR1	Initial value of x_{r1}, used to compute the rapid time dependent K^+ current

VARIABLE	DESCRIPTION
XR2	Initial value of x_{r2}, used to compute the rapid time dependent K⁺ current
XS	Initial value of x_s, used to compute slow time dependent K⁺ current
M	Initial value of m, used to compute the fast Na⁺ current
H	Initial value of h, used to compute the fast Na⁺ current
J	Initial value of j, used to compute the fast Na⁺ current
D	Initial value of d, used to compute the L-type Ca²⁺ current
F	Initial value of f, used to compute the L-type Ca²⁺ current

Card 13	1	2	3	4	5	6	7	8
Variable	F2	FCASS	S	R				
Type	F	F	F	F				
Default	none	none	none	none				
Ref	2	2	1	1				

VARIABLE	DESCRIPTION
F2	Initial value of f_2, used to compute the L-type Ca²⁺ current
FCASS	Initial value of f_{cass}, used to compute the L-type Ca²⁺ current
S	Initial value of s, used to compute the transient outward current
R	Initial value of r, used to compute the transient outward current

Remarks:

This is a model of the action potential of human ventricular cells that, while including a high level of electrophysiological detail, is computationally cost-effective enough to be applied in large-scale spatial simulations for the study of reentrant arrhythmias. Please see the references for details. This model is based on [2].

References:

[1]   ten Tusscher, K.H.W.J., D. Noble, P.J. Noble, and A.V. Panfilov, "A model for human ventricular tissue," Am J Physiol Heart Circ Physiol, vol 286, no 4, pp H1573-H1589, (2004).

[2]   ten Tusscher, K.H.W.J. and A.V. Panfilov, "Alternans and spiral breakup in human ventricular tissue model," Am J Physiol Heart Circ Physiol, vol 291, no 3, pp H1088-H1100, (2006).

*EM_EP_CELLMODEL_TOMEK

Purpose: Define a ToR-ORd model for cardiac electrophysiology [1].

> **WARNING:** As of version R15, this keyword is deprecated. Instead, use *EM_EP_CELLMODEL_TOR_ORD which is an updated version of this keyword.

Card 1	1	2	3	4	5	6	7	8
Variable	MID	PHIEND	PHIMYO					
Type	I	F	F					
Default	none	0.0	0.0					

VARIABLE	DESCRIPTION
MID	Material ID: refers to MID in the *PART card. If a negative value is entered, the cell model is defined on a node set instead of a part, and -MID is the node set where the cell model is defined.
PHIEND	Value between 0.0 and 1.0 giving the ratio of the cardiac tissue to be considered endocardial in the ToR-Ord cell model.
PHIMYO	Value between 0.0 and 1.0 giving the ratio of the cardiac tissue to be considered myocardial in the ToR-Ord cell model.

References:

[1]   Tomek J., Bueno-Orovio A., Passini E., Zhou X., Minchole A., Britton O., Bartolucci C., Severi S., Shrier A., Virag L., Varro A., and Rodriguez B., "Development, calibration, and validation of a novel human ventricular myocyte model in health, disease, and drug block," Elife (2019).

*EM_EP_CELLMODEL_TOR_ORD

Purpose: Define a ToR-ORd model for cardiac electrophysiology [1].

> **NOTE:** This keyword is an updated version of *EM_EP_CELLMODEL_-
> TOMEK. For versions R15 and later, *EM_EP_CELLMODEL_-
> TOR_ORD is the preferred keyword, and *EM_EP_CELLMOD-
> EL_TOMEK is deprecated.

Card 1	1	2	3	4	5	6	7	8
Variable	MID	LDID	PHIEND	PHIMYO				
Type	I	I	F	F				
Default	none	none	0.0	0.0				

VARIABLE	DESCRIPTION
MID	Material ID. It refers to MID in the *PART card. If a negative value is entered, the cell model is defined on a node set instead of a part, and -MID is the node set where the cell model is defined.
LDID	ID of the *EM_EP_LAPLACE_DIRICHLET solution to be used for transmural depth definition
PHIEND	Value between 0.0 and 1.0 giving the ratio of the cardiac tissue to be considered endocardial in the ToR-Ord cell model.
PHIMYO	Value between 0.0 and 1.0 giving the ratio of the cardiac tissue to be considered myocardial version in the ToR-Ord cell model.

References:

[1] Tomek J., Bueno-Orovio A., Passini E., Zhou X., Minchole A., Britton O., Bartolucci C., Severi S., Shrier A., Virag L., Varro A., and Rodriguez B., "Development, calibration, and validation of a novel human ventricular myocyte model in health, disease, and drug block," Elife (2019).

*EM_EP_CELLMODEL_USERMAT

Purpose: Specify a user material for an ionic cell model to be used in electrophysiology simulations.

Card 1	1	2	3	4	5	6	7	8
Variable	MID							
Type	I							

VARIABLE	DESCRIPTION
MID	Material ID. A unique number must be specified (see *PART). If a negative value is entered, the cell model is defined on a node set instead of a part, and -MID is the node set where the cell model is defined.

*EM_EP_CREATEFIBERORIENTATION

Purpose: Define fiber orientation by solving a Laplace-Dirichlet system defined by *EM_-EP_LAPLACE_DIRICHLET. This feature is based on [1].

Card 1	1	2	3	4	5	6	7	8
Variable	PSID	LDID1	LDID2	ALPHA	BETA	IEXPORT	IPRERUN	
Type	I	I	I	F	F	I	I	
Default	none	none	none	0.0	0.0	0	0	

VARIABLE	DESCRIPTION
PSID	Part set ID of the part set on which the system is solved
LDID1	ID of the Laplace system that is solved in the transmural direction
LDID2	ID of the Laplace system that is solved in the apicobasal direction
ALPHA	Helical angle with respect to the counterclockwise circumferential direction in the heart when looking from the base towards the apex.

        LT.0: |ALPHA| is the ID for the *DEFINE_FUNCTION giving the helical angle. See Remark 1 for available arguments.

BETA	Angle with respect to the outward transmural axis of the heart.

        LT.0: |BETA| is the ID for the *DEFINE_FUNCTION giving the angle. See Remark 1 for available arguments.

IEXPORT	Selects whether result files (ELEMENT_SOLID_ORTHO.k and vtk files) are exported:

        EQ.0: Not exported

        EQ.1: Exported

IPRERUN	Select whether the run is stopped after creating fibers:

        EQ.0: Do not stop after fiber creation

        EQ.1: Stop after fiber creation

Remarks:

1.   ***DEFINE_FUNCTION Arguments.** The arguments for the function defined with
     *DEFINE_FUNCTION may include the following: f(x_ele, y_ele, z_ele, phi_len,
     phi_thi). Here phi_len and phi_thi are the potentials corresponding to the poten-
     tials solved in LDID1 and LDID2, respectively.

References:

[1]   Bayer, J.D., Blake, R. C., Plank, G., and Trayanova, N. A., "A novel rule-based algorithm for assign-
      ing myocardial fiber orientation to computational heart models," Annals of biomedical engineering,
      40(10), 2243-2254 (2012).

*EM_EP_ECG

Purpose: Compute pseudo-ECGs on a set of virtual points. LS-DYNA exports a file named em_ECG_{ECGID}.dat.

Card 1	1	2	3	4	5	6	7	8
Variable	ECGID	PSID						
Type	I	I						
Default	none	none						

VARIABLE	DESCRIPTION
ECGID	ID of the ECG computation
PSID	Point set ID containing the list of virtual points on which the pseudo-ECGs are computed

*EM_EP_EIKONAL

Purpose: Set up the eikonal (EMSOL = 14) or reaction eikonal, RE, (EMSOL = 15) models.

Card 1	1	2	3	4	5	6	7	8
Variable	EIKID	EIKPST	EIKSNS	EIKSDF				
Type	I	I	I	I				
Default	none	none	none	0				

RE Card. Additional parameters for the RE model (EMSOL = 15)

Card 2	1	2	3	4	5	6	7	8
Variable	FTYPE	FT	FA					
Type	I	F	F					
Default	none	none	none					

VARIABLE	DESCRIPTION

EIKID   ID of the eikonal solver

EIKPST   Part set ID on which the eikonal solve is performed

EIKSNS   Node set ID where the seed (meaning initial activation time values) is set

EIKSDF   *DEFINE_FUNCTION ID for defining the seed value. Accepted arguments by the *DEFINE_FUNCTION are the node coordinates using the names "x_node, y_node, z_node." If no *DEFINE_-FUNCTION is used (EIKSDF = 0), the activation time is set to 0.0 on EIKSNS.

FTYPE   Type of foot current:

      EQ.1: Neic model. FA gives the foot current between the activation time and the activation time plus FT.

VARIABLE	DESCRIPTION
FT	Duration of the foot current
FA	Amplitude of the foot current

References:

[1]   A. Neic et al., "Efficient computation of electrograms and ECGs in human whole heart simulations using a reaction-eikonal model," Journal of Computational Physics, 346 (2017), 191–211.

*EM_EP_ISOCH

Purpose: Compute isochrones of activation/repolarization of a cardiac electrophysiology wave of one or several beats.

Card 1	1	2	3	4	5	6	7	8
Variable	ISOCHID	IDEPOL	DPLTHR	IREPOL	RPLTHR	CYCLEMIN	APDMIN	
Type	I	I	F	I	F	F	F	
Default	none	0	none	0	none	0.0	0.0	

VARIABLE	DESCRIPTION
ISOCHID	ID of the isochrone

IDEPOL	Flag to activate the computation of depolarization:
	    EQ.0: Off
	    EQ.1: On

DPLTHR	Amplitude threshold used for measuring depolarization

IREPOL	Flag to activate the computation of repolarization times:
	    EQ.0: Off
	    EQ.1: On

RPLTHR	Amplitude threshold used for measuring repolarization
CYCLEMIN	Minimum time between two consecutive depolarizations (used in the EP eikonal model with time stepping)
APDMIN	Minimum time between depolarization and repolarization (used in the EP eikonal model with time stepping)

*EM_EP_LAPLACE_DIRICHLET

Purpose: Define the boundary conditions of the Laplace-Dirichlet system to be solved to define fiber orientation, based on [1]. The system is solved by using *EM_EP_CREATE-FIBERORIENTATION. This keyword was formerly called *EM_EP_FIBERINITIAL in versions R14 and earlier.

Include as many of this card as needed. The next keyword ("*") card terminates this input.

Card 1	1	2	3	4	5	6	7	8
Variable	LDID	PID	STYPE	SID1	SID0			
Type	I	I	I	I	I			
Default	none	none	none	none	none			

VARIABLE	DESCRIPTION
LDID	ID of the Laplace system to solve (define a new ID with each new card)
PID	Part ID on which the system is solved
STYPE	Set type for the boundary condition: EQ.1: Segment set EQ.2: Node set
SID1	Set on which a potential of value 1 is prescribed
SID0	Set on which a potential of value 0 is prescribed

References:

[1]   Bayer, J.D., Blake, R. C., Plank, G., and Trayanova, N. A., "A novel rule-based algorithm for assigning myocardial fiber orientation to computational heart models," Annals of biomedical engineering, 40(10), 2243-2254 (2012).

*EM_EP_PURKINJE_NETWORK

Purpose: Define a Purkinje network that consists of conductive beams and lies on a given surface, based on Costabal et al [2016].

Card 1	1	2	3	4	5	6	7	8
Variable	PURKID	BUILDNET	SSID	MID	POINTSTX	POINTSTY	POINTSTZ	EDGELEN
Type	I	I	I	I	F	F	F	F

Card 2	1	2	3	4	5	6	7	8
Variable	NGEN	NBRINIT	NSPLIT	INODEID	IEDGEID			
Type	I	I	I	I	I			

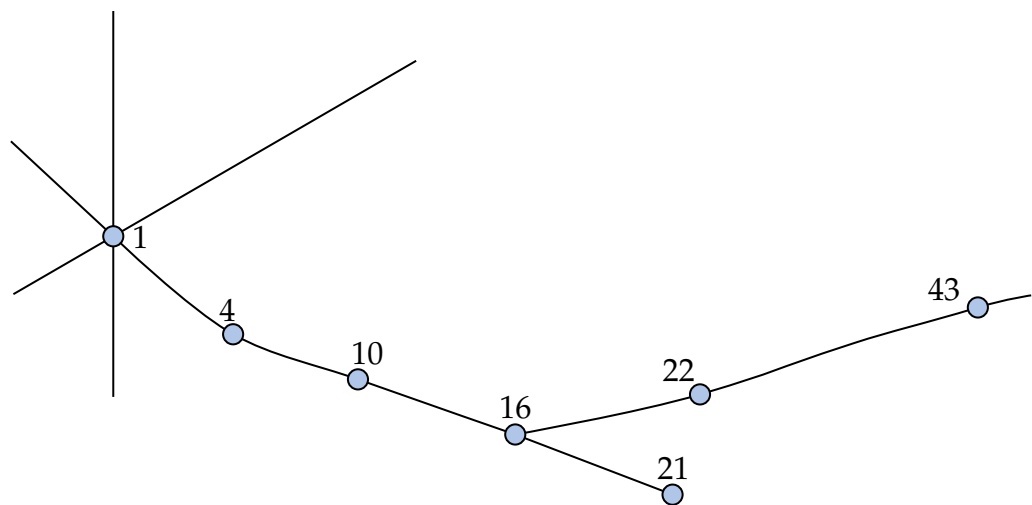| VARIABLE	DESCRIPTION
PURKID	ID for the Purkinje network

BUILDNET	Flag to create Purkinje network:
	    EQ.0: Purkinje network not created.
	    EQ.1: New Purkinje network created.

SSID	Segment set on which the Purkinje network is lying
MID	Material ID defined in the *MAT section.
POINTSTX	X coordinate of the tree origin
POINTSTY	Y coordinate of the tree origin
POINTSTZ	Z coordinate of the tree origin
EDGELEN	Edge length
NGEN	Number of generations of branches
NBRINIT	Number of branches attached to the tree origin

Figure 6-3. Example of part of a network. For this network, NSPLIT = 4.

VARIABLE	DESCRIPTION
NSPLIT	Number of nodes between two consecutive branchings as shown in Figure 6-3
INODEID	Initial node ID
IEDGEID	Initial edge ID. These edges are internally generated by LS-DYNA.

References:

Costabal, F.S., D. E. Hurtado, and E. Kuhl, "Generating Purkinje networks in the human heart," Journal of Biomechanics, vol. 49, issue 12, pp. 2455–2465, (2016).

*EM_EP_TENTUSSCHER_STIMULUS

Purpose: Define a stimulation pattern of a Tentusscher cell model (requires the use of *EM_EP_CELLMODEL_TENTUSSCHER).

Card 1	1	2	3	4	5	6	7	8
Variable	STIMID	SETTYPE	SETID					
Type	I	I	I					

Card 2	1	2	3	4	5	6	7	8
Variable	STIMSTRT	STIMT	STIMDUR	STIMAMP				
Type	F	F	F	F				

VARIABLE	DESCRIPTION
STIMID	ID of the stimulation
SETTYPE	Set type:
	EQ.1: Segment set
	EQ.2: Node set
SETID	Node set or segment set ID to be stimulated
STIMSTRT	Starting time of the stimulation
STIMT	Stimulation period
STIMDUR	Stimulation duration
STIMAMP	Stimulation amplitude (picoA/picoF)

*EM_EOS_BURGESS

Purpose: Define the parameters for a Burgess model giving the electrical conductivity as as a function of the temperature and the density, see:

T.J. Burgess, "Electrical resistivity model of metals", 4th International Conference on Megagauss Magnetic-Field Generation and Related Topics, Santa Fe, NM, USA, 1986

Card 1	1	2	3	4	5	6	7	8
Variable	EOSID	V0	GAMMA	THETA	LF	C1	C2	C3
Type	I	F	F	F	F	F	F	F
Default	none	none	none	none	none	none	none	none

Card 2	1	2	3	4	5	6	7	8
Variable	C4	K	EXPON	LGTUNIT	TIMUNIT	TEMUNI	ADJUST	
Type	F	F	I	F	F	I	I	
Default	none	none	none	none	none	none	none	

In the following, UUS stands for User Units System and BUS for Burgess Units

VARIABLE	DESCRIPTION
EOSID	ID of the EM_EOS (specified by an *EM_MAT card)
V0	Reference specific volume V_0 (UUS).
GAMMA0	Reference Gruneisen value γ_0.(no units).
THETA	Reference melting temperature $\theta_{m,0}$ in eV (BUS).
LF	Latent heat of fusion L_F in kJoule/mol (BUS).
C1	C1 constant (BUS)
C2	C2 constant (no units)

VARIABLE	DESCRIPTION
C3	C3 constant (no units)
C4	C4 constant (no units)
K	Parameter k (no units).
EXPON	Exponent in equations (2) (see remarks)
LGTUNIT	Length units for UUS (relative to meter, i.e. = 1.e-3 if UUS in mm).
TIMUNIT	Time units for UUS (relative to seconds).
TEMUNIT	Temperature units
	EQ.1: temperature in Celsius
	EQ.2: temperature in Kelvins
ADJUST	Conductivity modification
	EQ.0: (default) The conductivity is given by the Burgess formula.
	EQ.1: The conductivity is adjusted so that it is equal to the conductivity defined in *EM_MAT card σ_{mat} at room temperature:

$$\sigma(\theta) = \sigma_{\text{Burgess}}(\theta) \frac{\sigma_{\text{mat}}}{\sigma_{\text{Burgess}}(\theta_{\text{room}})}$$

Remarks:

1. The Burgess model gives the electrical resistivity vs temperature and density for the solid phase, liquid phase and vapor phase. At this time, only the solid and liquid phases are implemented. To check which elements are in the solid and in the liquid phase, a melting temperature is first computed by:

$$\theta_m = \theta_{m,0} \left(\frac{V}{V_0} \right)^{-\frac{1}{3}} e^{(2\gamma_0 - 1)(1 - \frac{V}{V_0})}$$

    a) If $T < \theta_m$: solid phase model applies.

       The solid phase electrical resistivity corresponds to the Meadon model:

$$\eta_S = (C_1 + C_2\theta^{C_3})f_c\left(\frac{V}{V_0}\right), \tag{1}$$

where θ is the temperature, V is the specific volume, and V_0 is the reference specific volume (zero pressure, solid phase). In (1), the volume dependence is given by:

$$f_c\left(\frac{V}{V_0}\right) = \begin{cases} \left(\frac{V}{V_0}\right)^{2\gamma-1} & \text{EXPON.EQ.} -1 & \text{(most materials)} \\ \left(\frac{V}{V_0}\right)^{2\gamma+1} & \text{EXPON.EQ.} +1 & \text{(tungsten)} \\ \left(\frac{V}{V_0}\right)^{2\gamma} & \text{EXPON.EQ.} 0 & \text{(stainless steel)} \end{cases} \tag{2}$$

with

$$\gamma = \gamma_0 - \left(\gamma_0 - \frac{1}{2}\right)\left(1 - \frac{V}{V_0}\right) \tag{3}$$

b) If $T > \theta_m$: liquid phase model:

$$\eta_L = (\eta_L)_{\theta_m}\left(\frac{\theta}{\theta_m}\right)^{C_4} \tag{4}$$

with

$$(\eta_L)_{\theta_m} = \Delta\eta(\eta_S)_{\theta_m}$$

where

$$\Delta\eta = \begin{cases} ke^{0.69L_F/\theta_m} & k > 0 \\ 1 + 0.0772(2 - \theta_m) & k = -1 & \text{(tungsten)} \\ 1 + 0.106(0.846 - \theta_m) & k = -2 & \text{(stainless steel SS-304)} \end{cases} \tag{5}$$

The following table reports some sets of parameters given by Burgess in his paper:

Parameter	Cu	Ag	Au	W	Al(2024)	SS(304)
V_0(cm³/gm)	0.112	0.0953	0.0518	0.0518	0.370	0.1265
γ_0	2.00	2.55	3.29	1.55	2.13	2.00
$\theta_{m,0}$ (BUS)	0.117	0.106	0.115	0.315	0.0804	0.156
L_F (BUS)	0.130	0.113	0.127	0.337	0.107	0.153
C_1 (BUS)	-4.12e-5	-3.37e-5	-4.95e-5	-9.73e-5	-5.35e-5	0

Parameter	Cu	Ag	Au	W	Al(2024)	SS(304)
C_2	0.113	0.131	0.170	0.465	0.233	0.330
C_3	1.145	1.191	1.178	1.226	1.210	0.4133
EXPON	-1	-1	-1	+1	-1	0
C_4	0.700	0.672	0.673	0.670	0.638	0.089
k	0.964	0.910	1.08	-1.	0.878	-2.

*EM_EOS_MEADON

Purpose: Define the parameters for a Meadon model, giving the electrical conductivity as a function of the temperature and the density; see:

T.J. Burgess, "Electrical resistivity model of metals", 4th International Conference on Megagauss Magnetic-Field Generation and Related Topics, Santa Fe, NM, USA, 1986

Card 1	1	2	3	4	5	6	7	8
Variable	EOSID	C1	C2	C3	TEMUNI	V0	GAMMA	EXPON
Type	I	F	F	F	I	F	F	I
Default	none	none	none	none	none	none	none	none

Card 2	1	2	3	4	5	6	7	8
Variable	LGTUNIT	TIMUNIT	ADJUST					
Type	F	F	I					
Default	none	none	none					

In the following, UUS stands for User Units System and BUS for Burgess Units.

VARIABLE	DESCRIPTION
EOSID	ID of the EM_EOS
C1	C1 constant (BUS)
C2	C2 constant (no units)
C3	C3 constant (no units)
TEMUNIT	Temperature units
	EQ.1: temperature in Celsius
	EQ.2: temperature in Kelvins

VARIABLE	DESCRIPTION
V0	Reference specific volume V0 (UUS).
GAMMA0	Reference Gruneisen value γ_0.(no units).
EXPON	Exponent in equations (7)
LGTUNIT	Length units for UUS (relative to meter, i.e. = 1.e-3 if UUS in mm).
TIMUNIT	Time units for UUS (relative to seconds).
ADJUST:	EQ.0: (default) the conductivity is given by the Burgess formula.
	EQ.1: The conductivity is adjusted so that it is equal to the conductivity defined in the *EM_MAT card σ_{mat} at room temperature:

$$\sigma(\theta) = \sigma_{Burgess}(\theta) \frac{\sigma_{mat}}{\sigma_{Burgess}(\theta_{room})}$$

Remarks:

1. The Meadon model is a simplified Burgess model with the solid phase equations only.

    The electrical resistivity is given by:

    $$\eta_S = \left(C_1 + C_2\theta^{C_3}\right)f_c\left(\frac{V}{V_0}\right) \tag{6}$$

    where θ is the temperature, V is the specific volume, and V_0 is the reference specific volume (zero pressure, solid phase).

    In (6), the volume dependence is given by:

    $$f_c\left(\frac{V}{V_0}\right) = \begin{cases} \left(\dfrac{V}{V_0}\right)^{2\gamma-1} & \text{EXPON.EQ.} -1 & \text{(most materials)} \\[2ex] \left(\dfrac{V}{V_0}\right)^{2\gamma+1} & \text{EXPON.EQ.} +1 & \text{(tungsten)} \\[2ex] \left(\dfrac{V}{V_0}\right)^{2\gamma} & \text{EXPON.EQ.0} & \text{(stainless steel)} \\[2ex] 1 & \text{VO.EQ.0} & \text{(default value for } V_0 \text{ is zero)} \end{cases} \tag{7}$$

    (In this last case, only EOSID, C1, C2, C3, TEMUNIT, TIMUNIT and LGTUNIT need to be defined)

    with,

$$\gamma = \gamma_0 - \left(\gamma_0 - \frac{1}{2}\right)\left(1 - \frac{V}{V_0}\right) \tag{8}$$

The following table reports some sets of parameters given by Burgess in his paper:

Parameter	Cu	Ag	Au	W	Al(2024)	SS(304)
V_0(cm³/gm)	0.112	0.0953	0.0518	0.0518	0.370	0.1265
γ_0	2.00	2.55	3.29	1.55	2.13	2.00
C_1 (BUS)	-4.12e-5	-3.37e-5	-4.95e-5	-9.73e-5	-5.35e-5	0
C_2	0.113	0.131	0.170	0.465	0.233	0.330
C_3	1.145	1.191	1.178	1.226	1.210	0.4133
EXPON	-1	-1	-1	+1	-1	0

*EM_EOS_PERMEABILITY

Purpose: Define the parameters for the behavior of a material's permeability.

Card 1	1	2	3	4	5	6	7	8
Variable	EOSID	EOSTYPE	LCID	BS/POLY	MUR0	C	TC	
Type	I	I	I	F	F	F	F	
Default	none	none	none	0.	0.	0.	0.	

VARIABLE	DESCRIPTION

EOSID   ID of the EM_EOS

EOSTYPE   Define the type of EOS:

> EQ.1: Permeability defined by B as a function of H curve ($B = \mu H$). The abscissa of the curve is H, and the ordinate is B.

> EQ.2: Permeability defined by a H function of B curve ($H = B/\mu$). The abscissa of the curve is B, and the ordinate is H.

> EQ.3: Permeability defined by a load curve where B-H curves ($B = \mu H$) may be defined as a function of von Mises stress. The abscissa of the curve is von Mises stress, and the ordinate is a load curve ID for the B-H load curves. The abscissa for each B-H load curve is H, and the ordinate is B.

> EQ.4: Permeability defined by a load curve where B-H load curves ($B = \mu H$) may be defined as a function of temperature. The abscissa of the curve is temperature, and the ordinate is load curve ID for the B-H load curves. The abscissa for each B-H load curve is H, and the ordinate is B.

> EQ.7: Permeability given by an analytical arctan law defining B as a function of H and optionally temperature. See Remark 1.

> EQ.8: Permeability given by the Froelich law defining B as a function of H and optionally temperature. See

VARIABLE	DESCRIPTION
	Remark 2.
LCID	Load curve ID for EOSTYPE = 1, 2, 3, and 4. Ignored if EOSTYPE = 7 or 8.
BS/MUR0/C/TC	Saturation magnetic flux (B_s), relative permeability at a reference temperature (μ_{r0}), constant value (C), and Curie temperature (T_c), respectively. These parameters are used by the analytical laws (EOSTYPE = 7 and 8). See Remarks 1 and 2.
POLY	Applies a polynomial smoothing on the input load curve for EOSTYPE = 1 and 2. See Remark 3.
	EQ.0: Off
	EQ.1: On

Remarks:

1. **Arctan analytical law.** For EOSTYPE = 7, the solver applies the following analytical law:

    $$B(H, T) = \mu_0 H + \frac{2B_s}{\pi} \operatorname{atan}\left(\frac{\pi}{2B_s} H\mu_0(\mu_{r0} - 1.) \right) \times F(T) \times \mathrm{SF}$$

    SF is an optional coefficient defined by the material properties (see Remark 3 on *EM_MAT_002). $F(T)$ provides temperature dependence. B_s and μ_{r0} are input parameters. μ_0 is the permeability of free space and is hard-coded in the solver. By default, $\mathrm{SF} = 1$ and $F(T) = 1$. If C is defined, $F(T)$ becomes:

    $$F(T) = \max\left(0., 1. - \exp\left(\frac{T - T_c}{C} \right) \right)$$

    T_c is an input parameters.

2. **Froelich analytical law.** For EOSTYPE = 8, the solver applies the following analytical law:

    $$B(H, T) = \mu_0 H + H\frac{B_s}{1. + \mu_{r0}H} \times F(T) \times \mathrm{SF}$$

    SF is an optional coefficient defined by material properties (see Remark 3 on *EM_MAT_002). $F(T)$ provides temperature dependence. By default, $\mathrm{SF} = 1$ and $F(T) = 1$. If C is defined, $F(T)$ becomes:

    $$F(T) = \max\left(0., 1. - \exp\left(\frac{T - T_c}{C} \right) \right)$$

    T_c is an input parameters.

3.   **Polynomial approach.**   For EOSTYPE = 1 or 2, in some cases the input *B-H* curve contains few points or has some ill-defined areas. In such scenarios, it can be useful to reconstruct the curve using a polynomial approach. Accuracy can increase with reduced computational time. The smoothed load curve is output to a keyword file em_polyCurve_LCID.dat for reference. It is not necessarily recommended to use this feature if the original *B-H* curve is well defined.

*EM_EOS_TABULATED1

Purpose: Define the electrical conductivity or permeability depending on the material referencing this EOS as a function of temperature by using a load curve.

Card 1	1	2	3	4	5	6	7	8
Variable	EOSID	LCID						
Type	I	I						
Default	none	none						

VARIABLE	DESCRIPTION
EOSID	ID of the EM EOS
LCID	Load curve ID. See Remark 1.

Remarks:

1. **Suggestions for the Load Curve.** The load curve describes the electrical conductivity or permeability (ordinate) as a function of the temperature (abscissa). You need to make sure the temperature and the electrical conductivity / permeability given by the load curve are in the correct units. Also, we advise giving some bounds to the load curve (conductivities / permeabilities at very low and very high temperatures) to avoid bad extrapolations of the conductivity if the temperature gets out of the load curve bounds.

*EM_EOS_TABULATED2

Purpose: Define the electrical conductivity or permeability (depending on the material model referencing this EOSID) as a function of time by using a load curve.

Card 1	1	2	3	4	5	6	7	8
Variable	EOSID	LCID	IFLAG					
Type	I	I	I					
Default	none	none	0					

VARIABLE	DESCRIPTION
EOSID	ID of the EM EOS
LCID	Load curve ID (see Remark 1), function ID (see *DEFINE_FUNCTION), table ID or 2D table ID. For the arguments for the *DEFINE_FUNCTION, see Remark 2.
IFLAG	If LCID is a table ID or 2D table ID, conductivity / permeability is a function of temperature and material density. This flag dictates how LS-DYNA interprets the table. In other words, it specifies which property (temperature or material density) is the value for the table and which is the ordinate for load curves in the table:

        EQ.0: Temperature (value) indexes each conductivity/permeability (ordinate) versus material density (abscissa) load curve.

        EQ.1: Material density indexes each conductivity/permeability (ordinate) versus temperature (abscissa) load curve.

Remarks:

1. **Suggestions for the Load Curve.** The load curve describes the electrical conductivity / permeability (ordinate) as a function of time (abscissa). You need to make sure the time and the electrical conductivity / permeability given by the load curve are in the correct units. Also, we advise giving some bounds to the load curve (conductivities / permeabilities at $t = 0$ and after a long time) to avoid bad extrapolations of the conductivity / permeability if the run time gets out of the load curve bounds.

2.   ***DEFINE_FUNCTION Arguments.** LCID can also refer to a *DEFINE_FUNC-
TION ID. If a *DEFINE_FUNCTION is used, the following parameters are al-
lowed: f(vx, vy, vz, temp, pres, vol, mass, Ex, Ey, Ex, Bx, By, Bz, Fx, Fy, Fz,
JHrate, time, x, y, z). (Fx, Fy, Fz) refers to the Lorentz force vector.

*EM_EXTERNAL_FIELD

Purpose: Define the components of a time-dependent exterior field uniform in space applied on the conducting parts.

Card 1	1	2	3	4	5	6	7	8
Variable	FIELDID	FTYPE	FDEF	LCIDX	LCIDY	LCIDZ		
Type	I	I	F	I	I	I		
Default	0	0	0	0	0	0		

Optional Card. Additional input for frequency-based Eddy current cases (EMSOL = 4 in *EM_CONTROL).

Card 2	1	2	3	4	5	6	7	8
Variable				LCIDXI	LCIDYI	LCIDZI		
Type				I	I	I		
Default				optional	optional	optional		

VARIABLE	DESCRIPTION
FIELDID	External Field ID
FTYPE	Field type:

        EQ.1: Magnetic field

        EQ.2: Electric field (not available yet)

        EQ.3: Charge density (resistive heating solver only). See Remark 1.

| FDEF | Field defined by: |

        EQ.1: Load curves

        EQ.2: Define function (see *DEFINE_FUNCTION). If a define function is used, the following parameters are accepted: x, y, z, time. See Remark 2. For FTYPE = 3, the additional

VARIABLE	DESCRIPTION
	following parameters are accepted: emdt, pot, curr, sigma.
	EQ.4: Subroutine `usermat_getextfield` in the usermat package. See Remark 3.
LCID[X,Y,Z]	Load curve ID defining the (X, Y, Z) component of the field function of time for FTYPE = 1. For FTYPE = 3, only LCIDY is used and should be a simple a load curve or define function ID.
LCIDI[X,Y,Z]	Only available for EMSOL = 4 in *EM_CONTROL. Load curve ID defining the (X, Y, Z) component of the optional phase shift function of time for FTYPE = 1. Unit is in degrees.

Remarks:

1. **Electrostatic problems.** FTYPE = 3 is mostly used in electrostatic problem configurations. The material's conductivity then represents the permittivity.

2. **Spatially varying magnetic fields.** Using FTYPE = 1 and FDEF = 2 enables defining a spatially varying field. The coordinates given as arguments by the *DEFINE_FUNCTION represent the coordinates at the midpoint of the BEM edges.

3. **Defining field with usermat.** Using FTYPE = 1 and FDEF = 4 allows defining a spatially varying field in even greater detail by accessing the routine called `usermat_getextfield` in dyn21em.f when compiling LS-DYNA in usermat mode. With this subroutine, the user can implement his own law and rules.

*EM_ISOPOTENTIAL

Purpose: Define an isopotential. In other words, constrain nodes so that they have the same scalar potential value. This keyword card can only be used with the type 3 EM solver.

Card 1	1	2	3	4	5	6	7	8
Variable	ISOID	SETTYPE	SETID	RDLTYPE				
Type	I	I	I	I				
Default	none	none	none	0				

VARIABLE	DESCRIPTION
ISOID	ID of the isopotential
SETTYPE	Set type: EQ.1: Segment Set EQ.2: Node Set EQ.3: Fluid surface part. See *ICFD_PART.
SETID	Set ID
RDLTYPE	Used for the battery application (see *EM_RANDLES_BATMAC or *EM_RANDLES_TSHELL). Selects which layers of the underlying battery cell are associated with the isopotential: EQ.0: Default. No specific treatment. EQ.1: Current Collector Positive EQ.2: Positive Electrode EQ.3: Separator EQ.4: Negative Electrode EQ.5: Current Collector Negative The function of a layer is defined in *EM_MAT_001.

*EM_ISOPOTENTIAL_CONNECT

Purpose: Define a connection between two isopotentials or between an isopotential and the ground.

Card Summary:

Card 1a. Include this card for CONTYPE = 1 (short circuit).

CONID	CONTYPE	ISOID1	ISOID2				

Card 1b. Include this card for CONTYPE = 2, 3, 4, 6, or 7.

CONID	CONTYPE	ISOID1	ISOID2	VAL	LCID		

Card 1c. Include this card for CONTYPE = 5 (meshless Randles circuit).

CONID	CONTYPE	ISOID1	ISOID2		RDLID	PSID	

Card 2. Include this card for CONTYPE = 6 (RLC circuit).

L	C	V0					

Data Card Definitions:

Short Circuit Connection Card. Include this card if CONTYPE= 1.

Card 1a	1	2	3	4	5	6	7	8
Variable	CONID	CONTYPE	ISOID1	ISOID2				
Type	I	I	I	I				
Default	none	none	none	0				

VARIABLE	DESCRIPTION
CONID	Connection ID
CONTYPE	Connection type:
	EQ.1: Short circuit
ISOID1	ID of the first isopotential to be connected

VARIABLE	DESCRIPTION
ISOID2	Optional ID of the second isopotential to be connected

Resistance, Voltage Source, Current Source, and RLC Circuit Connection Card.
Include this card if CONTYPE= 2, 3, 4, 6, or 7.

Card 1b	1	2	3	4	5	6	7	8
Variable	CONID	CONTYPE	ISOID1	ISOID2	VAL	LCID		
Type	I	I	I	I	F	I		
Default	none	none	none	0	none	0		

VARIABLE	DESCRIPTION
CONID	Connection ID
CONTYPE	Connection type:

> EQ.2: Resistance
>
> EQ.3: Voltage source
>
> EQ.4: Current source
>
> EQ.6: RLC circuit
>
> EQ.7: Power (See Remark 1)

ISOID1	ID of the first isopotential to be connected
ISOID2	Optional ID of the second isopotential to be connected
VAL	Value of the resistance, voltage, or current depending on CONTYPE. Ignored for CONTYPE = 2 through 4 if LCID ≠ 0.
LCID	Load curve ID giving the value of the resistance, voltage, or current as a function of time. Only available for CONTYPE = 2 through 4.

> LT.0: |LCID| is a *DEFINE_FUNCTION ID. The following arguments are allowed: f(time, emdt, curr1, curr2, pot1, pot2, rmesh). pot1 and pot2 are the potential at the previous time step and at two previous time steps. curr1 and curr2 are the current at the previous time step and two previous time steps. rmesh is the mesh resistance calculated

VARIABLE	DESCRIPTION
	by the solver at this isopotential.

Meshless Randles Circuit Connection Card. Include this card if CONTYPE = 5.

Card 1c	1	2	3	4	5	6	7	8
Variable	CONID	CONTYPE	ISOID1	ISOID2		RDLID	PSID	
Type	I	I	I	I		I	I	
Default	none	none	none	0		none	0	

VARIABLE	DESCRIPTION
CONID	Connection ID
CONTYPE	Connection type:
	EQ.5: Meshless Randles circuit (used to represent a cell by one lumped Randles circuit)
ISOID1	ID of the first isopotential to be connected
ISOID2	Optional ID of the second isopotential to be connected
VAL	Value of the resistance, voltage, or current depending on CONTYPE
RDLID	ID of the Randles circuit defined by *EM_RANDLES_MESHLESS
PSID	Used if the variable R0TOTH of *EM_RANDLES_MESHLESS equals 1. Part set ID where LS-DYNA adds the joule heating corresponding to the resistance r_0 in *EM_RANDLES_MESHLESS, averaged over the part set.

RLC Circuit Parameters Card. Only defined if CONTYPE = 6.

Card 2	1	2	3	4	5	6	7	8
Variable	L	C	V0					
Type	F	F	F					
Default	none	none	none					

VARIABLE	DESCRIPTION
L/C/V0	Circuit inductance, capacity, and initial voltage. VAL gives the resistance.

Remarks:

1. **Power boundary condition.** This condition is only available when using the EM resistive heating solver (EMSOL = 3 in *EM_CONTROL_SOLVER). When active, the solver solves the resistive heating problem in two steps per time step. In the first solve, it applies a Dirichlet boundary condition with an imposed voltage of 1 to each power boundary condition. Once the first solve is complete, it retrieves the current on the boundary in order to update the voltage boundary condition to the value corresponding to the user-defined expected value for power and solves again.

   In classic resistive heating applications, the classic Ohm's law is used to determine the relationship between power, voltage, and current:

   $$P = VI$$

   In radiofrequency applications (meaning when complex numbers are present), power is found by calculating the sum of the real and imaginary parts:

   $$P = V_r I_r + V_i I_i$$

*EM_ISOPOTENTIAL_ROGO

Purpose: measures the total current flowing through a given section of the conductor and outputs it in an ASCII file called em_rogoCoil.dat

Card 1	1	2	3	4	5	6	7	8
Variable	ISOID	SETTYPE	SETID					
Type	I	I	I					
Default	none	none	none					

VARIABLE	DESCRIPTION
ISOID	ID of the Rogo coil.
SETTYPE	Set type: 　　EQ.1: Segment Set.
SETID	Set ID

*EM_MAT_001

Purpose: Define the electromagnetic material type and properties for a material whose permeability equals the free space permeability. Electromagnetic materials act like a *MAT_ADD, so they must be associated with a *MAT material or an ICFD part. See Remark 1.

Card 1	1	2	3	4	5	6	7	8
Variable	MID	MTYPE	SIGMA	EOSID		EPLAMDA	DEATHT	RDLTYPE
Type	I	I	F	I		F	F	I
Default	none	none	none	optional		optional	10^{28}	0

Optional RF Heating Card. Additional material parameters for radio-frequency heating (RF) cases.

Card 2	1	2	3	4	5	6	7	8
Variable		FREQ	EPSRR	EOSID2	EPSRI	EOSID3	EPS0	
Type		F	F	I	F	I	F	
Default		0.	0.	optional	0.	optional	↓	

VARIABLE	DESCRIPTION
MID	Material ID. For all MTYPE except MTYPE = 3, MID must reference a *MAT material since the electromagnetic properties are added onto the *MAT properties. If MTYPE = 3, MID can be left blank for the electromagnetic properties to apply to the ICFD entire fluid or it can be the PID of a *ICFD_PART_VOL to apply to an ICFD fluid part. See Remark 1.
MTYPE	Defines the electromagnetism type of the material:

        EQ.0: Air or vacuum

        EQ.1: Insulator material. These materials have the same electromagnetism behavior as MTYPE = 0.

        EQ.2: Conductor carrying a source. In these conductors, the

VARIABLE	DESCRIPTION
	eddy current problem is solved, which gives the actual current density. Typically, this material would correspond to the coil.
	EQ.3: Fluid conductor. In this case, MID refers to the ID given in *ICFD_PART_VOL. See Remark 2.
	EQ.4: Conductor not connected to any current or voltage source, where the Eddy current problem is solved. Typically, this material would correspond to the workpiece.
SIGMA	Initial electrical conductivity of the material. For the eikonal solvers (EMSOL = 14 and 15 on *EM_CONTROL), SIGMA is the wave velocity.
EOSID	Optional ID of the EOS to be used for the electrical conductivity (see *EM_EOS cards).
EPLAMDA	Optional. When defined, this field activates the computation of extracellular potentials in the purkinje network with the anisotropy ratio given by EPLAMDA.
DEATHT	Death time for the material. After DEATHT, the material will no longer be considered a conductor and removed from the EM solve. If a negative value is entered, a *DEFINE_FUNCTION will be expected. The following parameters are allowed: (vx, vy, vz, temp, vol, mass, Ex, Ey, Ez, Bx, By, Bz, Fx, Fy, Fz, JHrate, time). Fx, Fy, Fz refers to the Lorentz force vector. A negative value returned by the *DEFINE_FUNCTION corresponds to a "dead" or inactive element. Once an element has been removed from the EM solve, it cannot return.
RDLTYPE	Used for composite Tshell batteries modeled with *EM_RANDLES_TSHELL. RDLTYPE specifies the function of the layer associated to MID:
	EQ.0: Default. Conductor which is not part of a battery cell.
	EQ.1: Current Collector Positive
	EQ.2: Positive Electrode
	EQ.3: Separator
	EQ.4: Negative Electrode
	EQ.5: Current Collector Negative

VARIABLE	DESCRIPTION
FREQ	Frequency used for the RF solve.
EPSRR/EPSRI	Real and imaginary part of the relative permeability (dielectric constant and dielectric loss terms).
EOSID2/EOSID3	Optional IDs defining equation of states for EPSRR and EPSRI respectfully.
EPS0	Vacuum permittivity. The default is $8.8541878128 \times 10^{-12}$

Remarks:

1. **Input decks with EM materials.** EM materials must be associated with a *MAT material for MTYPE ≠ 3 or an ICFD fluid for MTYPE = 3. These EM properties are added onto the normal material properties like *MAT_ADD material properties. Thus, when added onto a *MAT material, MID here must refer to the MID of the *MAT material. For example, an input deck can have the following to define a conductor:

   ```
   *PART
   2,1,20
   *MAT_RIGID
   20,&dens,&young,$nu
   *EM_MAT_001
   20,2,&cond
   ```

   In this case, if *MAT_RIGID is not included, the conduction properties are not applied.

   For MTYPE = 3, MID can refer to the PID of a *ICFD_PART_VOL or be left blank. If it is left blank, the EM properties apply to the entire ICFD fluid.

2. **Coupling ICFD to EM.** Only the resistive heating solver is currently available when coupling the ICFD solver with the EM solver (see *EM_CONTROL).

3. **Eikonal solvers.** For the eikonal solvers (EMSOL = 14 and 15 on *EM_CONTROL), this material is supported for beam elements.

*EM_MAT_002

Purpose: Define an electromagnetic material type and properties with a permeability different than the free space permeability. Electromagnetic materials act like a *MAT_-ADD, so they must be associated with a *MAT material. See Remark 1.

Card 1	1	2	3	4	5	6	7	8
Variable	MID	MTYPE	SIGMA	EOSID	MUREL	EOSMU	DEATHT	
Type	I	I	F	I	F	I	F	
Default	none	none	none	none	none	optional	10^{28}	

Optional card

Card 2	1	2	3	4	5	6	7	8
Variable		EOSIDSF						
Type		I						
Default		optional						

VARIABLE	DESCRIPTION
MID	Material identification. MID must reference a *MAT material since the electromagnetic properties are added onto the *MAT properties. See Remark 1.
MTYPE	Electromagnetism type of the material: EQ.0: Air or vacuum EQ.1: Insulator material. These materials have the same electromagnetism behavior as MTYPE = 0. EQ.2: Conductor carrying a source. In these conductors, the eddy current problem is solved, which gives the actual current density. Typically, this would correspond to the coil. EQ.4: Conductor not connected to any current or voltage source, where the Eddy current problem is solved. Typically, this

VARIABLE	DESCRIPTION
	would correspond to the workpiece.
SIGMA	Initial electrical conductivity of the material
EOSID	ID of the EOS to be used for the electrical conductivity (see *EM_-EOS cards)
MUREL	Relative permeability which is the ratio of the permeability of a specific medium to the permeability of free space ($\mu_r = \mu/\mu_0$). See Remark 2.
EOSMU	ID of the EOS to be used to define the nonlinear behavior of μ. It is optional. Note: if EOSMU is defined, MUREL will be used for the initial value only. See *EM_EOS_PERMEABILITY.
DEATHT	Death time for the material. After DEATHT, the material will no longer be considered a conductor and will be removed from the EM solve. If a negative value is entered, a *DEFINE_FUNCTION will be expected. The following parameters are allowed: (vx, vy, vz, temp, vol, mass, Ex, Ey, Ez, Bx, By, Bz, Fx, Fy, Fz, JHrate, time). Fx, Fy, and Fz refer to the components of the Lorentz force vector. A negative value returned by the *DEFINE_FUNCTION corresponds to a 'dead' or inactive element. Once an element has been removed from the EM solve, it cannot return.
EOSIDSF	Optional ID of the EOS for specifying a scale factor to the permeability EOS defined in EOSMU. This field only applies if EOSMU is defined, but it is optional. If used, the EOS must be either *EM_-EOS_TABULATED1 or *EM_EOS_TABULATED2. See Remark 3.

Remarks:

1. **Input decks with EM materials.** EM materials must be associated with a *MAT material. These EM properties are added onto the normal material properties like *MAT_ADD material properties. Thus, MID here must refer to the MID of the *MAT material. For example, an input deck can have the following to define a conductor:

    ```
    *PART
    2,1,20
    *MAT_RIGID
    20,&dens,&young,$nu
    *EM_MAT_002
    20,2,&cond,&eosid,&murel
    ```

In this case, if *MAT_RIGID is not included, the conduction properties are not applied.

2. **Solver recommendations.** If $\mu \neq \mu_0$, then it is recommended to switch to the monolithic solver (See *EM_SOLVER_FEMBEM_MONOLITHIC) for better stability.

3. **Scale factor applied on permeability.** EOSIDSF is an equation of state for specifying a scale factor to the permeability specified with EOSMU. The scale factor is applied in the following way:

$$B(H, T) = \mu_0 H + G(H) \times \text{SF}$$

In other words, the nonlinear behavior of $B(H, T)$ is decomposed into a linear part ($\mu_0 H$) and a nonlinear part ($G(H) \times \text{SF}$). The linear part represents what happens at very high H values, such as when saturation is reached. $G(H)$ in the nonlinear term depends on the curve or law specified with EOSMU. The scale factor, SF, is determined with EOSIDSF. In general, this scale factor is a function of temperature, but the capability is not limited to it (see options available in *EM_EOS_TABULATED1 and *EM_EOS_TABULATED2).

*EM_MAT_003

Purpose: Define an electromagnetic material type whose electromagnetic conductivity is defined by a (3 × 3) tensor matrix. Applications include composite materials. This material only applies to solid elements. Electromagnetic materials act like a *MAT_ADD, so they must be associated with a *MAT material. See Remark 1.

Card 1	1	2	3	4	5	6	7	8
Variable	MID	MTYPE	SIGMA11	SIGMA22	SIGMA33	BETA	CM	
Type	I	I	F	F	F	F	F	

Card 2	1	2	3	4	5	6	7	8
Variable	SIGMA12	SIGMA13	SIGMA21	SIGMA23	SIGMA31	SIGMA32	AOPT	LAMBDA
Type	F	F	F	F	F	F	F	F

Card 3	1	2	3	4	5	6	7	8
Variable	XP	YP	ZP	A1	A2	A3	MACF	
Type	F	F	F	F	F	F	I	

Card 4	1	2	3	4	5	6	7	8
Variable	V1	V2	V3	D1	D2	D3		
Type	F	F	F	F	F	F		

VARIABLE	DESCRIPTION
MID	Material ID. . MID must reference a *MAT material since the electromagnetic properties are added onto the *MAT properties. See Remark 1.
MTYPE	Defines the electromagnetism type of the material:

VARIABLE	DESCRIPTION
	EQ.0: Air or vacuum
	EQ.1: Insulator material. These materials have the same electromagnetism behavior as MTYPE = 0.
	EQ.2: Conductor carrying a source. For these conductors, the EM solver solves the eddy current problem, which gives the actual current density. Typically, this type would correspond to the coil. In electrophysiology (EP), it corresponds to the tissue where the monodomain equations are solved for EMSOL = 11 or EMSOL = 13. For this case, an *EM_EP_CELLMODEL must be associated with this *EM_MAT_003.
	EQ.4: Conductor not connected to any current or voltage source, where the Eddy current problem is solved. Typically, this type would correspond to the workpiece. In electrophysiology (EP), for EMSOL = 11, 12 or 13, it corresponds to the bath surrounding the tissue for which only the external potential is found. In the case of electrophysiology, no *EM_EP_CELLMODEL should be associated with this material.
SIGMA11	The 1, 1 term in the 3 × 3 electromagnetic conductivity tensor matrix. For the eikonal solvers (EMSOL = 14 and 15 on *EM_CONTROL), this is the 1, 1 term in the 3 × 3 wave velocity tensor. Note that 1 corresponds to the **a** material direction.
	LT.0.0: |SIGMA11| corresponds to the ID of a *DEFINE_FUNCTION. See Remark 3 for available parameters.
SIGMA12	The 1, 2 term in the 3 × 3 electromagnetic conductivity tensor matrix. For the eikonal solvers (EMSOL = 14 and 15 on *EM_CONTROL), this is the 1, 2 term in the 3 × 3 wave velocity tensor. Note that 2 corresponds to the **b** material direction.
	LT.0.0: |SIGMA12| corresponds to the ID of a *DEFINE_FUNCTION. See Remark 3 for available parameters.
⋮	⋮
SIGMA33	The 3, 3 term in the 3 × 3 electromagnetic conductivity tensor matrix. For the eikonal solvers (EMSOL = 14 and 15 on *EM_CONTROL), this is the 3, 3 term in the 3 × 3 wave velocity tensor. Note that 3 corresponds to the **c** material direction.
	LT.0.0: |SIGMA33| corresponds to the ID of a *DEFINE_

VARIABLE	DESCRIPTION
	FUNCTION. See Remark 3 for available parameters.
BETA	Surface to volume ratio of the cell membrane (to be used only when EMSOL = 11 or 12 in *EM_CONTROL).
CM	Membrane capacitance per unit area (to be used only when EMSOL = 11 or 12 in *EM_CONTROL).
AOPT	Material axes option (see *MAT_002 for a more detailed description):

      EQ.0.0: Locally orthotropic with material axes determined by element nodes. The **a**-direction is from node 1 to node 2 of the element. The **b**-direction is orthogonal to the **a**-direction and is in the plane formed by nodes 1, 2, and 4.

      EQ.1.0: Locally orthotropic with material axes determined by a point in space, P, and the global location of the element center; this is the **a**-direction.

      EQ.2.0: Globally orthotropic with material axes determined by vectors defined below, as with *DEFINE_COORDINATE_VECTOR.

      EQ.3.0: Locally orthotropic material axes determined by a vector **v** and the normal vector to the plane of the element.The plane of a solid element is the midsurface between the inner surface and outer surface defined by the first four nodes and the last four nodes of the connectivity of the element, respectively. Thus, for solid elements, AOPT = 3 is only available for hexahedrons. **a** is determined by taking the cross product of **v** with the normal vector, **b** is determined by taking the cross product of the normal vector with **a**, and **c** is the normal vector. Then **a** and **b** are rotated about **c** by an angle BETA. BETA may be set in the keyword input for the element.

      EQ.4.0: Locally orthotropic in cylindrical coordinate system with the material axes determined by a vector, **v**, and an originating point, P, which define the centerline axis.

XP, YP, ZP	Coordinates of point, P, for AOPT = 1 and 4
A1, A2, A3	Components of vector, **a**, for AOPT = 2

VARIABLE	DESCRIPTION
MACF	Material axes change flag for solid elements:
	EQ.1: No change, default
V1, V2, V3	Components of vector, **v**, for AOPT = 3 and 4.
D1, D2, D3	Components of vector, **d**, for AOPT = 2
LAMBDA	Intra-to-extracellular conductivity ratio. When non-empty, the elliptic equation is solved to compute extracellular potentials (to be used only when EMSOL = 11 in *EM_CONTROL).

Remarks:

1. **Input decks with EM materials.** EM materials must be associated with a *MAT material. These EM properties are added onto the normal material properties like *MAT_ADD material properties. Thus, MID here must refer to the MID of the *MAT material. For example, an input deck can have the following to define a conductor:

    ```
    *PART
    2,1,20
    *MAT_RIGID
    20,&dens,&young,$nu
    *EM_MAT_003
    20,2,&cond11,&cond22,&cond33
    &cond12,&cond13,&cond21,&cond23,&cond31,&cond32
    ```

    In this case, if *MAT_RIGID is not included, the conduction properties are not applied.

2. **Material directions.** See the manual page for *MAT_002 for a description of how the principal material directions, {**a**, **b**, **c**}, are determined with AOPT. Note that *EM_MAT_003 only works for solid elements. The AOPT options illustrated in the AOPT figure of *MAT_002 can define the material directions for all elements of the parts that use the material.

3. **Function parameters.** The available parameters for the *DEFINE_FUNCTIONs are: f(time, emdt, x_ele, y_ele, z_ele, ieleuser). Here, time is the current EM time; emdt is the current EM time step; x_ele, y_ele, and z_ele are the location of the element; and ieleuser is the element ID.

4. **Eikonal solvers.** For the eikonal solvers (EMSOL = 14 and 15 on *EM_CONTROL), this material is supported for tetrahedral elements.

*EM_MAT_004

Purpose: Define the electromagnetic material type and properties for conducting shells in a 3D problem or in a 2D resistive heating problem. Electromagnetic materials act like a *MAT_ADD, so they must be associated with a *MAT material or an ICFD part. See Remark 1.

Card 1	1	2	3	4	5	6	7	8
Variable	MID	MTYPE	SIGMA	EOSID	NELE	MUREL	EOSMU	DEATHT
Type	I	I	F	I	I	F	I	F
Default	none	none	none	none	1	1.	optional	10^{28}

Optional RF heating Card. Additional material parameters for radio-frequency heating (RF) cases.

Card 2	1	2	3	4	5	6	7	8
Variable		FREQ	EPSRR	EOSID2	EPSRI	EOSID3	EPS0	
Type		F	F	I	F	I	F	
Default		0.	0.	0	0.	0	↓	

VARIABLE	DESCRIPTION
MID	Material ID. For all MTYPE except MTYPE = 3, MID must reference a *MAT material since the electromagnetic properties are added onto the *MAT properties. If MTYPE = 3, MID can be left blank for the electromagnetic properties to apply to the ICFD entire fluid or it can be the PID of a *ICFD_PART_VOL to apply to an ICFD fluid part. See Remark 1.
MTYPE	Defines the electromagnetism type of the material:

        EQ.0: Air or vacuum

        EQ.1: Insulator material. These materials have the same electromagnetism behavior as MTYPE = 0.

        EQ.2: Conductor carrying a source. In these conductors, the

VARIABLE	DESCRIPTION
	eddy current problem is solved, which gives the actual current density. Typically, this would correspond to the coil.
	EQ.3: Fluid conductor. In this case, MID refers to the ID given in *ICFD_PART_VOL. Note that this is only available for ICFD in 2D. See Remark 2.
	EQ.4: Conductor not connected to any current or voltage source, where the Eddy current problem is solved. Typically, this would correspond to the workpiece.
SIGMA	Initial electrical conductivity of the material
EOSID	ID of the EOS to be used for the electrical conductivity (see *EM_EOS cards).
NELE	Number of elements in the thickness of the shell. Note that you must make sure your mesh fine enough to correctly capture the inductive-diffusive effects (see skin depth definition).
MUREL	Relative permeability which is the ratio of the permeability of a specific medium to the permeability of free space ($\mu_r = \mu/\mu_0$).
EOSMU	ID of the EOS to be used to define the nonlinear behavior of μ. Note that if EOSMU is defined, MUREL will be used for the initial value only. See *EM_EOS_PERMEABILITY.
DEATHT	Death time for the material. After DEATHT, the material will no longer be considered a conductor and will be removed from the EM solve. If a negative value is entered, a *DEFINE_FUNCTION will be expected. The following parameters are allowed: (vx, vy, vz, temp, vol, mass, Ex, Ey, Ez, Bx, By, Bz, Fx, Fy, Fz, JHrate, time). Fx, Fy, and Fz refer to the components of the Lorentz force vector. A negative value returned by the *DEFINE_FUNCTION corresponds to a 'dead' or inactive element. Once an element has been removed from the EM solve, it cannot return.
FREQ	Frequency used for the RF solve.
EPSRR/EPSRI	Real and imaginary part of the relative permeability (dielectric constant and dielectric loss terms).
EOSID2/EOSID3	Optional IDs defining equations of state for EPSRR and EPSRI, respectfully

VARIABLE	DESCRIPTION
EPS0	Vacuum permittivity. The default is $8.8541878128 \times 10^{-12}$.

Remarks:

1. **Input decks with EM materials.** EM materials must be associated with a *MAT material for MTYPE ≠ 3 or an ICFD fluid for MTYPE = 3. These EM properties are added onto the normal material properties like *MAT_ADD material properties. Thus, when added onto a *MAT material, MID here must refer to the MID of the *MAT material. For example, an input deck can have the following to define a conductor:

    ```
    *PART
    2,1,20
    *MAT_RIGID
    20,&dens,&young,$nu
    *EM_MAT_004
    20,2,&cond,&eosid
    ```

    In this case, if *MAT_RIGID is not included, the conduction properties are not applied.

    For MTYPE = 3, MID can refer to the PID of a *ICFD_PART_VOL or be left blank. If it is left blank, the EM properties apply to the entire ICFD fluid.

2. **Coupling ICFD to EM.** Only the resistive heating solver is currently available when coupling the ICFD solver with the EM solver (see *EM_CONTROL).

*EM_MAT_005

Purpose: Define an electromagnetic material for which two material conductivities are specified per EM node and electromagnetic conductivities are defined by a (3 × 3) tensor matrix. Applications of this material include the Randles Batmac model (see Remark 2) and the electrophysiology bidomain model. This material is only supported for solid elements. Electromagnetic materials act like a *MAT_ADD, so they must be associated with a *MAT material. See Remark 1.

Card 1	1	2	3	4	5	6	7	8
Variable	MID	MTYPE	SIGMAXXA	SIGMAYYA	SIGMAZZA			
Type	I	I	F	F	F			

Card 2	1	2	3	4	5	6	7	8
Variable	SIGMAXYA	SIGMAXZA	SIGMAYXA	SIGMAYZA	SIGMAZXA	SIGMAZYA		
Type	F	F	F	F	F	F		

Card 3	1	2	3	4	5	6	7	8
Variable			SIGMAXXB	SIGMAYYB	SIGMAZZB			
Type			F	F	F			

Card 4	1	2	3	4	5	6	7	8
Variable	SIGMAXYB	SIGMAXZB	SIGMAYXB	SIGMAYZB	SIGMAZXB	SIGMAZYB		
Type	F	F	F	F	F	F		

Card 5	1	2	3	4	5	6	7	8
Variable	AOPT	XP	YP	ZP	A1	A2	A3	MACF
Type	F	F	F	F	F	F	F	I

Card 6	1	2	3	4	5	6	7	8
Variable	V1	V2	V3	D1	D2	D3		
Type	F	F	F	F	F	F		

VARIABLE	DESCRIPTION
MID	Material ID. MID must reference a *MAT material since the electromagnetic properties are added onto the *MAT properties. See Remark 1.
MTYPE	Defines the electromagnetism type of the material:

<blockquote>

EQ.0: Air or vacuum

EQ.1: Insulator material. These materials have the same electromagnetism behavior as MTYPE = 0.

EQ.2: In electrophysiology, it corresponds to the tissue, where the bidomain equations will be solved for EMSOL = 12 or EMSOL = 13. An *EM_EP_CELLMODEL must be associated with this material.

EQ.4: In electrophysiology, it corresponds to the bath where only the external potential is solved for. No *EM_EP_-CELLMODEL should be associated with this material.

EQ.5: Material associated with *EM_RANDLES_BATMAC. See Remark 2.

</blockquote>

SIGMAXXA/B	The 1, 1 term in the 3×3 electromagnetic conductivity tensor matrix for the two conductivities. For the BatMac model, A is for the potential on the positive current collector, and B is for the potential on the negative current collector. For the bidomain model in Electrophysiology, A is for the intracellular potential, and B is for the extracellular potential. Note that 1 corresponds to the **a** material direction.

VARIABLE	DESCRIPTION
	LT.0.0: |SIGMAXXA/B| corresponds to the ID of a *DEFINE_FUNCTION. See Remark 4 for available parameters.
SIGMAXYA/B	The 1, 2 term in the 3×3 electromagnetic conductivity tensor matrix for the two conductivities. Note that 2 corresponds to the **b** material direction.
	LT.0.0: |SIGMAXYA/B| corresponds to the ID of a *DEFINE_FUNCTION. See Remark 4 for available parameters.
$\vdots$	$\vdots$
SIGMAZZA/B	The 3, 3 term in the 3×3 electromagnetic conductivity tensor matrix for the two conductivities. Note that 3 corresponds to the **c** material direction.
	LT.0.0: |SIGMAZZA/B| corresponds to the ID of a *DEFINE_FUNCTION. See Remark 4 for available parameters.
AOPT	Material axes option (see *MAT_002 for a more detailed description):
	EQ.0.0: Locally orthotropic with material axes determined by element nodes. The **a**-direction is from node 1 to node 2 of the element. The **b**-direction is orthogonal to the **a**-direction and is in the plane formed by nodes 1, 2, and 4.
	EQ.1.0: Locally orthotropic with material axes determined by a point in space, P, and the global location of the element center; this is the **a**-direction.
	EQ.2.0: Globally orthotropic with material axes determined by vectors defined below, as with *DEFINE_COORDINATE_VECTOR.
	EQ.3.0: Locally orthotropic material axes determined by a vector **v** and the normal vector to the plane of the element. The plane of a solid element is the midsurface between the inner surface and outer surface defined by the first four nodes and the last four nodes of the connectivity of the element, respectively. Thus, for solid elements, AOPT = 3 is only available for hexahedrons. **a** is determined by taking the cross product of

VARIABLE	DESCRIPTION
	v with the normal vector, **b** is determined by taking the cross product of the normal vector with **a**, and **c** is the normal vector. Then **a** and **b** are rotated about **c** by an angle BETA. BETA may be set in the keyword input for the element.
	EQ.4.0: Locally orthotropic in cylindrical coordinate system with the material axes determined by a vector, **v**, and an originating point, *P*, which define the centerline axis.
XP, YP, ZP	Define coordinates of point **p** for AOPT = 1 and 4.
A1, A2, A3	Define components of vector **a** for AOPT = 2.
MACF	Material axes change flag for solid elements:
	EQ.1: No change, default
V1, V2, V3	Define components of vector **v** for AOPT = 3 and 4.
D1, D2, D3	Define components of vector **d** for AOPT = 2.

Remarks:

1. **Input decks with EM materials.** EM materials must be associated with a *MAT material. These EM properties are added onto the normal material properties like *MAT_ADD material properties. Thus, MID here must refer to the MID of the *MAT material. For example, an input deck can have the following to define a conductor:

```
*PART
2,1,20
*MAT_RIGID
20,&dens,&young,$nu
*EM_MAT_005
20,2,&cond11a,&cond22a,&cond33a
&cond12a,&cond13a,&cond21a,&cond23a,&cond31a,&cond32a
,,&cond11b,&cond22b,&cond33b
&cond12b,&cond13b,&cond21b,&cond23b,&cond31b,&cond32b
```

In this case, if *MAT_RIGID is not included, the conduction properties are not applied.

2. **Using this material with BatMac.** When this material is used in conjunction with the battery BatMac model, then the conductivities must be adjusted by the current collector thickness ratio over the total thickness of the cell. For example, if n_p is the number of positive current collectors, t_p the thickness of each

individual positive current collector and Th the total thickness of the cell, then the conductivity for the positive current collector must be scaled by:

$$\frac{n_p \times t_p}{\text{Th}} \quad .$$

3. **Material directions.** See the manual page for *MAT_002 for a description of how the principal material directions, $\{\mathbf{a}, \mathbf{b}, \mathbf{c}\}$, are determined with AOPT. Note that *EM_MAT_005 only works for solid elements. The AOPT options illustrated in the AOPT figure of *MAT_002 can define the material directions for all elements of the parts that use the material.

4. **Function parameters.** The available parameters for the *DEFINE_FUNCTIONs are: f(time, emdt, x_ele, y_ele, z_ele, ieleuser). Here, time is the current EM time; emdt is the current EM time step; x_ele, y_ele, and z_ele are the location of the element; and ieleuser is the element ID.

*EM_MAT_006

Purpose: Define two conductivities per EM node for special applications (Randles Batmac). Electromagnetic materials act like a *MAT_ADD, so they must be associated with a *MAT material. See Remark 1.

Card 1	1	2	3	4	5	6	7	8
Variable	MID	MTYPE	SIGP	EOSP	SIGN	EOSN	DEATHT	
Type	I	I	F	I	F	I	F	
Default	none	none	none	none	none	none	10^{28}	

VARIABLE	DESCRIPTION
MID	Material identification. MID must reference a *MAT material since the electromagnetic properties are added onto the *MAT properties. See Remark 1.
MTYPE	Defines the electromagnetism type of the material:

<div style="margin-left:3em">

EQ.0: Air or vacuum

EQ.1: Insulator material. These materials have the same electromagnetism behavior as MTYPE = 0.

EQ.5: Material associated to *EM_RANDLES_BATMAC

</div>

VARIABLE	DESCRIPTION
SIGP/SIGN	Conductivities of the positive / negative current collector materials
EOSP/EOSN	Optional ID of the EOS to be used for the two conductivities
DEATHT	Death time for the material. After DEATHT, the material will no longer be considered a conductor and removed from the EM solve. If a negative value is entered, a |DEATHT| is a *DEFINE_FUNCTION ID. The following parameters are allowed: (vx, vy, vz, temp, vol, mass, Ex, Ey, Ez, Bx, By, Bz, Fx, Fy, Fz, JHrate, time). The vector (Fx, Fy, Fz) refers to the Lorentz force vector. A negative value returned by the *DEFINE_FUNCTION corresponds to a "dead" or inactive element. Once an element has been removed from the EM solve, it cannot return.

Remarks:

1. **Input decks with EM materials.** EM materials must be associated with a *MAT material. These EM properties are added onto the normal material properties like *MAT_ADD material properties. Thus, MID here must refer to the MID of the *MAT material. For example, an input deck can have the following to define an insulator:

```
*PART
2,1,20
*MAT_RIGID
20,&dens,&young,$nu
*EM_MAT_006
20,1,&condp,&eosp,&condn,&eosn
```

In this case, if *MAT_RIGID is not included, the insulator properties are not applied.

2. **BatMac Model.** When this material is used in conjunction with the battery BatMac model, the conductivities must be adjusted by the current collector thickness ratio over the total thickness of the cell. For example, if n_p is the number of positive current collectors, t_p is the thickness of each individual positive current collector, and Th is the total thickness of the cell, the conductivity for the positive current collector must be scaled by: $n_p \times t_p/\text{Th}$.

*EM_OUTPUT

Purpose: Define the level of EM related output on the screen and in the messag file.

Card 1	1	2	3	4	5	6	7	8
Variable	MATS	MATF	SOLS	SOLF	MESH	MEM	TIMING	
Type	I	I	I	I	I	I	I	
Default	0	0	0	0	0	0	0	

VARIABLE	DESCRIPTION

MATS   Level of matrix assembly output to the screen:

    EQ.0: No output

    EQ.1: Basic assembly steps

    EQ.2: Basic assembly steps + percentage completed + final statistics

    EQ.3: Basic assembly steps + percentage completed + statistics at each percentage of completion

MATF   Level of matrix assembly output to the messag file:

    EQ.0: No output

    EQ.1: Basic assembly steps

    EQ.2: Basic assembly steps + percentage completed + final statistics

    EQ.3: Basic assembly steps + percentage completed + statistics at each percentage of completion

SOLS   Level of solver output on the screen:

    EQ.0: No output

    EQ.1: Global information at each FEM iteration

    EQ.2: Detailed information at each FEM iteration

SOLF   Level of solver output to the messag file:

    EQ.0: No output

VARIABLE	DESCRIPTION
	EQ.1: Global information at each FEM iteration
	EQ.2: Detailed information at each FEM iteration
MESH	Controls the output of the mesh data to the d3hsp file:
	EQ.0: No mesh output written.
	EQ.1: Mesh info written.
MEMORY	Controls the output of information about the memory used by the EM solve to the messag file:
	EQ.0: No memory information written.
	EQ.1: Memory information written.
TIMING	Controls the output of information about the time spent in the different parts of the EM solver to the messag file
	EQ.0: No timing information written.
	EQ.1: Timing information written.

*EM_OUTPUT_FORCES

Purpose: Cause the output of a binary file (emforcout) containing the node IDs, the coordinates, and the EM forces at each node. Additionally, ASCII files in keyword format containing these forces can be output.

Card 1	1	2	3	4	5	6	7	8
Variable	IOUT	OUTDT	LCOFF	SF				
Type	I	F	I	F				
Default	0	0.0	0	1.				

VARIABLE	DESCRIPTION
IOUT	Type of the output:

> EQ.1: Outputs the binary file only.
>
> EQ.2: Outputs the binary file and generates a set of keyword files em_loadnid and em_loadlcid giving the EM forces at each node at the given output time.
>
> EQ.3: Same as 2 except the forces are output as function of time.

OUTDT	Time period at which the keyword files are generated. Setting OUTDT to 0.0 causes the output to be generated at each EM time step. The absolute value of a negative value refers to a time-dependent load curve. See Remark 2.
LCOFF	Optional offset in the load curve IDs that are associated with the forces at each node when generating the keyword files.
SF	Optional scaling factor that can be applied to the output forces when generating the keyword files.

Remarks:

1. **2-step EM coupling.** This feature can be used to perform a coupled analysis in two steps. The first step solves the magnetostatic EM problem and outputs the forces. The second step loads those forces in a transient mechanical analysis. This capability enables quickly gaining a good understanding of the model before turning to a fully coupled transient EM solid mechanics analysis.

2.   **Memory cost.** The computational cost to generate the ASCII files can become high in large cases. When OUT=3 is used, there is also a memory cost associated to the output which can again become problematic in large cases. For this reason, it can recommended to use an OUTDT that is larger than the EM timestep to reduce the amount of times those ASCII files are output.

*EM_OUTPUT_VTK

Purpose: Cause the output of vtk files. It can be used in applications that require two material conductivities per EM node and whose electromagnetic conductivities are defined by a (3 × 3) tensor matrix. These applications include the Randles Batmac model and the Electrophysiology Bidomain model.

Card 1	1	2	3	4	5	6	7	8
Variable	VTKTYPE	VTKT						
Type	I	F						
Default	none	0.0						

VARIABLE	DESCRIPTION

VTKTYPE   Type of the vtk files output.

         EQ.1: A single .vtk file

         EQ.2: Parallel unstructured points data (.pvtu files), recommended in mpp executions.

VTKT   Time period at which vtk files are exported.

*EM_PERMANENT_MAGNET

Purpose: Defines a permanent magnet.

Card Summary:

Card 1. This card is required.

ID	PID	MTYPE	NORTH	SOUTH	HC		

Card 2a. This card is included if MTYPE = 3.

X	Y	Z					

Card 2b. This card is included if MTYPE = 4.

NID1	NID2						

Card 2c. This card is included if MTYPE = 5, 6, or 7.

X	Y	Z	NDIVIS	AXIS	DIR/X2	Y2	Z2

Card 3. This card is optional.

TTYPE	OX	OY	OZ	NX	NY	NZ	

Data Card Definitions:

Card 1	1	2	3	4	5	6	7	8
Variable	ID	PID	MTYPE	NORTH	SOUTH	HC		
Type	I	I	I	I	I	I		
Default	none	none	none	none	none	none		

VARIABLE	DESCRIPTION
ID	ID of the magnet
PID	Part ID

VARIABLE	DESCRIPTION
MTYPE	Magnet definition type:

        EQ.0: Magnet defined by two node sets for North and South Poles.

        EQ.1: Magnet defined by two segments sets for North and South Poles.

        EQ.3: Magnet defined by a global vector orientation.

        EQ.4: Magnet defined by a global vector orientation given by two node IDs

        EQ.5: Magnetic gear with NDIVIS magnets oriented around an axis given by AXIS and centered at point (X, Y, Z). The pole orientations alternate for each magnet in the gear, meaning they alternate at increments of 360/NDIVIS around the gear starting along the vector given by (X2, Y2, Z2). See Figure 6-4.

        EQ.6: Magnetic gear with NDIVIS magnets oriented around an axis given by AXIS and centered at point (X, Y, Z). The pole orientations alternate for each magnet in the gear, meaning they alternate at increments of 360/NDIVIS around the gear starting along the vector given by DIR. See Figure 6-4.

        EQ.7: Same as 5 except the North and South orientation of the magnets follows the gear rotation axis (see AXIS in Card 2c) rather than its radial direction.

        EQ.8: Same as 6 except the North and South orientation of the magnets follows the gear rotation axis (see AXIS in Card 2c) rather than its radial direction.

VARIABLE	DESCRIPTION
NORTH	Set ID of the magnet north face for MTYPE = 0 and 1
SOUTH	Set ID of the magnet south face for MTYPE = 0 and 1
HC	Coercive force, H_c. See Remark 1.

        LT.0.0: |HC| refers to a load curve ID giving the coercive force as a function of time.

MTYPE = 3 Card. This card is only included for MTYPE = 3.

Card 2a	1	2	3	4	5	6	7	8
Variable	X	Y	Z					
Type	F	F	F					
Default	0.	0.	0.					

VARIABLE	DESCRIPTION
X, Y, Z	Orientation of magnetization vector

MTYPE = 4 Card. This card is only included for MTYPE = 4.

Card 2b	1	2	3	4	5	6	7	8
Variable	NID1	NID2						
Type	I	I						
Default	none	none						

VARIABLE	DESCRIPTION
NID1 / NID2	Two node IDs defining the magnetization vector

Magnetic Gear Card. This card is only included if MTYPE = 5, 6, or 7. See Figure 6-4.

Card 2c	1	2	3	4	5	6	7	8
Variable	X	Y	Z	NDIVIS	AXIS	DIR/X2	Y2	Z2
Type	F	F	F	I	I	I/F	F	F
Default	0.	0.	0.	none	none	none	none	none

VARIABLE	DESCRIPTION
X, Y, Z	Origin / center point of the magnetic gear
NDIVIS	Number of subdivisions, that is, number of magnets around the circle
AXIS	Normal vector to the magnets:
	EQ.1: Global X axis
	EQ.2: Global Y axis
	EQ.3: Global Z axis
DIR	Directional vector giving the location of the starting magnet / starting magnetic orientation if MTYPE = 6:
	EQ.1: Global X axis
	EQ.2: Global Y axis
	EQ.3: Global Z axis
X2, Y2, Z2	Directional vector coordinates giving the starting magnet / starting magnetic orientation if MTYPE = 5 or 7.

Optional Card.   This card is only useful to change some magnet-related output quantities.

Card 3	1	2	3	4	5	6	7	8
Variable	TTYPE	OX	OY	OZ	NX	NY	NZ	
Type	I	F	F	F	I	I	I	
Default	0	none	none	none	none	none	none	

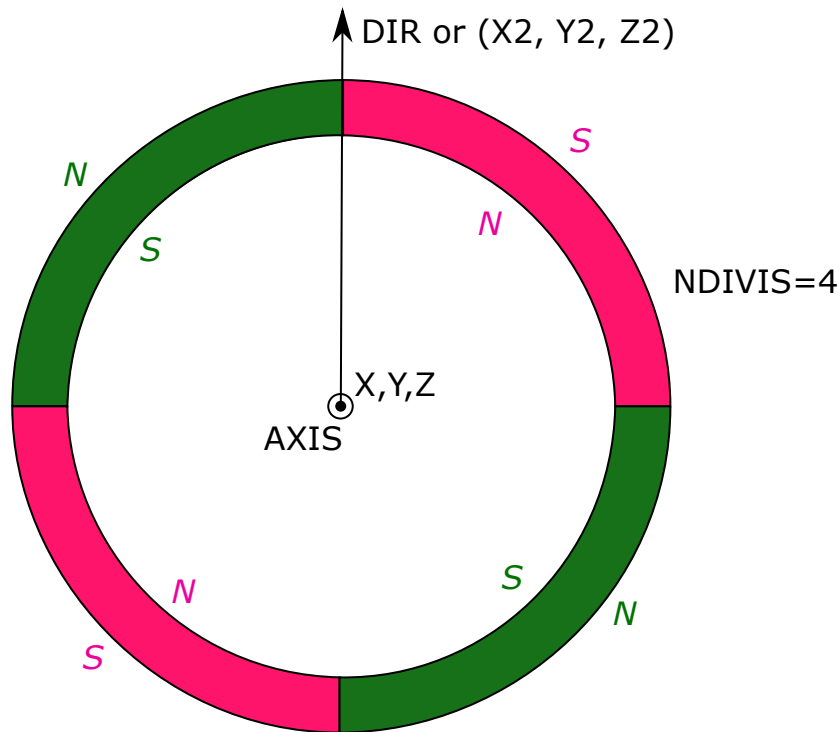| VARIABLE	DESCRIPTION
TTYPE	Torque calculation type:
	EQ.0: Default. Magnet torque is output as a vector based on the cross product of the EM force and the relative position of a given node with respect to the center of gravity.
	EQ.1: The position vector is based on a user-defined origin point and the result of the aforementioned cross product

Figure 6-4. Example of Magnetic Gear (MTYPE = 5 or 6)

VARIABLE	DESCRIPTION
	operation is projected onto a user-defined axis. As a result, the torque output becomes a scalar quantity.
OX/OY/OZ	Origin point for the magnet torque calculation if TTYPE = 1.
NX/NY/NZ	Axis on which the torque is projected if TTYPE = 1.

Remark:

1. **Coercive Force.** The absolute value of coercive force H_c applied to the magnet (A/m) relates to the Residual induction B_r by the following relation:

$$H_c = B_r / \mu$$

Here, μ is the magnet's permeability defined in *EM_MAT_002 using a constant relative permeability $\mu = \mu_r \mu_0$.

The coercive force can also be expressed using the energy product BH_{max} :

$$H_c = 2\sqrt{\frac{BH_{max}}{\mu}}$$

*EM_POINT_SET

Purpose: Create a set of points that can be used by *EM_DATABASE_POINTOUT.

Card 1	1	2	3	4	5	6	7	8
Variable	PTSID	PTSTYPE	VX	VY	VZ			
Type	I	I	F	F	F			
Default	0	0	0.	0.	0.			

Include as many cards as needed. This input ends at the next keyword ("*") card.

Card 2	1	2	3	4	5	6	7	8
Variable	PTID	X	Y	Z	IPOS			
Type	I	F	F	F	I			
Default	none	none	none	none	0			

VARIABLE	DESCRIPTION
PSID	Point set ID

PTSTYPE	Point set type :
	     EQ.0: Fixed points
	     EQ.1: Tracer points using prescribed velocity

VX, VY, VZ	Constant velocities used when PTSTYPE = 1
PTID	Point ID
X, Y, Z	Point initial coordinates
IPOS	Position flag (for 2D, see Remark 1): EQ.0: The solver determines if the point is inside or outside of the conductors.

VARIABLE	DESCRIPTION
	EQ.1: The point is outside of the conductors during the entire simulation. The solver does not check; hence a gain in computation time.

Remarks:

1. **2D axisymmetric.** If using *EM_2DAXI, notice that the conductors represent the corresponding 3D conductors.

*EM_RANDLES

The keywords in this section facilitate defining Randles circuit parameters for Randles cells. The available keywords in alphabetical order are as follows:

    *EM_RANDLES_BATMAC

    *EM_RANDLES_EXOTHERMIC_REACTION

    *EM_RANDLES_MESHLESS

    *EM_RANDLES_SHORT

    *EM_RANDLES_SOLID

    *EM_RANDLES_TSHELL

We have implemented four models for the Randles cell: *EM_RANDLES_BATMAC, *EM_RANDLES_MESHLESS, *EM_RANDLES_SOLID, and *EM_RANDLES_TSHELL. *EM_RANDLES_BATMAC is for defining the parameters for the Randles cell when using the batmac model. *EM_RANDLES_MESHLESS, *EM_RANDLES_SOLID, and *EM_RANDLES_TSHELL are for defining the parameters when the cell is not associated with a mesh, the cell is associated with a solid mechanical model, and the cell is associated with a composite tshell mechanical model, respectively. *EM_RANDLES_EXOTHERMIC_REACTION and *EM_RANDLES_SHORT enable adding additional parameters to the Randles cell for modeling thermal runaway and shorts, respectively.

Using *DEFINE_FUNCTION for Randles Cell Parameters:

Table 6-2. Many of the parameters for these models can be specified with a *DEFINE_FUNCTION. This table indicates the available arguments, depending on the kind of model. The first column lists the arguments in single quotes with a description. The second column gives what is available for the Randles circuit parameters. The third column indicates what is available for R0CHA and R0DIS for user-defined Equivalent Circuit models, depending on the model chosen. The fourth and fifth columns give the availability for parameters in *EM_RANDLES_SHORT and *EM_RANDLES_EXOTHERMIC_REACTION.

	Parameters with *DEFINE_FUNCTIONs			
Variable names	Randles circuit parameters $(r_0, r_{10}, c_{10},$ etc.$)$	RDLTYPE = -1	Internal short	Exothermic reaction
'time': Current EM time	All models	Solid/tshell/batmac models	Solid/tshell/batmac models	Solid/tshell/batmac models

Variable names	Parameters with *DEFINE_FUNCTIONs			
	Randles circuit parameters $(r_0, r_{10}, c_{10},$ etc.$)$	RDLTYPE = -1	Internal short	Exothermic reaction
'emdt': Current EM time step	All models	Solid/tshell/batmac models	Solid/tshell/batmac models	Solid/tshell/batmac models
'x_sep, y_sep, z_sep': Positive electrode coordinates	Solid/tshell models	Solid/tshell models	Solid/tshell models	Solid/tshell models
'x_sen, y_sen, z_sen': Negative electrode coordinates	Solid/tshell models	Solid/tshell models	Solid/tshell models	Solid/tshell models
'x_ccp, y_ccp, z_ccp': Positive Current collector coordinates	Solid/tshell/batmac models	Solid/tshell/batmac models	Solid/tshell/batmac models	Solid/tshell/batmac models
'x_ccn, y_ccn, z_ccn': Negative Current collector coordinates	Solid/tshell models	Solid/tshell models	Solid/tshell models	Solid/tshell models
'pres': Local pressure	Solid/tshell/batmac models	Solid/tshell/batmac models	Solid/tshell/batmac models	Solid/tshell/batmac models
'rho': Local density	Solid/tshell/batmac models	Solid/tshell/batmac models	Solid/tshell/batmac models	Solid/tshell/batmac models
'vmstress': Local von Mises stress	Solid/tshell/batmac models	Solid/tshell/batmac models	Solid/tshell/batmac models	Solid/tshell/batmac models
'cond': Local electrical conductivity	Solid/tshell/batmac models	Solid/tshell/batmac models	Solid/tshell/batmac models	Solid/tshell/batmac models
'temp': Local temperature	Solid/tshell/batmac models	Solid/tshell/batmac models	Solid/tshell/batmac models	Solid/tshell/batmac models
'tempRand': Temperature associated to Randles circuit	Solid/tshell/batmac models	Solid/tshell/batmac models	Solid/tshell/batmac models	Solid/tshell/batmac models
'efstrain': Local effective strain	Solid/tshell/batmac models	Solid/tshell/batmac models	Solid/batmac models	Solid/batmac models
'strainLocX/Y/Z': Local strain in the X/Y/Z directions	Solid/tshell/batmac models	Solid/tshell/batmac models	Solid/batmac models	Solid/batmac models
'soc,soceff': Local state of charge, effective state of charge	All models	Solid/tshell/batmac models	Solid/tshell/batmac models	Solid/tshell/batmac models
'current': Transverse Randles current	All models	Solid/tshell/batmac models	Solid/tshell/batmac models	Solid/tshell/batmac models
'ocv, vc, volt, r0': Open charge voltage, damping voltage, total voltage, r0 resistance.	All models	Solid/tshell/batmac models	Solid/tshell/batmac models	Solid/tshell/batmac models
'H_ex': Exothermal heating power integrated over time	Solid/tshell/batmac models	Solid/tshell/batmac models	Solid/tshell/batmac models	Solid/tshell/batmac models

| Variable names | Parameters with *DEFINE_FUNCTIONs | | | |
	Randles circuit parameters $(r_0, r_{10}, c_{10},$ etc.$)$	RDLTYPE = -1	Internal short	Exothermic reaction
(= exothermal heating energy) when exothermic reaction keyword is present.				
'short': Short gives the state of the Randles circuit. If short = 0, then the circuit is not shorted, if short = 1, then it is shorted.	Solid/tshell/batmac models	Solid/tshell/batmac models	Solid/tshell/batmac models	Solid/tshell/batmac models
'ero': Ero gives the state of the erosion. If ero = 1, then the circuit is adjacent to an element that has been eroded, ero = 0 otherwise.	Solid/batmac models	Solid/batmac models	Solid/batmac models	Solid/batmac models
'areaCircuit, areaCell, areashortGlob': Local Randles circuit area, total Randles cell area, total cell shorted area.	Solid/tshell/batmac models	Solid/tshell/batmac models	Solid/tshell/batmac models	Solid/tshell/batmac models
'save1, save2, save3…, save10': Ten local variables that the user can define and that will be saved during the run and associated with each local Randles circuits.	No models	Solid/tshell/batmac models	No models	No models

*EM_RANDLES_BATMAC

Purpose: Define the distributed Randles circuit parameters for a Randles cell when using the batmac model. The batmac model is a macro battery model where solid elements are retained for the solid mechanics and thermal solve, and each conducting node has its own Randles circuit associated with it. It must be used with *EM_MAT_005 or *EM_MAT_-006.

Card Summary:

Card 1. This card is required.

RDLID	RDLTYPE	RDLAREA	PSID				

Card 2. This card is required.

Q	CQ	SOCINIT	SOCTOU				

Card 3. This card is required.

R0CHA	R0DIS	R10CHA	R10DIS	C10CHA	C10DIS		

Card 4. This card is only read if RDLTYPE > 1. It is optional.

R20CHA	R20DIS	C20CHA	C20DIS	R30CHA	R30DIS	C30CHA	C30DIS

Card 5. This card is optional.

TEMP	FRTHER	R0TOTH	DUDT	TEMPU			

Card 6. This card is optional

USESOCS	TAU	FLCID					

Data Card Definitions:

Card 1	1	2	3	4	5	6	7	8
Variable	RDLID	RDLTYPE	RDLAREA	PSID				
Type	I	I	I	I				
Default	none	none	none	none				

VARIABLE	DESCRIPTION
RDLID	ID of the Randles cell
RDLTYPE	Type of Randles cell:

RDLTYPE description:

EQ.-1: User-defined equivalent circuit model. See Remark 3.

EQ.0:   0-order Randles Cell

EQ.1:   1-order Randles Cell

EQ.2:   2-order Randles Cell

EQ.3:   3-order Randles Cell

RDLAREA — Randles area:

EQ.1: The parameters are per unit area and are scaled in each Randle circuit by a factor depending on the local area of the circuit. Unit consistency in SI: Ohms times square meters.

EQ.2: The parameters are defined for the whole cell and are scaled in each Randle circuit by a factor depending on the local area of the circuit and the global area of the cell (default). Unit consistency in SI: Ohms.

EQ.3: The parameters are not scaled by area factors. Unit consistency in SI: Ohms.

EQ.11: Same as 1, except the parameters are defined for the whole cell and are scaled in each Randles circuit by a factor depending on the local volume of the circuit and the global volume of the cell.

EQ.22: Same as 2, except the parameters are defined for the whole cell and are scaled in each Randles circuit by a factor depending on the local volume of the circuit and the global volume of the cell.

PSID — Part set ID of all the parts composing the cell

Card 2	1	2	3	4	5	6	7	8
Variable	Q	CQ	SOCINIT	SOCTOU				
Type	F	F	F	F				
Default	none	none	none	none				

VARIABLE	DESCRIPTION
Q	Cell capacity
CQ	SOC conversion factor (%/s). It is known to be equal to 1/36 in SI units.
SOCINIT	Initial state of charge of the cell
SOCTOU	Equilibrium voltage (OCV):

> **GE.0.0:** Constant value
>
> **LT.0.0:** |SOCTOU| can refer to a load curve ID defining equilibrium voltage (OCV) as a function of the state of charge (SOC) or to a table ID with temperature indexing load curves that give OCV as a function of SOC.

Card 3	1	2	3	4	5	6	7	8
Variable	R0CHA	R0DIS	R10CHA	R10DIS	C10CHA	C10DIS		
Type	F	F	F	F	F	F		
Default	none	none	none	none	none	none		

VARIABLE	DESCRIPTION
R0CHA/ R10CHA/ C10CHA	$r_0/r_{10}/c_{10}$ when the current flows in the charge direction:

> **GE.0.0:** Constant value
>
> **LT.0.0:** Absolute value is a function (see *DEFINE_FUNCTION) or table ID. See Table 6-2 in *EM_RANDLES for the accepted function arguments. For a table, the circuit

VARIABLE	DESCRIPTION
	parameters can be made a function of the SOC and temperature.
R0DIS/ R10DIS/ C10DIS	$r_0/r_{10}/c_{10}$ when the current flows in the discharge direction: **GE.0.0:** Constant value **LT.0.0:** Absolute value is a function (see *DEFINE_FUNCTION) or table ID. See Table 6-2 in *EM_RANDLES for the accepted function arguments. For a table, the circuit parameters can be made a function of the SOC and temperature.

Optional Card for RDLTYPE > 1. This card is only read for RDLTYPE > 1. It is optional.

Card 4	1	2	3	4	5	6	7	8
Variable	R20CHA	R20DIS	C20CHA	C20DIS	R30CHA	R30DIS	C30CHA	C30DIS
Type	F	F	F	F	F	F	F	F
Default	0.	0.	0.	0.	0.	0.	0.	0.

VARIABLE	DESCRIPTION
R20CHA/ R30CHA/ C20CHA/ C30CHA	$r_{20}/r_{30}/c_{20}/c_{30}$ when the current flows in the charge direction: **GE.0.0:** Constant value **LT.0.0:** Absolute value is a function (see *DEFINE_FUNCTION) or table ID. See Table 6-2 in *EM_RANDLES for the accepted function arguments. For a table, the circuit parameters can be made a function of the SOC and temperature.
R20DIS/ R30DIS/ C20DIS/ C30DIS	$r_{20}/r_{30}/c_{20}/c_{30}$ when the current flows in the discharge direction: **GE.0.0:** Constant value **LT.0.0:** Absolute value is a function (see *DEFINE_FUNCTION) or table ID. See Table 6-2 in *EM_RANDLES for the accepted function arguments. For a table, the circuit parameters can be made a function of the SOC and temperature.

Optional Thermal Card.

Card 5	1	2	3	4	5	6	7	8
Variable	TEMP	FRTHER	R0TOTH	DUDT	TEMPU			
Type	F	I	I	F	I			
Default	0.	0	0	0.0	0			

VARIABLE	DESCRIPTION

TEMP   Constant temperature value used for the Randles circuit parameters when there is no coupling with the thermal solver (FRTHER = 0)

FRTHER   Flag setting where the temperature is coming from:

       EQ.0: The temperature used in the Randles circuit parameters is TEMP.

       EQ.1: The temperature used in the Randles circuit parameter is the temperature from the thermal solver.

R0TOTH   Flag for adding joule heating from r_0 to the thermal solve:

       EQ.0: The joule heating in the resistance r_0 is not added to the thermal solve.

       EQ.1: The joule heating in the resistance r_0 is added to the thermal solve.

DUDT   Reversible heat:

       GE.0.0: Constant value

       LT.0.0: |DUDT| is a load curve ID for the curve giving the reversible heat as a function of SOC.

TEMPU   Temperature unit:

       EQ.0: Celsius

       EQ.1: Kelvin

Optional SOCShift Card.

Card 6	1	2	3	4	5	6	7	8
Variable	USESOCS	TAU	FLCID					
Type	I	F	I					
Default	0	0.0	0					

VARIABLE	DESCRIPTION
USESOCS	Use SOC shift (see Remark 2):

> EQ.0: Do not use the added SOCshift
>
> EQ.1: Use the added SOCshift

TAU	Damping time in the SOCshift equation (see Remark 2)
FLCID	Load curve giving $f(i)$ where i is the total current in the unit cell (see Remark 2)

Remarks:

1. **Model combinations.** The batmac model cannot be mixed with the solid or thick shell Randles models. It can, however, be used in conjunction with the meshless model.

2. **Accounting for diffusion limitations.** Sometimes, an extra term called SOC-shift (or SocS) can be added to high-rate discharges to account for diffusion limitations. The SOCshift is added to SOC for the calculation of the OCV, $u(\text{SOC} + \text{SOCshift})$, and $r_0(\text{SOC} + \text{SOCshift})$. SOCshift satisfies the following equation:

$$\frac{d(\text{SOCshift})}{dt} + \frac{\text{SOCshift}}{\tau} = \frac{f(i(t))}{\tau}$$

with $\text{SOCshift}(t = 0) = 0$.

3. **User-defined ECMs.** Randles circuits are based on the finite element Robin boundary condition, acting similarly to a convection boundary condition for the heat equation. As such, the circuit equation is decomposed into a term that enters the left-hand side of the stiffness matrix and a term that is added to the right-hand side. Changing the definition of those terms permits replacing the Randles circuits with any type of Equivalent Circuit model (ECM). This is the purpose

of RDLTYPE = -1 where the term entering the left-hand side is defined by a negative integer referring to a *DEFINE_FUNCTION ID in R0CHA (unit consistency: resistance) while a negative integer in R0DIS associated with a *DEFINE_FUNCTION gives the term entering in the right-hand side (unit consistency: current).

*EM_RANDLES_EXOTHERMIC_REACTION

Purpose: Add an extra heat source term to the Randles circuit nodes to account for thermal runaway situations.

Card 1	1	2	3	4	5	6	7	8
Variable	AREATYPE	FUNCTID						
Type	I	I						
Default	2	none						

VARIABLE	DESCRIPTION
AREATYPE	Works the same way as RDLAREA in *EM_RANDLES_SOLID or *EM_RANDLES_TSHELL:

EQ.1: The heat source in FUNCTID is per unit area so that, for each local Randles circuit, the result returned by FUNCTID is multiplied by a factor areaLoc. areaLoc is the local area associated with each Randles circuit while areaGlob is the area of the whole cell. Unit consistency in SI: W*m2.

EQ.2: The heat source in FUNCTID is for the whole cell (the whole cell is shorted), so that, for each Randles circuit, the result returned by FUNCTID is multiplied by a factor areaLoc/areaGlob (default). Unit consistency in SI: W.

EQ.3: The heat source returned by FUNCTID is taken as is in each Randles circuit. Unit consistency in SI: W.

EQ.11: Same as 1, except the parameters are defined for the whole cell and are scaled in each Randles circuit by a factor depending on the local volume of the circuit and the global volume of the cell.

EQ.22: Same as 2, except the parameters are defined for the whole cell and are scaled in each Randles circuit by a factor depending on the local volume of the circuit and the global volume of the cell.

FUNCTID	DEFINE_FUNCTION ID giving the local heat source as a function of local parameters for the local Randles circuit. See Table 6-2 in *EM_RANDLES.

*EM_RANDLES_MESHLESS

Purpose: Define the distributed Randles circuit parameters for a Randles cell that is not associated with a mesh (lumped Randles circuit).

Card Summary:

Card 1. This card is required.

RDLID	RDLTYPE						

Card 2. This card is required.

Q	CQ	SOCINIT	SOCTOU				

Card 3. This card is required.

R0CHA	R0DIS	R10CHA	R10DIS	C10CHA	C10DIS		

Card 4. This card is only read if RDLTYPE > 1. It is optional.

R20CHA	R20DIS	C20CHA	C20DIS	R30CHA	R30DIS	C30CHA	C30DIS

Card 5. This card is optional.

TEMP			DUDT	TEMPU			

Card 6. This card is optional.

USESOCS	TAU	FLCID					

Data Card Definitions:

Card 1	1	2	3	4	5	6	7	8
Variable	RDLID	RDLTYPE						
Type	I	I						
Default	none	none						

VARIABLE	DESCRIPTION
RDLID	ID of the Randles cell
RDLTYPE	Type of Randles cell:

        EQ.0: 0-order Randles cell

        EQ.1: 1-order Randles cell

        EQ.2: 2-order Randles cell

        EQ.3: 3-order Randles cell

Card 2	1	2	3	4	5	6	7	8
Variable	Q	CQ	SOCINIT	SOCTOU				
Type	F	F	F	F				
Default	none	none	none	none				

VARIABLE	DESCRIPTION
Q	Cell capacity
CQ	SOC conversion factor (%/s). It is known to be equal to 1/36 in SI units.
SOCINIT	Initial state of charge of the cell
SOCTOU	Equilibrium voltage (OCV):

        GE.0.0: Constant value

        LT.0.0: |SOCTOU| is a load curve ID defining the equilibrium voltage (OCV) as a function of the state of charge (SOC).

Card 3	1	2	3	4	5	6	7	8
Variable	R0CHA	R0DIS	R10CHA	R10DIS	C10CHA	C10DIS		
Type	F	F	F	F	F	F		
Default	none	none	none	none	none	none		

VARIABLE	DESCRIPTION
R0CHA/ R10CHA/ C10CHA	$r_0/r_{10}/c_{10}$ when the current flows in the charge direction: **GE.0.0:** Constant value **LT.0.0:** Absolute value is a function (see *DEFINE_FUNCTION) or table ID. See Table 6-2 in *EM_RANDLES for the accepted function arguments. For a table, the circuit parameters can be made a function of the SOC and temperature.
R0DIS/ R10DIS/ C10DIS	$r_0/r_{10}/c_{10}$ when the current flows in the discharge direction: **GE.0.0:** Constant value **LT.0.0:** Absolute value is a function (see *DEFINE_FUNCTION) or table ID. See Table 6-2 in *EM_RANDLES for the accepted function arguments. For a table, the circuit parameters can be made a function of the SOC and temperature.

Optional Card for RDLTYPE > 1. This card is only read if RDLTYPE is greater than 1. It is optional.

Card 4	1	2	3	4	5	6	7	8
Variable	R20CHA	R20DIS	C20CHA	C20DIS	R30CHA	R30DIS	C30CHA	C30DIS
Type	F	F	F	F	F	F	F	F
Default	0.	0.	0.	0.	0.	0.	0.	0.

VARIABLE	DESCRIPTION
R20CHA/ R30CHA/ C20CHA/ C30CHA	$r_{20}/r_{30}/c_{20}/c_{30}$ when the current flows in the charge direction: GE.0.0: Constant value LT.0.0: Absolute value is a function (see *DEFINE_FUNCTION) or table ID. See Table 6-2 in *EM_RANDLES for the accepted function arguments. For a table, the circuit parameters can be made a function of the SOC and temperature.
R20DIS/ R30DIS/ C20DIS/ C30DIS	$r_{20}/r_{30}/c_{20}/c_{30}$ when the current flows in the discharge direction: GE.0.0: Constant value. LT.0.0: Absolute value is a function (see *DEFINE_FUNCTION) or table ID. See Table 6-2 in *EM_RANDLES for the accepted function arguments. For a table, the circuit parameters can be made a function of the SOC and temperature.

Optional Thermal Card.

Card 5	1	2	3	4	5	6	7	8
Variable	TEMP			DUDT	TEMPU			
Type	F			F	I			
Default	0.			none	0			

VARIABLE	DESCRIPTION
TEMP	Constant temperature value used for the Randles circuit parameters
DUDT	Reversible heat: GE.0.0: Constant value LT.0.0: |DUDT| is a load curve ID for the curve giving the reversible heat as a function of SOC.
TEMPU	Temperature unit: EQ.0: Celsius

VARIABLE	DESCRIPTION
	EQ.1: Kelvin

SOC shift Optional card.

Card 6	1	2	3	4	5	6	7	8
Variable	USESOCS	TAU	FLCID					
Type	I	F	I					
Default	none	none	none					

VARIABLE	DESCRIPTION
USESOCS	Use SOCshift (see Remark 1):
	EQ.0: Do not use the added SOCshift.
	EQ.1: Use the added SOCshift.
TAU	Damping time in the SOCshift equation (see Remark 1)
FLCID	Load curve giving $f(i)$ where i is the total current in the unit cell (see Remark 1)

Remarks:

1. **Accounting for diffusion limitations.** Sometimes, an extra term called SOC-shift (or SocS) can be added to high-rate discharges to account for diffusion limitations. The SOCshift is added to SOC for the calculation of the OCV, $u(\text{SOC} + \text{SOCshift})$, and $r_0(\text{SOC} + \text{SOCshift})$. SOCshift satisfies the following equation:

$$\frac{d(\text{SOCshift})}{dt} + \frac{\text{SOCshift}}{\tau} = \frac{f(i(t))}{\tau}$$

    with $\text{SOCshift}(t = 0) = 0$.

*EM_RANDLES_TSHELL

Purpose: Define the distributed Randles circuit parameters for a Randles cell when using a composite tshell mechanical model.

Card Summary:

Card 1. This card is required.

RDLID	RDLTYPE	RDLAREA	PSID				

Card 2. This card is required.

Q	CQ	SOCINIT	SOCTOU				

Card 3. This card is required.

R0CHA	R0DIS	R10CHA	R10DIS	C10CHA	C10DIS		

Card 4. This is only read if RDLTYPE > 1. It is optional.

R20CHA	R20DIS	C20CHA	C20DIS	R30CHA	R30DIS	C30CHA	C30DIS

Card 5. This card is optional.

TEMP	FRTHER	R0TOTH	DUDT	TEMPU			

Card 6. This card is optional.

USESOCS	TAU	FLCID					

Data Card Definitions:

Card 1	1	2	3	4	5	6	7	8
Variable	RDLID	RDLTYPE	RDLAREA	PSID				
Type	I	I	I	I				
Default	none	none	2	none				

VARIABLE	DESCRIPTION
RDLID	ID of the Randles Cell
RDLTYPE	Type of Randles Cell:

        EQ.-1: User-defined equivalent circuit model. See Remark 3.

        EQ.0: 0-order Randles Cell

        EQ.1: 1-order Randles Cell

        EQ.2: 2-order Randles Cell

        EQ.3: 3-order Randles Cell

VARIABLE	DESCRIPTION
RDLAREA	Randles Area:

        EQ.1: The parameters are per unit area and will be scaled in each Randles circuit by a factor depending on the local area of the circuit. Unit consistency in SI: Ohms times square meters.

        EQ.2: The parameters are defined for the whole cell and will be scaled in each Randles circuit by a factor depending on the local area of the circuit and the global area of the cell (default). Unit consistency in SI: Ohms.

        EQ.3: The parameters are not scaled by area factors. Unit consistency in SI: Ohms.

VARIABLE	DESCRIPTION
PSID	Part set ID of all the parts composing the cell (see Remark 1)

Card 2	1	2	3	4	5	6	7	8
Variable	Q	CQ	SOCINIT	SOCTOU				
Type	F	F	F	F				
Default	none	none	none	none				

VARIABLE	DESCRIPTION
Q	Cell capacity
CQ	SOC conversion factor (%/s). It is known to be equal to 1/36 in SI units.

VARIABLE	DESCRIPTION
SOCINIT	Initial state of charge of the cell
SOCTOU	Equilibrium voltage (OCV):

> GE.0.0: Constant value
>
> LT.0.0: |SOCTOU| is a load curve ID defining equilibrium voltage (OCV) as a function of the state of charge (SOC).

Card 3	1	2	3	4	5	6	7	8
Variable	R0CHA	R0DIS	R10CHA	R10DIS	C10CHA	C10DIS		
Type	F	F	F	F	F	F		
Default	none	none	none	none	none	none		

VARIABLE	DESCRIPTION
R0CHA/ R10CHA/ C10CHA	$r_0/r_{10}/c_{10}$ when the current flows in the charge direction:

> GE.0.0: Constant value
>
> LT.0.0: Absolute value is a function (see *DEFINE_FUNCTION) or table ID. See Table 6-2 in *EM_RANDLES for the accepted function arguments. For a table, the circuit parameters can be made a function of the SOC and temperature.

R0DIS/ R10DIS/ C10DIS	$r_0/r_{10}/c_{10}$ when the current flows in the discharge direction:

> GE.0.0: Constant value
>
> LT.0.0: Absolute value is a function (see *DEFINE_FUNCTION) or table ID. See Table 6-2 in *EM_RANDLES for the accepted function arguments. For a table, the circuit parameters can be made a function of the SOC and temperature.

Optional Card for RDLTYPE > 1. This card is only read if RDLTYPE > 1. It is optional.

Card 4	1	2	3	4	5	6	7	8
Variable	R20CHA	R20DIS	C20CHA	C20DIS	R30CHA	R30DIS	C30CHA	C30DIS
Type	F	F	F	F	F	F	F	F
Default	0.	0.	0.	0.	0.	0.	0.	0.

VARIABLE	DESCRIPTION
R20CHA/ R30CHA/ C20CHA/ C30CHA	$r_{20}/r_{30}/c_{20}/c_{30}$ when the current flows in the charge direction: GE.0.0: Constant value LT.0.0: Absolute value is a function (see *DEFINE_FUNCTION) or table ID. See Table 6-2 in *EM_RANDLES for the accepted function arguments. For a table, the circuit parameters can be made a function of the SOC and temperature.
R20DIS/ R30DIS/ CDIS/ C30DIS	$r_{20}/r_{30}/c_{20}/c_{30}$ when the current flows in the discharge direction: GE.0.0: Constant value LT.0.0: Absolute value is a function (see *DEFINE_FUNCTION) or table ID. See Table 6-2 in *EM_RANDLES for the accepted function arguments. For a table, the circuit parameters can be made a function of the SOC and temperature.

Optional Thermal Card.

Card 5	1	2	3	4	5	6	7	8
Variable	TEMP	FRTHER	R0TOTH	DUDT	TEMPU			
Type	F	I	I	F	I			
Default	0.	0	0	0.0	0			

VARIABLE	DESCRIPTION
TEMP	Constant temperature value used for the Randles circuit parameters when there is no coupling with the thermal solver (FRTHER = 0)
FRTHER	Flag about where the temperature is coming from:
	EQ.0: The temperature used in the Randles circuit parameters is TEMP.
	EQ.1: The temperature used in the Randle circuit parameter is the temperature from the thermal solver.
R0TOTH	Flag for adding joule heating from r_0 to the thermal solve:
	EQ.0: The joule heating in the resistance r_0 is not added to the thermal solve.
	EQ.1: The joule heating in the resistance r_0 is added to the thermal solve.
DUDT	Reversible heat:
	GE.0.0: Constant value
	LT.0.0: |DUDT| is a load curve ID for the curve givig the reversible heat as a function of SOC.
TEMPU	Temperature unit:
	EQ.0: Celsius
	EQ.1: Kelvin

Optional SOCShift Card.

Card 6	1	2	3	4	5	6	7	8
Variable	USESOCS	TAU	FLCID					
Type	I	F	I					
Default	0	0.0	0					

VARIABLE	DESCRIPTION
USESOCS	Use SOCshift (see Remark 2):
	EQ.0: Do not use the added SOCshift.
	EQ.1: Use the added SOCshift.
TAU	Damping time in the SOCshift equation (see Remark 2)
FLCID	Load curve giving $f(i)$ where i is the total current in the unit cell (see Remark 2)

Remarks:

1. **Sectioning of a circuit.** *PART_COMPOSITE_TSHELL defines each part of PSID. With this keyword for defining the part, each layer of a part can serve a different function, namely, as a current collector positive, current collector negative, separator, negative electrode, or positive electrode. The RDLTYPE field of *EM_MAT_001 sets a given layer's function.

2. **Accounting for diffusion limitations.** Sometimes, an extra term called SOCshift (or SocS) can be added to high-rate discharges to account for diffusion limitations. The SOCshift is added to SOC for the calculation of the OCV, $u(\text{SOC} + \text{SOCshift})$, and $r_0(\text{SOC} + \text{SOCshift})$. SOCshift satisfies the following equation:

$$\frac{d(\text{SOCshift})}{dt} + \frac{\text{SOCshift}}{\tau} = \frac{f(i(t))}{\tau}$$

   with $\text{SOCshift}(t = 0) = 0$.

3. **User-defined ECMs.** Randles circuits are based on the finite element Robin boundary condition, acting similarly to a convection boundary condition for the heat equation. As such, the circuit equation is decomposed into a term that enters the left-hand side of the stiffness matrix and a term that is added to the right-hand side. Changing the definition of those terms permits replacing the Randles circuits with any type of Equivalent Circuit model (ECM). This is the purpose of RDLTYPE = -1 where the term entering the left-hand side is defined by a negative integer referring to a *DEFINE_FUNCTION ID in R0CHA (unit consistency: resistance) while a negative integer in R0DIS associated with a *DEFINE_FUNCTION gives the term entering in the right-hand side (unit consistency: current).

*EM_RANDLES_SHORT

Purpose: For a battery cell internal short, define conditions to turn on a Randles short (replace one or several Randles circuits by resistances). Also, define the value of the short resistance.

Card 1	1	2	3	4	5	6	7	8
Variable	AREATYPE	FUNCTID						
Type	I	I						
Default	2	none						

VARIABLE	DESCRIPTION
AREATYPE	Works the same way as RDLAREA in *EM_RANDLES_SOLID or *EM_RANDLES_TSHELL:

EQ.1:   The resistance inverse in FUNCTID is per unit area so that, for each local Randles circuit, the result returned by FUNCTID is multiplied by a factor 1./areaLoc (areaLoc is the local area associated with each Randles circuit, while areaGlob is the area of the whole cell). Unit consistency in SI: Ohms times square meters.

EQ.2:   The resistance in FUNCTID is for the whole cell (the whole cell is shorted), so that, for each Randles circuit, the result returned by FUNCTID is multiplied by a factor areaGlob/areaLoc (default). Unit consistency in SI: Ohms.

EQ.3:   The resistance returned by FUNCTID is taken as is for each Randles circuit. Unit consistency in SI:Ohms.

EQ.11: Same as 1, except the parameters are defined for the whole cell and are scaled in each Randles circuit by a factor depending on the local volume of the circuit and the global volume of the cell.

EQ.22: Same as 2, except the parameters are defined for the whole cell and are scaled in each Randles circuit by a factor depending on the local volume of the circuit and the global volume of the cell.

VARIABLE	DESCRIPTION
FUNCTID	Function ID (see *DEFINE_FUNCTION) for the function giving the local resistance function of local parameters for the local Randles circuit. See Remark 1. See Table 6-2 in *EM_RANDLES for the accepted function arguments.

Remarks:

1. **Short criterion.** If the return value of the function is zero, there is no short. The Randles circuit is maintained. A positive returned value causes replacing the Randles circuit with the returned short resistance. To ensure that the short is maintained even after the original criterion is no longer met, the default positive value may be replaced by a negative value. The solver then takes the absolute value returned and adopts it as the new short resistance in case the original short criterion is no longer met rather than reverting to a Randles circuit.

2. ***Example *DEFINE_FUNCTION.** The following partial input provides an example of a function:

```
*DEFINE_FUNCTION
FID (Function Id)
Float resistance_short_randle(
float time,
float x_ccp,float y_ccp,float z_ccp,
float x_sep,float y_sep,float z_sep,
float x_sem,float y_sem,float z_sem,
float x_ccm,float y_ccm,float z_ccm)
{
  float seThick0;
  seThick0=1.e-5;
  seThick=(sqrt(x_sep-x_sem)^2+(y_sep-y_sem)^2+(z_sep-z_sem)^2);
  if (seThick >= seThick0) then
  return 1.e-2;
  else
  return -1.e-3;
  endif
}
```

    In this example, as long as seThick is smaller than seThick0, no short occurs. Once seThick becomes larger than seThick0, a short occurs, and the short resistance is 1.e-2. If during the run, seThick once again becomes smaller than seThick0, the short is maintained and the short resistance becomes 1.e-3. Replacing 1.e-3 by 0.0 causes the short to revert to the original Randles circuit.

3. **Erosion.** For the solid model (see *EM_RANDLES_SOLID), when an erosion-based criterion is defined, the erosion variable, ero, enables distinguishing which component of the battery has been eroded and adjusts the short resistance law accordingly:

a) ero = 1 when the eroded element comes from the positive current collector.

b) ero = 10 when the eroded element comes from the negative current collector.

c) ero = 100 when the eroded element comes from the separator.

d) ero = 1000 when the eroded element comes from the positive electrode.

e) ero = 10000 when the eroded element comes from the negative electrode.

When multiple components have eroded elements, ero is the sum of the indicators. For example, a returned value of 1001 indicates that both the elements coming from the positive electrode and the positive current collector have been eroded.

*EM_RANDLES_SOLID

Purpose: Define the distributed Randles circuit parameters for a Randles cell when using a solid mechanical model.

Card Summary:

Card 1. This card is required.

RDLID	RDLTYPE	RDLAREA	CCPPART	CCNPART	SEPPART	PELPART	NELPART

Card 2. This card is required.

Q	CQ	SOCINIT	SOCTOU				

Card 3. This card is required.

R0CHA	R0DIS	R10CHA	R10DIS	C10CHA	C10DIS		

Card 4. This card is only read for RDLTYPE > 1. It is optional.

R20CHA	R20DIS	C20CHA	C20DIS	R30CHA	R30DIS	C30CHA	C30DIS

Card 5. This card is optional.

TEMP	FRTHER	R0TOTH	DUDT	TEMPU			

Card 6. This card is optional.

USESOCS	TAU	FLCID					

Data Card Definitions:

Card 1	1	2	3	4	5	6	7	8
Variable	RDLID	RDLTYPE	RDLAREA	CCPPART	CCNPART	SEPPART	PELPART	NELPART
Type	I	I	I	I	I	I	I	I
Default	none	none	none	none	none	none	none	none

VARIABLE	DESCRIPTION
RDLID	ID of the Randles Cell
RDLTYPE	Type of Randles Cell:

> EQ.-1: User-defined equivalent circuit model. See Remark 3.
>
> EQ.0:   0-order Randles Cell
>
> EQ.1:   1-order Randles Cell
>
> EQ.2:   2-order Randles Cell
>
> EQ.3:   3-order Randles Cell

RDLAREA	Randles Area:

> EQ.1: The parameters are per unit area and will be scaled in each Randles circuit by a factor depending on the local area of the circuit. Unit consistency in SI: Ohms times square meters.
>
> EQ.2: The parameters are defined for the whole cell and will be scaled in each Randles circuit by a factor depending on the local area of the circuit and the global area of the cell (default). Unit consistency in SI: Ohms.
>
> EQ.3: The parameters are not scaled by area factors. Unit consistency in SI: Ohms.

CCPPART	Current collector positive (CCP) part ID
CCNPART	Current collector negative (CCN) part ID
SEPPART	Separator part ID
PELPART	Positive electrode part ID
NELPART	Negative electrode part ID

Card 2	1	2	3	4	5	6	7	8
Variable	Q	CQ	SOCINIT	SOCTOU				
Type	F	F	F	F				
Default	none	none	none	none				

VARIABLE	DESCRIPTION
Q	Cell capacity
CQ	SOC conversion factor (%/s). It is known to be equal to 1/36 in SI units.
SOCINIT	Initial state of charge of the cell
SOCTOU	Equilibrium voltage (OCV):

> GE.0.0: Constant value
>
> LT.0.0: |SOCTOU| can refer to a load curve ID defining equilibrium voltage (OCV) as a function of the state of charge (SOC) or to a table ID with temperature indexing load curves that give OCV as a function of SOC.

Card 3	1	2	3	4	5	6	7	8
Variable	R0CHA	R0DIS	R10CHA	R10DIS	C10CHA	C10DIS		
Type	F	F	F	F	F	F		
Default	none	none	none	none	none	none		

VARIABLE	DESCRIPTION
R0CHA/ R10CHA/ C10CHA	$r_0/r_{10}/c_{10}$ when the current flows in the charge direction:

> GE.0.0: Constant value
>
> LT.0.0: Absolute value is a function (see *DEFINE_FUNCTION) or table ID. See Table 6-2 in *EM_RANDLES for the accepted function arguments. For a table, the circuit parameters can be made a function of the SOC and temperature.

R0DIS/ R10DIS/ C10DIS	$r_0/r_{10}/c_{10}$ when the current flows in the discharge direction:

> GE.0.0: Constant value
>
> LT.0.0: Absolute value is a function (see *DEFINE_FUNCTION) or table ID. See Table 6-2 in *EM_RANDLES for the accepted function arguments. For a table, the circuit

VARIABLE	DESCRIPTION
	parameters can be made a function of the SOC and temperature.

Optional Card for RDLTYPE > 1. This card is only read for RDLTYPE greater than 1. It is optional.

Card 4	1	2	3	4	5	6	7	8
Variable	R20CHA	R20DIS	C20CHA	C20DIS	R30CHA	R30DIS	C30CHA	C30DIS
Type	F	F	F	F	F	F	F	F
Default	0.	0.	0.	0.	0.	0.	0.	0.

VARIABLE	DESCRIPTION
R20CHA/ R30CHA/ C20CHA/ C30CHA	$r_{20}/r_{30}/c_{20}/c_{30}$ when the current flows in the charge direction: GE.0.0: Constant value LT.0.0: Absolute value is a function (see *DEFINE_FUNCTION) or table ID. See Table 6-2 in *EM_RANDLES for the accepted function arguments. For a table, the circuit parameters can be made a function of the SOC and temperature.
R20DIS/ R30DIS/ C20DIS/ C30DIS	$r_{20}/r_{30}/c_{20}/c_{30}$ when the current flows in the discharge direction: GE.0.0: Constant value LT.0.0: Absolute value is a function (see *DEFINE_FUNCTION) or table ID. See Table 6-2 in *EM_RANDLES for the accepted function arguments. For a table, the circuit parameters can be made a function of the SOC and temperature.

Optional Thermal Card.

Card 5	1	2	3	4	5	6	7	8
Variable	TEMP	FRTHER	R0TOTH	DUDT	TEMPU			
Type	F	I	I	F	I			
Default	0.	0	0	0.0	0			

VARIABLE	DESCRIPTION
TEMP	Constant temperature value used for the Randles circuit parameters when there is no coupling with the thermal solver (FRTHER = 0)
FRTHER	Flag about where the temperature is coming from:

    EQ.0: The temperature used in the Randles circuit parameters is TEMP.

    EQ.1: The temperature used in the Randle circuit parameter is the temperature from the thermal solver.

R0TOTH	Flag for adding joule heating from r_0 to the thermal solve:

    EQ.0: The joule heating in the resistance r_0 is not added to the thermal solve.

    EQ.1: The joule heating in the resistance r_0 is added to the thermal solve.

DUDT	Reversible heat:

    GE.0.0: Constant value

    LT.0.0: |DUDT| is a load curve ID for the curve giving the reversible heat as a function of SOC.

TEMPU	Temperature unit:

    EQ.0: Celsius

    EQ.1: Kelvin

Optional SOC Shift Card.

Card 6	1	2	3	4	5	6	7	8
Variable	USESOCS	TAU	FLCID					
Type	I	F	I					
Default	0	0.0	0					

VARIABLE	DESCRIPTION
USESOCS	Use SOCshift (see Remark 2):

         EQ.0: Do not use the added SOCshift.

         EQ.1: Use the added SOCshift.

TAU	Damping time in the SOCshift equation (see Remark 2)
FLCID	Load curve giving $f(i)$ where i is the total current in the unit cell (see Remark 2)

Remarks:

1. **Element normal vector orientation.** The solid element normal vectors must all be oriented in the direction pointing from the positive current collector to the negative current collector to detect which current collector nodes are connected to one another. Furthermore, any number of layers can be modeled, but the meshes of the CCP, anode, separator, cathode, and CCN must be continuous and have merged nodes at the boundaries.

2. **Accounting for diffusion limitations.** Sometimes, an extra term called SOC-shift (or SocS) can be added to high-rate discharges to account for diffusion limitations. The SOCshift is added to SOC for the calculation of the OCV, $u(\text{SOC} + \text{SOCshift})$, and $r_0(\text{SOC} + \text{SOCshift})$. SOCshift satisfies the following equation:

$$\frac{d(\text{SOCshift})}{dt} + \frac{\text{SOCshift}}{\tau} = \frac{f(i(t))}{\tau}$$

    with $\text{SOCshift}(t = 0) = 0$.

3. **User-defined ECMs.** Randles circuits are based on the finite element Robin boundary condition, acting similarly to a convection boundary condition for the heat equation. As such, the circuit equation is decomposed into a term that

enters the left-hand side of the stiffness matrix and a term that is added to the right-hand side. Changing the definition of those terms permits replacing the Randles circuits with any type of Equivalent Circuit model (ECM). This is the purpose of RDLTYPE = -1 where the term entering the left-hand side is defined by a negative integer referring to a *DEFINE_FUNCTION ID in R0CHA (unit consistency: resistance) while a negative integer in R0DIS associated with a *DE-FINE_FUNCTION gives the term entering in the right-hand side (unit consistency: current).

*EM_ROTATION_AXIS

Purpose: Define a rotation axis for the EM solver. This keyword is used with the 2D axisymmetric solver. The axis is defined by a point and a direction.

Card 1	1	2	3	4	5	6	7	8
Variable	XP	YP	ZP	XD	YD	ZD	NUMSEC	
Type	F	F	F	F	F	F	I	
Default	none	none	none	none	none	none	none	

Optional Card. Define an additional vector normal to the rotation vector that gives the rotation direction. See Remark 1.

Card 2	1	2	3	4	5	6	7	8
Variable	XT	YT	ZT	XH	YH	ZH		
Type	F	F	F	F	F	F		
Default	none	none	none	none	none	none		

VARIABLE	DESCRIPTION
XP, YP, ZP	x, y, and z coordinates of the point
XD, YD, ZD	x, y, and z components of direction of the axis
NUMSEC	Number of sectors. This field gives the ratio of the full circle to the angular extension of the mesh. This has to be a power of two. For example, NUMSEC = 4 means that the mesh of the part represents one-fourth of the total circle. If NUMSEC = 0 for *EM_2DAXI, the solver replaces it with this value.
XT/YT/ZT and XH/YH/ZH	Tail and head coordinates of the additional vector orthogonal to the rotation axis that gives the direction of the rotation. See Remark 1.

Remarks:

1. **Simplified 2D axisymmetric input.** Starting with R15, the EM 2D axisymmetric solver enables specifying an additional vector orthogonal to the rotation axis that provides the rotation direction. When used, *EM_2DAXI is no longer needed. Also, SIDCUR, SIDVIN, and SIDVOUT in *EM_CIRCUIT are no longer needed, but PID becomes mandatory. This results in a simplified input deck (fewer segment sets and keywords need to be defined).

*EM_SOLVER_BEM

Purpose: Define the type of linear solver and pre-conditioner as well as tolerance for the EM_BEM solve.

Card 1	1	2	3	4	5	6	7	8
Variable	RELTOL	MAXITE	STYPE	PRECON	USELAST	NCYLBEM		
Type	I	I	I	I	I	I		
Default	10^{-6}	1000	2	2	1	5000		

VARIABLE	DESCRIPTION
RELTOL	Relative tolerance for the iterative solvers (PCG or GMRES). If the results are not accurate enough, the user should try to decrease this tolerance. More iterations will then be needed.
MAXITER	Maximum number of iterations for the iterative solvers
STYPE	Solver type:

           EQ.1: Direct solve. The matrices are considered dense.

           EQ.2: Pre-conditioned gradient method (PCG). This method allows for block matrices with low-rank blocks and thus reduces the memory used.

           EQ.3: GMRES method. This method allows for block matrices with low-rank blocks and thus reduces the memory used. The GMRES option only works in serial for now.

| PRECON | Preconditioner type for PCG or GMRES iterative solves: |

           EQ.-1: No preconditioner

           EQ.1:   Diagonal line

           EQ.2:   Diagonal block (default)

           EQ.3:   Broad diagonal including all neighbor faces

           EQ.4:   LLT factorization

| USELAST | Only used for iterative solvers (PCG or GMRES). |

           EQ.-1: Start from 0 as the initial guess for the solution of the

VARIABLE	DESCRIPTION
	linear system.
	EQ.1: Starts from the previous solution normalized by the RHS change. See Remark 1.
NCYLBEM	Number of electromagnetism cycles between the recalculation of BEM matrices. If negative, the absolute value refers to a load curve giving the number of cycles as a function of time. See Remarks 2 and 3.

Remarks:

1. **USELAST.** Using USELAST = 1 can save many iterations in the subsequent solves if the vector solution of the present solve can be assumed to be nearly parallel to the vector solution of the previous solve, as usually happens in time-domain eddy-current problems.

2. **Moving conductors.** Since the BEM matrices depend on (and only on) the surface node coordinates of the conductors, recalculating them when the conductors are moving is important. NCYLBEM controls the frequency with which they are updated. Note that very small values, for example, NCYLBEM = 1, should, generally, be avoided since this calculation involves a high computational cost. However, when two conductors are moving and in contact with each other, we recommend recalculating the matrices at *every* time step.

3. **Order of precedence for NCYLBEM.** You can set NCYLBEM with *EM_CONTROL_SOLUTION, *EM_SOLVER_FEM/BEM, and *EM_CONTROL. *EM_CONTROL_SOLUTION has the highest priority for setting this field. If NCYLBEM is the default value on *EM_CONTROL_SOLUTION, LS-DYNA looks at the setting of NCYLBEM on *EM_SOLVER_BEM. If left as default on this keyword, LS-DYNA looks at the setting of NCYLBEM on *EM_CONTROL.

*EM_SOLVER_BEMMAT

Purpose: Define the type of BEM matrices as well as the way they are assembled.

Card 1	1	2	3	4	5	6	7	8
Variable	MATID							RELTOL
Type	I							F
Default	none							10^{-6}

VARIABLE	DESCRIPTION
MATID	Defines which BEM matrix the card refers to:
	EQ.1: **P** matrix
	EQ.2: **Q** matrix
	EQ.3: **W** matrix
RELTOL	Relative tolerance on the sub-blocks of the matrix when doing low rank approximations. The user should try to decrease these tolerances if the results are not accurate enough. More memory will then be needed.

Remarks:

1. The **W** matrix only exists when the monolithic solver is activated (see *EM_-SOLVER_FEMBEM_MONOLITHIC).

*EM_SOLVER_FEM

Purpose: Define some parameters for the EM FEM solver.

Card 1	1	2	3	4	5	6	7	8
Variable	RELTOL	MAXITE	STYPE	PRECON	USELAST	NCYLFEM		
Type	I	I	I	I	I	I		
Default	10⁻³	1000	1	1	1	5000		

VARIABLE	DESCRIPTION
RELTOL	Relative tolerance for the iterative solvers (PCG). If the results are not accurate enough, try decreasing this tolerance. More iterations will then be needed.
MAXITER	Maximum number of iterations for iterative solvers
STYPE	Solver type: EQ.1: Direct solve EQ.2: Pre-conditioned Gradient Method (PCG)
PRECON	Preconditioner type for PCG. EQ.0: No preconditioner EQ.1: Diagonal line
USELAST	This is used only for iterative solvers (PCG). EQ.-1: Starts from 0 as the initial solution of the linear system. EQ.1: Starts from the previous solution normalized by the right-hand-side change. See Remark 1.
NCYLFEM	Number of electromagnetism cycles between the recalculation of FEM matrices. If negative, the absolute value refers to a load curve giving NCYCLFEM as a function of time. See Remarks 2 and 3.

Remarks:

1. **Starting from the previous solution.** Using USELAST = 1 can save many iterations in the subsequent solves if the vector solution of the present solve can be assumed to be nearly parallel to the vector solution of the previous solve, as usually happens in time-domain eddy-current problems.

2. **NCYLFEM.** When the conductor parts are deforming or undergoing changes in their EM material properties (conductivity for example), the FEM matrices should be recalculated more often, so NCYLFEM may need to be changed.

3. **Order of precedence for NCYLFEM.** You can set NCYLFEM with *EM_CONTROL_SOLUTION, *EM_SOLVER_FEM, and *EM_CONTROL. *EM_CONTROL_SOLUTION has the highest priority for setting this field. If NCYLFEM is the default value on *EM_CONTROL_SOLUTION, LS-DYNA looks at the setting of NCYLFEM on *EM_SOLVER_FEM. If left as default on this keyword, LS-DYNA looks at the setting on *EM_CONTROL.

*EM_SOLVER_FEMBEM

Purpose: Define some parameters for the standard coupling between the EM_FEM and EM_BEM solvers.

Card 1	1	2	3	4	5	6	7	8
Variable	RELTOL	MAXITE	FORCON					
Type	F	I	I					
Default	10^{-2}	50	0					

VARIABLE	DESCRIPTION
RELTOL	Relative tolerance for the FEM/BEM system solve. If the results are not accurate enough, try decreasing this tolerance. A smaller tolerance will, however, require more iterations.
MAXITER	Maximal number of iterations
FORCON	Force convergence:
	EQ.0: The code stops with an error if no convergence.
	EQ.1: The code continues to the next time step even if the RELTOL convergence criteria has not been reached.

Remarks:

This keyword couples the FEM and BEM systems with the Richardson method. At each time step, the solver will iterate between the FEM and the BEM system until reaching convergence (based on the choice of RELTOL and MAXITER). The cost for this solve is low. However, to ensure stability, we recommend imposing a limit on the timestep based on the characteristic diffusion time (See *EM_CONTROL_TIMESTEP). Furthermore, it can be unstable whenever magnetic materials are involved (conductor's permeability different than vacuum permeability). The monolithic solver invoked with *EM_SOLVER_-FEMBEM_MONOLITHIC aims to remove those two limitations by solving both the FEM and BEM systems in one single monolithic bloc. For such cases, it is, therefore, the recommended choice (See *EM_SOLVER_FEMBEM_MONOLITHIC).

*EM_SOLVER_FEMBEM_MONOLITHIC

Purpose: Replaces *EM_SOLVER_FEMBEM and turns on the monolithic FEM-BEM solver.

Card 1	1	2	3	4	5	6	7	8
Variable	MTYPE	STYPE	ABSTOL	RELTOL	MAXIT			
Type	I	I	F	F	I			
Default	0	0	10^{-6}	10^{-4}	500			

Optional Card. Optional card for nonlinear magnetic cases.

Card 2	1	2	3	4	5	6	7	8
Variable		NTSTOL	NTATOL	NTRTOL	NTMIT			
Type		F	F	F	I			
Default		10^{-5}	10^{-12}	10^{-4}	20			

Optional Card. Optional card for nonlinear magnetic cases.

Card 3	1	2	3	4	5	6	7	8
Variable	LS_ON							
Type	I							
Default	0							

VARIABLE	DESCRIPTION
MTYPE	Monolithic solver type:
	EQ.0: Direct symmetric solver

VARIABLE	DESCRIPTION
STYPE	Solver type:
	EQ.0: MINRES iterative solver
	EQ.1: GMRES iterative solver
ABSTOL	Absolute tolerance
RELTOL	Relative tolerance
MAXIT	Maximum number of iterations
NTSTOL/NTATOL/ NTROL	Solution change tolerance, absolute tolerance, and relative tolerance used during the nonlinear Newton step. These tolerances only apply when the EM model includes nonlinear magnetic materials.
NTMIT	Maximum nonlinear iterations
LS_ON	Line search:
	EQ.0: Off
	EQ.1: On (only used for nonlinear magnetic materials)

Remarks:

The monolithic solver aims to overcome the limitations of the classic Richardson iterative coupling between the FEM and BEM systems. The monolithic solver offers better stability for large timesteps and for simulations involving ferromagnetic materials. We recommend this method whenever the *EM_MAT_002 keyword is present.