

FMEA-Failure Modes & Effects Analysis for Incident Investigation

ELECTRIC ARC FURNACE -EBT SYSTEM

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Abstract: Although FMEA is traditionally a tool for prevention, it can be adjusted to serve as an investigation method. When an incident occurs, using FMEA allows for a thorough and structured analysis of the failure modes that conduct to it. This approach assists in identifying root causes, understanding the impact of each failure mode, and developing corrective actions to prevent recurrence. The systematic nature of FMEA ensures that all possible factors contributing to the incident are considered, leading to a comprehensive understanding and robust preventive measures. The study demonstrates the application of FMEA to investigate for an incident involving an EBT system at electrical arc furnace EAF in a steel complex. The incident in question involves the sudden movement of ladle car parked under EAF to receive the molten metal leading to taping molten metal out the ladle, by the applying of FMEA, the investigation team aims to identify the failure modes that contributed to this incident, assess their effects, calculate their criticality, and develop corrective actions to prevent similar incidents in the future.

Keywords: FMEA, Electrical Arc Furnace (EAF), Eccentric Bottom Tapping (EBT) system, safety.

1. INTRODUCTION

The operation of Electrical Arc Furnaces (EAFs) in steel melt shops depends on highly reliable and safe systems for handling molten metal. Among these, the Eccentric Bottom Tapping (EBT) mechanism is crucial for facilitating controlled and efficient metal tapping operations. However, incidents can compromise both operational safety and production efficiency.[1]

This study investigates a significant incident occurred involving the EBT system at an EAF in February 2024. During the metal tapping process, a ladle car unexpectedly moved, leading to the unintended release of molten metal out of ladle. This sequence is documented in the following photos: Fig-1 shows the ladle car positioned before the tapping operation, Fig-2 captures the EBT opening, and Fig-3 illustrates the situation after the ladle car moved during tapping.



Fig1 : Before tapping operation (Recording system)



Fig 2 : Start Tapping operation in the Ladle (Recording system)



Fig 3 : Incident (Recording system)

The incident posed immediate safety risks and raised broader concerns regarding operational reliability and system robustness. In response, an investigation team was formed to conduct a thorough analysis. The ultimate goal is to develop effective corrective actions to prevent similar incidents in the future. By applying FMEA, this research uncovers underlying root causes, evaluates their implications on operational safety and production continuity, and recommends

targeted improvements. The findings are expected to contribute valuable insights into enhancing the reliability, safety, and efficiency of EAF operations. Through a detailed exploration of the EBT system incident and its FMEA analysis, this study seeks to provide actionable recommendations for mitigating risks, improving operational practices, and advancing safety protocols in steel melt shop environments. By addressing the complexities and challenges associated with industrial incidents, this study aims to foster a culture of continuous improvement and safety excellence in steelmaking operations.

2. SYSTEM DESCRIPTION AND SPECIFICATION

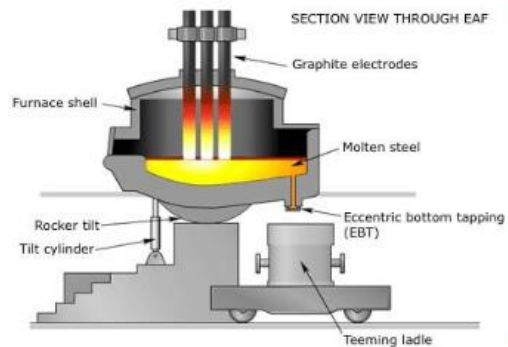


Fig 4 : schematic diagram of EAF

An Electric Arc Furnace (EAF) is a furnace that heats charged material through an electric arc to melt and refine metals. Fig 4 illustrates the basic components of an EAF.[3]

Graphite electrodes introduce electric arcs to melt scrap steel or direct reduced iron. The molten steel is collected in the furnace shell and is eventually tapped through an Eccentric Bottom Tapping (EBT) system. The rocker tilt and tilt cylinder mechanisms help in tilting the furnace to facilitate the tapping process. This method is energy-efficient and allows for precise control over the temperature and composition of the steel.

The Eccentric Bottom Tapping "EBT"(see Fig 5) is installed at the bottom part of the electric arc furnace.



Fig 5: Eccentric bottom

With the eccentric bottom tapping (EBT) a clear and concentrated cast is obtained with a consequent reduction in tapping time; therefore, the receptiveness of undesired elements (O₂ N₂H₂) is kept as low as possible and temperature losses are reduced.[4]

The eccentric bottom tapping (EBT) has other advantages, such as tapping without slags; as a matter of fact, the steel collected in the ladle is without the furnace oxidizing slag and can later be treated inside the reheating furnace, in the ladle, with no removal of slag; moreover, the increased height of the shell cooled panels (due to a reduction of the rotation angles for tapping) allows a considerable reduction of the refractory on the shell walls.[5]

Generally speaking, EBT is made up of the parts described in Fig 6.

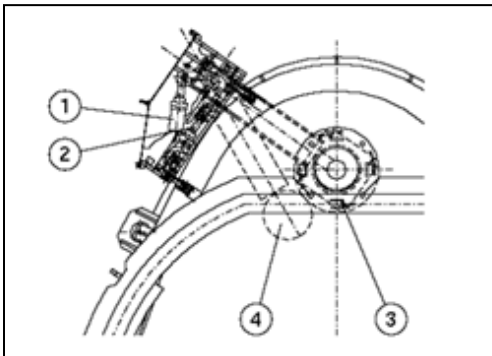


Fig 6: EBT Drive devices

The system consists of:

- A double solenoid valve for unlocking the EBT system movements.
- Two mechanical switches for controlling the locking and unlocking positions.
- A double solenoid valve for EBT system movements.

Two mechanical switches for controlling the EBT system open and close positions. [5]

3. OPERATING SEQUENCE:

Opening the EBT system for tapping:

When the furnace has reached a tilt of approximately 4° on the tapping side, the operator (consisting of 2 independent lever mechanisms for opening and eccentric locking, respectively, which control the slide gate) opens the EBT to allow the steel to flow into the ladle.

When reaching a few tons from the end of the set quantity of steel, (car equipped with weighing cells and weight display within the local control station), the operator, who is in a condition to visually control the tapping operation, inverts the furnace motion. The furnace is stopped at a tilting angle of approximately 8° on the deslagging door side, so that the remaining liquid does not cover the EBT tapping hole.

Cleaning and inspection of the EBT system tapping:

At the end of the tapping operation, when the furnace has returned to its original position, the operator, by means of the lever mechanism, closes the EBT so that it is free from the remaining steel drops that have not yet solidified. Afterwards, by using the mobile access walkways, the operator visually inspects the status of the EBT tapping hole.

Preparation of the EBT tapping hole:

If the inspection is positive, the furnace operator closes the EBT by means of the lever mechanism. Another operator proceeds with filling olivine granules in the tapping hole, using a suitable hopper with associated material feeding funnel. At the end of this operation, the furnace is brought back into horizontal position. At this point, the operator inserts the vertical locks that are fixed to the platform (imperative condition for charging the scrap bucket).

A. EBT system unlocking:

In Fig 7, the flowchart illustrates the sequence of operations required to unlock the Eccentric Bottom Tapping (EBT) system. The process begins with a series of preconditions that must be met, including the deactivation of emergency protocols, the activation of hydraulic units, and the correct positioning of the ladle car. Upon meeting these conditions, a request to unlock the EBT is initiated, leading to the activation of the unlocking valve. The system incorporates a 10-second delay to ensure safe and proper functioning before deactivating the unlocking valve, completing the unlocking process.

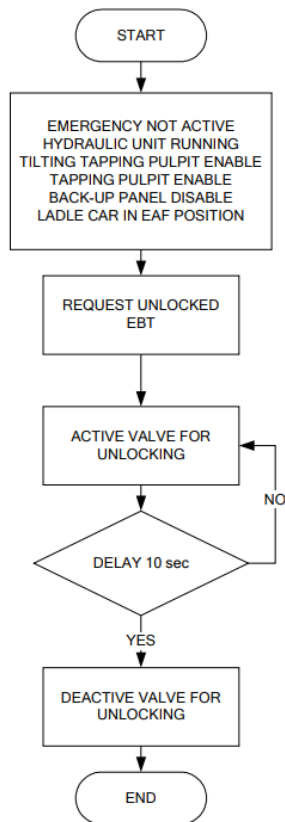


Fig 7 : EBT system unlocking process flowchart

B. EBT system open:

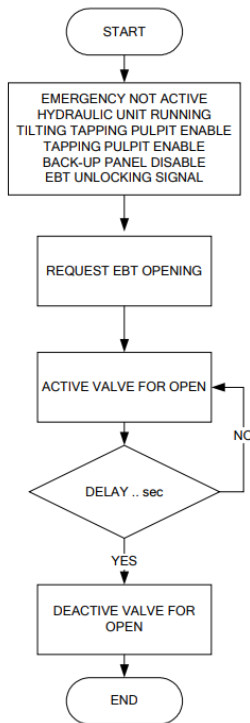


Fig 8 : EBT system opening sequence

This flowchart above (Fig 8) details the steps involved in opening the Eccentric Bottom Tapping (EBT) system. The process begins with verifying several initial conditions, such as ensuring the emergency protocols are inactive, hydraulic units are operational, an EBT opening request is made, which triggers the activation of the opening valve. The system then incorporates a delay for a specified number of seconds to ensure safe operation. Once this delay has elapsed, the opening valve is deactivated, completing the EBT opening process.

C. EBT system close

The flowchart “Fig 9” illustrates the systematic procedure for closing the Eccentric Bottom Tapping (EBT) system. The process begins with verifying that certain preconditions are met, such as the emergency state being inactive and the hydraulic unit running. It then checks if the EBT is in the unlocking state. If it is, the system requests the EBT to close, activates the closing valve, and introduces a 10-second delay to allow the closing action to complete. Finally, the valve is deactivated, successfully completing the EBT closing procedure. This structured approach ensures safe and efficient operation of the EBT system.

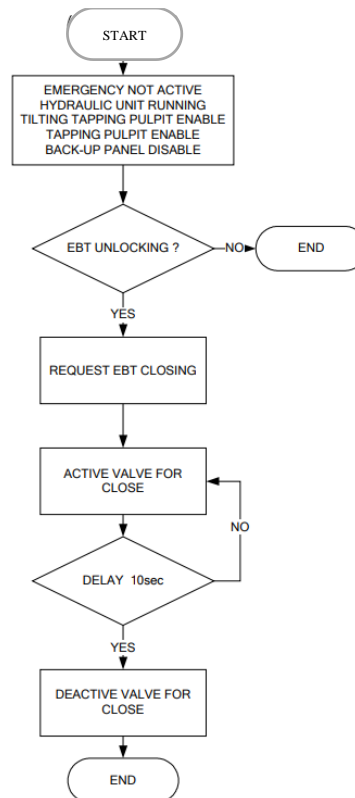


Fig 9: EBT system closing sequence

D. EBT system locking:

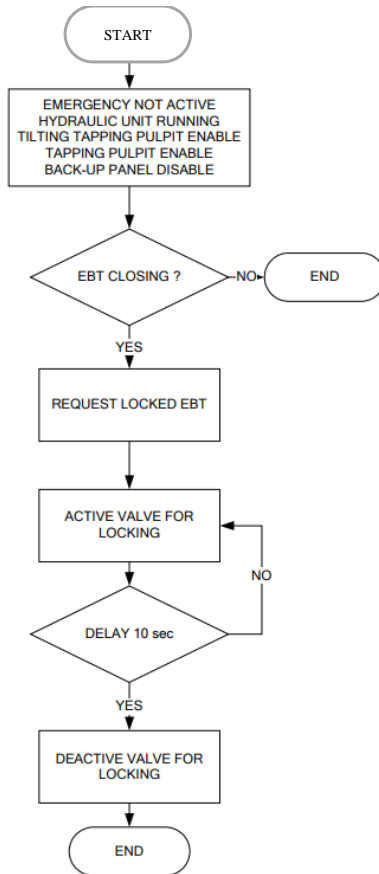


Fig 10: EBT system locking sequence

The flowchart “Fig 10” outlines the procedure for locking the Eccentric Bottom Tapping (EBT) system. The process starts with ensuring specific preconditions are met, such as the emergency state being inactive and the hydraulic unit running. It then checks if the EBT is in the closing state. If it is, the system requests the EBT to lock, activates the locking valve, and introduces a 10-second delay to complete the locking action. Once the delay is over, the valve is deactivated, finalizing the EBT locking procedure. This methodical approach ensures the EBT system is locked safely and efficiently. [6]

4. MEA & INVESTIGATION METHODOLOGY

Failure mode and effect analysis (FMEA), as a powerful and effective risk assessment tool in reliability and safety analysis, has been extensively applied in different fields to enhance the reliability of a system. However, the traditional FMEA method has exposed some significant defects in practical applications. Furthermore, the risk

ranking of failure modes is not convenient for subsequent maintenance strategies, and the interactions between risk criteria are not considered in most multiple criteria decision-making based methods.[7]

In this context, we aim to use FMEA not only as a tool for preventive risk assessment but also for incident investigation. By applying FMEA in incident investigations, we can systematically identify and evaluate potential failure modes and their effects. This approach provides a structured framework for understanding the root causes of incidents, facilitating a thorough analysis of the underlying issues, and developing effective corrective actions. Through this method, we aim to enhance the overall reliability and safety of the system by addressing both proactive risk management and reactive incident resolution.[8]

Documentation PROCEDURE FOR FMEA:

A. Item and its Functions :

Specify all the functions of an item, including the environment in which it has to operate.[9]

B. Potential Failure Mode:

A potential failure mode is the specific manner or way in which a process, product, or system could fail to meet its intended function. It represents any defect or issue that might occur, impacting the performance, safety, or reliability of the system. Identifying potential failure modes helps in analyzing their effects, causes, and likelihood, and in developing measures to prevent or mitigate these failures.[10]

C. Severity:

Severity is a rating corresponding to the seriousness of an effect of a potential failure mode. Severity or seriousness of the risk is considered just in case of “the effect”; reducing the risk severity is possible only through changing the process and the manner of performing activities.[11]

D. Occurrence:

The occurrence of a failure refers to its failure frequency and is rated from very unlikely to occur to almost inevitable, the occurrence of the fixed failure can be denoted by probability statistics so can the detection for the failure, The occurrence refers to the failure probability representing the relative number of failures anticipated during the design life of the system.[12]

E. Detection:

The detection of a failure refers to the likelihood to detect or not detect it by the control method before

it incurs aggravated effects, which is judged from almost sure detection to almost sure non-detection. The detectability refers to the assessment of the ability of a proposed design verification program to identify a potential weakness before the part or assembly is released to production [13]

Table 1-3 show the qualitative scales commonly used for the severity, the occurrence and the detect ability indexes

Table 1. Severity table (1-10 qualitative scale) [13]

Effect	Rank	Criteria
No	1	No effect
Very Slight	2	Insignificant system disturbance
Slight	3	Minor system anomaly with no operational impact
Minor	4	Minor operational disruption
Moderate	5	Noticeable operational inefficiency
Significant	6	Considerable operational inefficiency
Major	7	Significant operational delay or disruption
Extreme	8	Severe operational impact and downtime
Serious	9	Potential safety hazard or equipment damage
Hazardous	10	Severe safety hazard or catastrophic equipment failure

Table 2. Occurrence table (1-10 qualitative scale) [13]

Effect	Rank	Criteria
Almost never	1	Failure unlikely. History shows no failure
Remote	2	Rare number of failures likely
Very slight	3	Very few failures likely
Slight	4	Few failures likely
Low	5	Occasional number of failures likely
Medium	6	Medium number of failures likely
Moderately high	7	Moderately high number of failures likely
High	8	High number of failures likely
Very high	9	Very high number of failures likely
Almost certain	10	Failure almost certain

Table 3. Detectability table (1-10 qualitative scale) [13]

Effect	Rank	Criteria
Almost certain	1	Proven detection methods available in concept stage
Very high	2	Proven computer analysis available in early design stage
High	3	Simulation and/or modeling in early stage
Moderately high	4	Tests on early prototype system elements
Medium	5	Tests on preproduction system components

Low	6	Tests on similar system components
Slight	7	Test on product with prototypes and system components installed
Very slight	8	Proving durability tests on products with system components installed
Remote	9	Only unproven or unreliable technique available
Almost impossible	10	No known techniques available

F. Risk Priority Number RPN:

The risk associated with each failure mode is evaluated using Risk Priority Number (RPN) which is calculated by multiplying severity (S), occurrence (O) and detection (D) ratings.

In general, the three risk factors S, O and D are rated on a scale 1–10 for each failure mode using the guidelines for design FMEA. It is calculated using the equation (1).

$$RPN = S \times O \times D(1)$$

The RPN value ranges between 1 and 1000 for each failure mode. According to RPN value, the failure modes are prioritized and suitable corrective actions will be proposed for the highest RPN value. After implementation of corrective actions, new RPN values will be calculated for each failure mode.

Generally, there is no threshold value for addressing RPNs in traditional FMEA approach. The FMEA team will identify necessary corrective action for the failure mode with highest RPN.[14]

G. Risk Prioritization:

This risk level determined the risk that could be ignored or accepted, eliminated the source of the threat, mitigated risk, or monitoring the source of the threat.

H. Recommendation actions:

This step was documentation for risk evaluation on the sustainability of risk assessments that had carried out control recommendations.[15]

In this investigation, we considered both risks with high RPN and low RPN having one or two above mentioned factors, while determining risk criterion and decision making for considering a failure within the acceptable or unacceptable risk domain. Crisis grade is composed of normal, semi-critical, and critical levels which are explained in detail below:

Level 1: Normal level in which all the three factors of RPN (especially the severity and probability of occurrence) have values less than 5. Or RPN number is very low and does not require corrective and preventive actions (usually $RPN < 70$).

- **Level 2:** Semi-critical level in which at least a factor of three factors of RPN (especially the severity and probability of occurrence) has a value greater than 5 but RPN is relatively low. In this case, corrective/preventive action is essential (typically $70 < RPN < 140$).
- **Level 3:** Critical level in which at least two factors of the three-factor of RPN have high values or RPN number is too high. Since this level has been considered for high RPN, it is obvious and clear that it has a corrective / preventative action (usually $RPN > 140$).

5. CASE STUDY AND FMEA ANALYSIS

A. Define the Scope and Assemble the Team

- **Scope:** Analyze the critical components of a EBT system.
- **Team:** Include individuals with relevant knowledge about the system, process, and incident witnesses, in addition to safety, automation and maintenance engineers.

B. Discription of Event (incident)

During a normal melting process in EAF after obtaining the green light to start the tapping phase, the EBT unlocked and opened, the molten metal start to discharged into the ladle parked under EAF on the normal and mandatory position. suddenly the ladle car moved from its place, which lead the metal to come out, at this moment the operator tilted the furnace back to let the metal to leak on the slagging chamber.

C. Results:

Table 4 , summarize the results of EBT system FMEA

Function	Potential Failure Mode	Potential Effects of Failure	Potential Causes	Current Controls	S	O	D	RPN
EBT Unlocking Mechanism	Failure to verify ladle position before unlocking	Molten metal discharges when ladle car is not in place, causing spillage and potential safety hazards	Operator error, switch in maintenance mode, control system bypass	Operator training, visual indicators on ladle car position	9	7	3	189
			Inadequate interlock system, human factors (distraction, fatigue)	Maintenance mode indicators, procedures for switching modes				
EBT Control System	Control system allows EBT unlocking in maintenance mode	EBT unlocks and opens inappropriately, leading to uncontrolled discharge of molten metal	Control system logic flaw, inadequate safety interlocks	Regular control system audits, manual checks by operators	9	7	3	189
			Switch design allows for bypass, maintenance procedures not followed	Regular system checks, maintenance logs				
Ladle Car Positioning	Ladle car moves unexpectedly	Molten metal discharges without containment, causing spills and potential damage to equipment and safety hazards	Mechanical failure(position limit switch failure), Operator error, control system error	Regular maintenance of ladle car mechanisms, operator training	9	7	2	126
	Position limit switch failure	Incorrect feedback on ladle car position, leading to unsafe EBT operations	Mechanical wear, environmental conditions	Regular inspection and replacement schedule, Redundant switches				
EBT Open/Close Mechanism	Failure to open /close EBT	Inability to properly tap or seal molten metal, disrupting production and risking safety	Mechanical failure, control system error	Regular maintenance and lubrication, operator checks	9	3	2	54
EBT Locking mechanism	Failure to lock EBT	Unintended opening of EBT during operation, risking molten metal spillage	Mechanical failure, control system error	Regular maintenance and lubrication, operator checks	9	3	2	54
Safety interlocks	Interlock failure during EBT operation	Unsafe conditions during EBT operation, risking operator safety and equipment damage	Electrical failure, mechanical wear	Redundant interlocks, regular testing	9	2	4	72
Emergency shutdown system	Failure to activate during critical EBT incidents	Inability to quickly stop EBT operations in emergencies, escalating safety risks	Control system failure, electrical issues	Regular testing and maintenance operator training	9	2	1	18
Power supply system	Power failure during EBT operation	Loss control over EBT function, risking safety and production interruptions	Electrical grid issues, equipment failure	Backup power systems, surge protectors	9	3	1	27

D. Discussion:

In this investigation, the FMEA table categorizes risks into three levels: normal, semi-critical, and critical, with each level guiding the necessity for corrective and preventive actions. Normal level risks, such as the EBT Open/Close Mechanism, EBT Locking Mechanism, Emergency Shutdown System, and Power Supply System, have RPNs below 70. These risks, with lower severity, occurrence, and detection ratings, do not require immediate corrective actions but should be monitored to maintain operational safety and efficiency. Semi-critical risks, including Ladle Car Positioning and Safety Interlocks, have RPNs between 70 and 140. These functions exhibit higher occurrence rates and moderate detection ratings, necessitating essential corrective and preventive actions to reduce potential hazards and improve reliability. Critical risks are identified in the EBT Unlocking Mechanism and EBT Control System, both with RPNs of 189. These high-risk functions exhibit severe potential impacts, high occurrence rates, and moderate detection capabilities, indicating significant safety hazards and operational disruptions. Immediate corrective actions are crucial for these critical functions to prevent uncontrolled discharge of molten metal and ensure the safety of personnel and equipment. Our focus was particularly on these three functions: the EBT Unlocking Mechanism, EBT Control System, and Ladle Car Positioning.

Based on the results of this FMEA table, we were able to narrow down the cause of the incident to three things:

- EAF position limit switch.
- EAF in maintenance mode.
- Ladle car operating mode.

After the necessary checks (using IBA analyzer data acquisition and recording software) we noted that the limit switches are intact, but maintenance mode is activated, and the Ladle car's manual mode is activated. Additionally, there is insufficient coordination between the EAF main control room operator and the tapping control room operator.

E. Recommendations:

EBT Unlocking Mechanism

- Implement an interlock system to prevent unlocking unless the ladle car is in position.
- Enhance operator training.
- Implement strict procedures for mode switching.

EBT Control System

- Update control system logic to disable unlocking in maintenance mode and add automated checks.
- Redesign switch to prevent bypass.
- Enhance maintenance procedures.

Ladle Car Positioning

- Implement an automatic locking mechanism for the ladle car during tapping.

- Add position sensors.

Position limit switch failure

- Enhance position switch durability.
- Implement redundant position sensing.

6. CONCLUSION:

In this study, we employed a comprehensive Failure Modes and Effects Analysis (FMEA) to investigate an incident involving the EBT system within an electrical arc furnace (EAF) in a steel melt shop. Our analysis focused on critical functions. By categorizing risks into three levels—normal, semi-critical, and critical—based on their Risk Priority Numbers (RPN), we were able to identify and prioritize the necessary corrective and preventive actions.

The FMEA approach proved to be an effective tool in facilitating our investigation, allowing us to systematically analyze potential failure modes and their effects. This method enabled us to narrow down the causes of the incident to three primary factors: the EAF position limit switch, the EAF being in maintenance mode, and the ladle car operating mode. Despite the limit switches being intact, the activation of maintenance and manual modes, coupled with insufficient coordination between the EAF main control room operator and the tapping control room operator, contributed to the incident.

The recommendations derived from this analysis include implementing interlock systems, enhancing operator training, updating control system logic, redesigning switches, and improving maintenance procedures. By addressing these high-risk areas, we aim to mitigate potential hazards, ensure the safety of personnel and equipment, and enhance the overall efficiency of the EBT system in the EAF.

In conclusion, this FMEA method not only facilitated our investigation but also effectively limited the possible causes of the incident, providing a clear pathway for targeted corrective actions. This systematic approach underscores the value of detailed risk assessment in preventing industrial incidents and improving operational safety and reliability in steel manufacturing processes.

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