

A Process-Stage Analysis Using FAST lab 2 of Surface Retention and Interfacial Transport in Functional Sorbent Materials During Automated [^{18}F] FDG Synthesis

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Abstract: Radioactive fluoride, fluidic channels, and functional sorbent materials interact in a number of ways during automated [^{18}F] FDG synthesis. Nevertheless, it is still unclear how downstream radioactive material movement affects run-to-run yield variability. This work used a FAST lab 2 platform connected to a PET trace 800 cyclotron to assess stage-resolved F activity during automated FDG synthesis. The analysis includes 16 successful runs with enough process-stage data out of 27 distinct production records. The decay-corrected yield was $63.63 \pm 15.84\%$, but the mean final synthesis yield was $55.63 \pm 13.74\%$. While reactor-labeling retention and downstream transfer averaged $82.96 \pm 6.46\%$ and $78.74 \pm 14.10\%$, respectively, QMA trapping demonstrated a high and steady efficiency of $98.60 \pm 0.98\%$. The highest correlation was found between the downstream transfer efficiency toward the tC18/hydrolysis stage and the ultimate [^{18}F] FDG yield (Pearson's $r = 0.731$, $R^2 = 0.534$). These findings demonstrate that initial fluoride collection was fairly constant, while downstream radioactive-material transportation was mostly responsible for the observed yield variability. The results provide process-level evidence for fluidic transport, interfacial retention, and mass-transfer effects throughout the synthesis pathway from the perspective of materials physics. A quantitative basis for locating areas that are vulnerable to transportation during automated [^{18}F] FDG synthesis.

Keywords: FAST Lab2, Interfacial Transport, Surface Retention, Radioactive-Material Transfer, MA; Tc18, Materials Physics.

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I. INTRODUCTION

Fluorine-18 (^{18}F) is widely used in positron emission tomography (PET), particularly for the production of 2- [^{18}F] fluoro-2-deoxy-D-glucose ([^{18}F] FDG). It is commonly produced via the $^{18}\text{O}(\text{p},\text{n})^{18}\text{F}$ reaction using enriched ^{18}O -water. Due to its short physical half-life of approximately 109.8 min, efficient recovery and transfer of radioactive material are essential for maintaining sufficient activity during synthesis [1–3]. In automated [^{18}F] FDG production, [^{18}F] fluoride passes through several stages, including QMA trapping and elution, drying, radiofluorination, hydrolysis, purification, and final transfer. During this process, the

radioactive material interacts with cartridges, reactor surfaces, tubing, valves, and other components, where incomplete transfer and interfacial retention may affect overall activity recovery [4–10]. However, little is known about the stage-resolved behavior of F activity and how it relates to the final synthesis yield. Production records from a GE FASTlab 2 system connected to a PETtrace 800 cyclotron were examined in this work to assess the retention of F activity at various stages of synthesis and its correlation with final yield. Particular emphasis was devoted to QMA entrapment and elution, reactor-labeling retention, and transfer toward the tC18/hydrolysis step. A materials-physics approach was used to understand the observed activity

balance, emphasizing fluidic transport, interfacial retention, and mass-transfer behavior.

II. DESIGN OF THE STUDY AND DATA SOURCE

This study was carried out as a retrospective process-stage examination of automated [^{18}F] A GE FAST lab 2 automated radiosynthesis platform connected to a PETtrace 800 medical cyclotron was used to produce FDG. The distribution and retention of ^{18}F activity throughout the synthesis process were assessed by reviewing production data produced during regular [^{18}F] FDG fabrication. Initially, 29 operational [^{18}F] FDG manufacturing data were examined. 27 distinct production runs were kept after duplicate entries were eliminated. The quantitative study includes 16 of these successful runs with adequate process-stage activity data. Instead of concentrating only on the ultimate synthesis yield, the investigation examined stage-resolved radioactive-material movement and retention.

➤ Automated [^{18}F] FDG Production

[^{18}F] was generated by proton irradiation of enriched ^{18}O -water using a PETtrace 800 medical cyclotron and subsequently processed utilizing a GE FAST lab 2 automated synthesis platform. QMA fluoride trapping, QMA elution, azeotropic drying, precursor radiofluorination, hydrolysis, tC18/Al 2O_3 purification, and end product transfer comprised the synthesis sequence. The synthesis pathway was viewed as a series of distinct transport stages for the purposes of this investigation, which made it possible to assess variations in observed F activity across various interfaces and transfer steps within the cassette and related fluidic pathway.

➤ Process-Stage Activity Assessment

At the main stages of the synthesis process—start of synthesis (SOS), QMA trapping, QMA elution, drying, labeling start, labeling end, first, second, and third tC18 trapping (if applicable), washing, basic hydrolysis, and final product transfer—activity measurements were taken from the production records. Starting and end activity, synthesis yield, decay-corrected yield, processed volume, activity concentration, process duration, production status, and available cassette diagnostic data were among the other characteristics that were captured. Each of the radioactive material was transferred, transferred, transferred, appraised.

➤ Activity-Balance Analysis

The activity retention between two consecutive process stages was calculated as:

$$R_i(\%) = \frac{A_{i+1}}{A_i} \times 100 \quad (1)$$

Where A_i and A_{i+1} represent the measured ^{18}F activity at the upstream and downstream stages, respectively. This method is in line with activity-based efficiency and recovery estimates that are frequently employed in automated radiochemical processing [12,13]. In these calculations, the activity recovered at a later processing step is compared to the

activity available at the previous stage. The corresponding apparent activity loss was calculated as:

$$L_i(\%) = 100 - R_i \quad (2)$$

A stage-resolved activity profile was created using these characteristics, and process areas linked to comparatively significant variations in observed activity were identified. Measured activity variations were interpreted in relation to the amount of time that had passed throughout the synthesis process since ^{18}F undergoes radioactive decay. Decay-corrected values were taken into account separately when available. Similar stage-specific activity efficiencies and recovery values using measured activity at consecutive processing steps have been reported in earlier radiochemical experiments.

The QMA-to-reactor transition's slight apparent negative loss was not thought to be the result of physical exercise. This is due to the fact that the fact that the following: an activity may be obtained from an automated geometry. As a result, rather than being a real increase in radioactive activity, this seeming negative figure was seen as a measurement-related discrepancy.

➤ Functional Sorbent and Fluidic Stage Evaluation

The QMA and tC18 stages received special interest because they offer direct solid-liquid interfaces that allow radioactive species to be caught, transported, and released. While downstream transfer was evaluated from activity entering and exiting the reactor/tC18-hydrolysis pathway, QAM performance was evaluated using measured trapping and elution activities. Fluoride trapping, transfer, and recovery during automated radiochemical processing have been assessed using comparable stage-specific activity measures. The observed activity differences were not assigned exclusively to adsorption. Instead, they were interpreted as process-level indicators that may include material-surface retention, adsorption/desorption, ion-exchange interactions, incomplete mass transfer, residence-time effects, and other stage-specific transport phenomena.

➤ Statistical Analysis

For the primary activity, retention, and production variables, descriptive statistics were computed. Relationships between process-stage factors and the final [^{18}F] FDG synthesis yield were assessed using Pearson correlation coefficients and linear regression analysis. The interquartile range (IQR) method was used to assess potentially anomalous observations. Identification was found in relation to their respective production production.

➤ Materials-Physics Interpretation

The observed activity distribution was understood within a materials-physics framework in which radioactive-material transport is controlled by fluidic motion and interactions at solid-liquid interfaces. Surface residence, residence, ion exchange time, ion exchange time, mass, ion exchange, adsorption, ion-exchange, adsorption, adsorption, adsorption, adsorption. As a result, the FASTlab 2 route was viewed as a coupled material-transport system where the final

synthesis yield may be affected by the physicochemical properties of fluidic interfaces and functional sorbents. Because there are no direct measurements of surface chemistry, adsorption isotherms, interfacial energy, microscopic residence durations, or material-specific sorption coefficients in the production records that are currently available, the interpretation was kept at the process level.

III. RESULTS AND DISCUSSION

➤ Total Process Performance and Stage-Resolved ^{18}F Activity.

After duplicate entries were eliminated, 27 distinct [^1F] FDG production records were found. Sixteen successful runs were included in the quantitative analysis because they included process-stage data that was sufficiently thorough. The decay-corrected yield was $63.63 \pm 15.84\%$, while the mean final synthesis yield was $55.63 \pm 13.74\%$. Measurements of stage-resolved activity showed that the distribution of F was not uniform throughout the synthesis route. While QMA elution reached $98.45 \pm 0.57\%$, QMA trapping demonstrated a high and comparatively consistent mean retention of $98.60 \pm 0.98\%$. On the other hand, reactor. Transfer to the tC18/hydrolysis stage averaged $78.74 \pm 14.10\%$, while reactor-labeling retention averaged $82.96 \pm 6.46\%$. During QMA trapping, reactor labeling, and transfer

to the tC18/hydrolysis stage, the associated apparent activity losses were roughly 1.40%, 17.04%, and 21.26%, respectively. The coefficient of variation increased from roughly 1.0% for QMA trapping to 7.8% for reactor-labeling retention and 17.9% for downstream transfer. As a result, the initial fluoride-capture stage was very repeatable, although reactor processing and subsequent downstream transfer showed more run-to-run variability. The slight apparent negative loss recorded for the QMA-to-reactor transition was not interpreted as a physical increase in radioactive activity. Small deviations from an ideal activity balance may result from variations in measurement geometry and detector response since the recorded activities were collected by detector-based measurements at various points inside the automated system. This apparent negative number was therefore considered a measurement-related aberration rather than a real increase in F activity.

Overall, the stage-resolved activity profile shows that the behavior of radioactive material inside the synthesis system cannot be adequately described by the final synthesis yield alone. Rather, activity-retention measurements provide the foundation for investigating the connection between downstream transfer efficiency and final synthesis yield by identifying particular process locations where transport variability and apparent activity losses become more noticeable.

Table 1 Stage-Resolved ^{18}F Activity Retention and Apparent Activity Loss During Automated [^{18}F] FDG Synthesis.

Process stage	Mean retention (%)	Mean apparent loss (%)
QMA trapping	98.60 ± 0.98	1.40
QMA elution	98.45 ± 0.57	1.55
Reactor/labeling	82.96 ± 6.46	17.04
Transfer to tC18/hydrolysis	78.74 ± 14.10	21.26

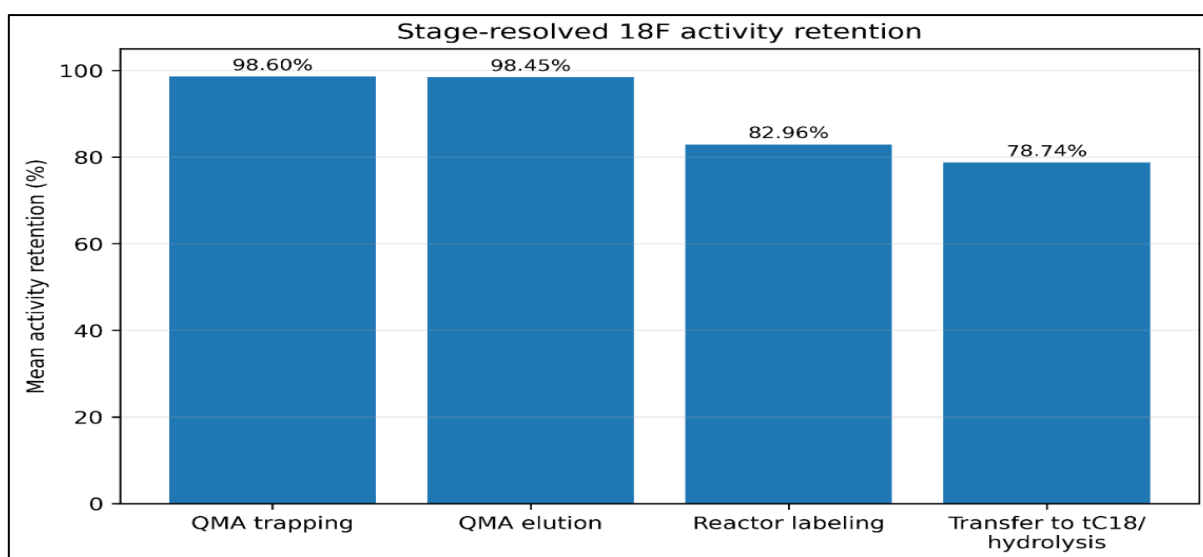


Fig 1 Stage-Resolved Mean ^{18}F Activity Retention Across the Automated FASTlab 2 Synthesis Pathway.

➤ Downstream Transfer as a Strong Process-Stage Correlate of Yield.

Using the 16 successful runs with sufficiently complete process-stage data, Pearson correlation and linear regression analyses were conducted to identify which process factors were most closely associated with final synthesis

performance. With a Pearson's correlation coefficient of ($r=0.731$) and ($R^2=0.534$), transfer efficiency toward the tC18/hydrolysis stage showed the best positive link with final [^{18}F] FDG yield. The observed yield variation in the matching yield slope was about 53. Compared to the first QMA phases, this link was significantly stronger. While QMA elution

efficiency had virtually no linear association ($r=-0.048$), ($R^2=0.002$), QMA trapping efficiency only showed a modest positive correlation with final yield ($r=0.267$), ($R^2=0.071$). The low variability and high mean QMA trapping and elution

efficiency suggest that downstream transfer was more closely linked to the observed yield variance than variations in initial fluoride collection and release.

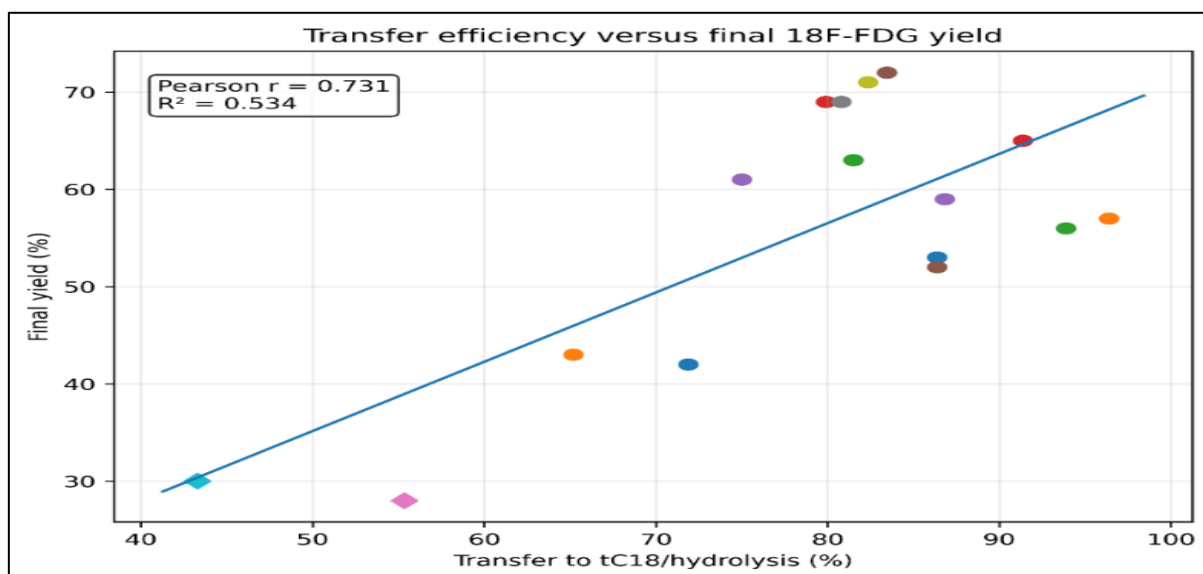


Fig 2 Relationship Between Downstream Transfer Efficiency Toward the tC18/Hydrolysis Stage and Final [^{18}F] FDG Synthesis Yield.

Rather from being a direct assessment of a particular physical mechanism, the downstream transfer parameter should be viewed as a process-level signal. Incomplete transfer, surface retention, adsorption/desorption effects, residence-time variations, and mass-transfer limits are all possible outcomes of integrating the behavior of radioactive material as it passes through interconnected components. The reactor-to-tC18/hydrolysis pathway is thus identified as a significant measurable location of process variability because to the strong correlation between downstream transfer efficiency and final yield.

➤ Reactor-Labeling Retention and Other Process Variables.

With a Pearson's correlation coefficient of ($r=0.410$) and ($R^2=0.168$), reactor-labeling retention demonstrated the

second-strongest positive link with final [^{18}F] FDG yield. Although not as strongly as downstream transfer toward the tC18/hydrolysis step, this moderate association shows that radioactive material retention through the reactor-labeling stage was linked to end process performance. Higher initial activity alone did not account for the significant difference in final synthesis performance, as seen by the weaker association between starting activity and final yield ($r=0.350$, $R^2=0.123$). Relatively modest correlations with final yield were also found for drying time ($r=0.303$, ($R^2=0.092$)) and third tC18 trapping time ($r=0.282$, ($R^2=0.080$)).

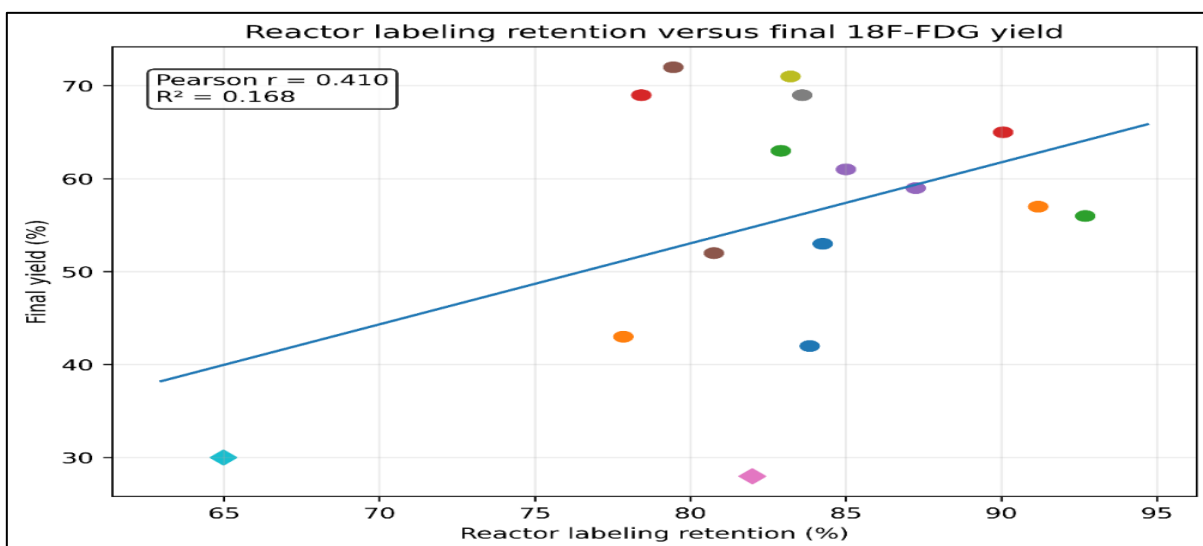


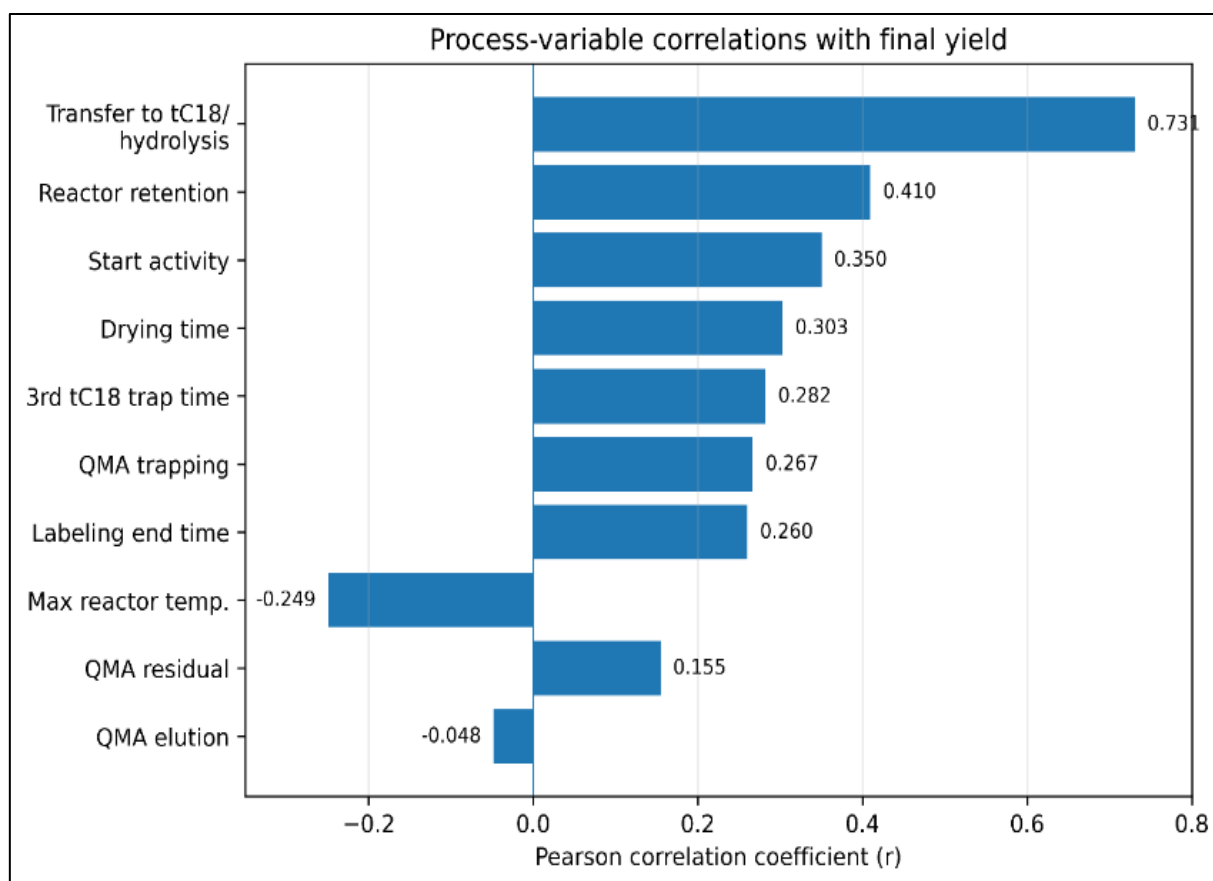
Fig 3 Relationship Between Reactor-Labeling Retention and Final [^{18}F]FDG Synthesis Yield.

Table 2 Univariate Relationships Between Process Variables and Final [^{18}F] FDG Synthesis Yield.

Process variable	Pearson r	R^2
Transfer to tC18/hydrolysis	0.731	0.534
Reactor-labeling retention	0.410	0.168
Starting activity	0.350	0.123
Drying time	0.303	0.092
Third tC18 trapping time	0.282	0.080
QMA trapping efficiency	0.267	0.071
Labeling-end time	0.260	0.068
Maximum reactor temperature	-0.249	0.062
QMA residual after elution	0.155	0.024
QMA elution efficiency	-0.048	0.002

Similarly, there were only weak linear correlations between final yield and labeling-end time ($r=0.260$), ($R^2=0.068$) and maximum reactor temperature ($r=-0.249$), ($R^2=0.062$). Only a weak residual activity. All of these findings suggest that the amount of initial radioactive

material capture was insufficient to account for the performance of the end synthesis. Rather, for factors that describe the retention and transfer of radioactive materials at subsequent stages of the synthesis process, the observed relationships became stronger.

Fig 4 Summary of Pearson Correlation Coefficients Between Selected Process Variables and Final [^{18}F] FDG Synthesis Yield.

➤ Low-Performance Runs and Downstream Activity Loss

Reduced downstream radioactive-material transmission was demonstrated in two production runs. Run 20003494 had a reactor-labeling retention of 81.99% and a QMA trapping efficiency of 99.06%, although the ultimate yield was just 28%. At the tC18/hydrolysis stage, its transfer efficiency dropped to 55.34%. In a similar vein, run 20003610 yielded 30% overall, with downstream transfer efficiency of 43.28%, reactor-labeling retention of 64.99%, and QMA trapping of 96.13%. Effective initial fluoride capture was followed in

both runs by significantly reduced activity retention following further processing. These findings demonstrate the usefulness of stage-resolved activity measurements for locating process regions linked to decreased radioactive-material transfer and show that poor final yield was not always linked to ineffective QMA trapping. As a result, the two scenarios offer real-world illustrations that align with the statistical analysis, where downstream transfer had the best correlation with final synthesis yield.

Table 3 Representative Low-Performance [^{18}F] FDG Production Runs Illustrating Downstream Activity Loss Following Efficient QMA Trapping.

Report No.	Start activity	Final yield	Corrected yield	QMA trapping	Reactor retention	Transfer to tC18/hydrolysis
20003494	4509	28	32	99.06	81.99	55.34
20003610	2010	30	34	96.13	64.99	43.28



Fig 5 Comparison of Representative Low-Performance Production Runs Showing Efficient QMA Trapping But Reduced Downstream Radioactive-Material Transfer.

➤ Relationship Between Process Time, Temperature, and Final Yield

These results reveal that low final yield was not necessarily associated with inefficient QMA trapping and highlight the value of stage-resolved activity measurements for identifying process regions associated with reduced radioactive-material transfer. Because downstream transfer showed the strongest link with final synthesis yield, the two scenarios provide real-world examples that support the statistical study. The average labeling-end time was 793.94 ± 12.86 seconds, while the average drying time was 666.94 ± 11.89 seconds. The third tC18 trapping period averaged 991.56 ± 12.60 s, and the maximum reactor temperature was 126.06 ± 1.18 °C. comparably, the comparably consistent standard operational production were rather tiny. Despite this temporal and thermal durability, the associations with final yield were quite poor. While labeling-end time ($r = 0.260$, $R^2 = 0.068$) and third tC18 trapping time ($r = 0.282$, $R^2 = 0.080$) shown equally moderate correlations, drying time demonstrated a good correlation with final yield ($r = 0.303$, $R^2 = 0.092$). The final yield reactor temperature temperature (r). These findings suggest that only a small portion of the observed variance in ultimate yield was explained by the temporal and thermal variables under investigation. Thus, there were no significant linear relationships between yield variability and the relatively steady process timing and reactor temperature within the examined operating range.

➤ Materials-Physics Interpretation of the Downstream Losses

The observed downstream variability can be interpreted from a materials-physics perspective as the result of mass transfer across multiple material interfaces, fluidic transport, radioactive decay, and interfacial retention. The high and reproducible QMA trapping efficiency suggests a relatively well-controlled ion-exchange interface. After elution, however, the radioactive fluoride passes through a more complex pathway involving the reaction vessel, tubing, valves, and purification materials, where residence time, incomplete displacement, and possible surface interactions may contribute to activity losses. The present data do not allow the individual contributions of adsorption, surface diffusion, residence time, or material chemistry to be quantified independently. Therefore, the observed relationship should be regarded as process-level evidence of downstream transport and retention rather than direct evidence of a specific microscopic mechanism. The weak correlations between temperature or process-time variables and final yield further suggest that these operating parameters alone do not adequately explain the observed variability. Given its relatively strong association with final yield and its greater variability, the reactor-to-tC18/hydrolysis pathway represents the most relevant stage for further investigation. Controlled materials characterization and direct surface or

adsorption measurements are required to identify the underlying interfacial mechanisms.

IV. DISCUSSION

➤ *Principal Finding and Its Materials-Physics Significance*

The principal finding was that downstream radioactive-material transfer showed the strongest association with final [^{18}F] FDG yield ($r = 0.731$, $R^2 = 0.534$), whereas QMA fluoride trapping was highly reproducible. This indicates that process variability may arise predominantly during reactor labeling and subsequent transfer toward the tC18/hydrolysis stage. From a materials-physics perspective, these differences may reflect cumulative fluid–material interactions, interfacial retention, transport resistance, and incomplete transfer within the synthesis pathway. However, the present data provide process-level evidence rather than direct proof of a specific adsorption mechanism. The two low-performance runs, which maintained high QMA trapping efficiency but showed reduced downstream transfer, further support the importance of downstream transport processes. These findings identify the reactor-to-tC18/hydrolysis pathway as a key target for further investigation of surface retention and interfacial transport behavior.

➤ *Comparison with Previous FASTlab 2 Studies and Process Implications.*

Previous FASTlab 2 studies have mainly focused on radiochemical yield, product quality, cassette configuration, and process optimization [4,5,8–10]. Modifications to precursor amount, FTAG trapping, tC18 purification, cassette valves, and tubing flushing have been reported to influence production performance [10]. In contrast, the present study examined the distribution and retention of ^{18}F activity across successive process stages, providing insight into where transfer efficiency decreases and process variability becomes more pronounced.

The results showed relatively stable QMA trapping but greater variability during reactor processing and transfer toward the tC18/hydrolysis stage. This stage-resolved approach therefore provides complementary information that may not be captured by final yield alone. From a practical perspective, downstream material interfaces and fluidic transitions should be considered alongside conventional reaction parameters. However, the present data do not identify a specific material or component as the direct cause of activity losses; controlled studies of materials, tubing configurations, surface characteristics, and flow conditions are required to determine the underlying mechanisms.

V. CONCLUSIONS

This study investigated automated [^{18}F] FDG synthesis using a stage-resolved activity-balance approach from a materials-physics perspective. Among 27 unique production records, 16 successful runs with sufficiently complete process-stage data were included in the quantitative analysis. The results showed that initial QMA fluoride trapping was highly reproducible, whereas greater variability occurred during reactor labeling and subsequent downstream transfer.

In particular, transfer efficiency toward the tC18/hydrolysis stage showed the strongest measurable association with final [^{18}F] FDG synthesis yield ($r = 0.731$, $R^2 = 0.534$). This finding indicates that final synthesis performance was more closely associated with downstream radioactive-material transfer than with the initial fluoride-capture stage. The stage-resolved activity profile is consistent with the contribution of coupled fluidic transport and material–interface interactions, including possible surface retention, adsorption/desorption, residence-time effects, and mass-transfer limitations. However, the present data represent integrated process-level behavior and do not establish a specific microscopic mechanism responsible for the observed activity losses.

Overall, the study demonstrates that stage-resolved radioactive-material measurements can provide information that is not apparent from final synthesis yield alone. The reactor-to-tC18/hydrolysis pathway was identified as the principal measurable region associated with downstream variability and therefore represents an important target for further investigation. Future studies combining controlled material characterization with direct surface, adsorption, and fluidic measurements may help distinguish the specific interfacial mechanisms contributing to radioactive-material retention and transfer during automated [^{18}F] FDG synthesis.

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